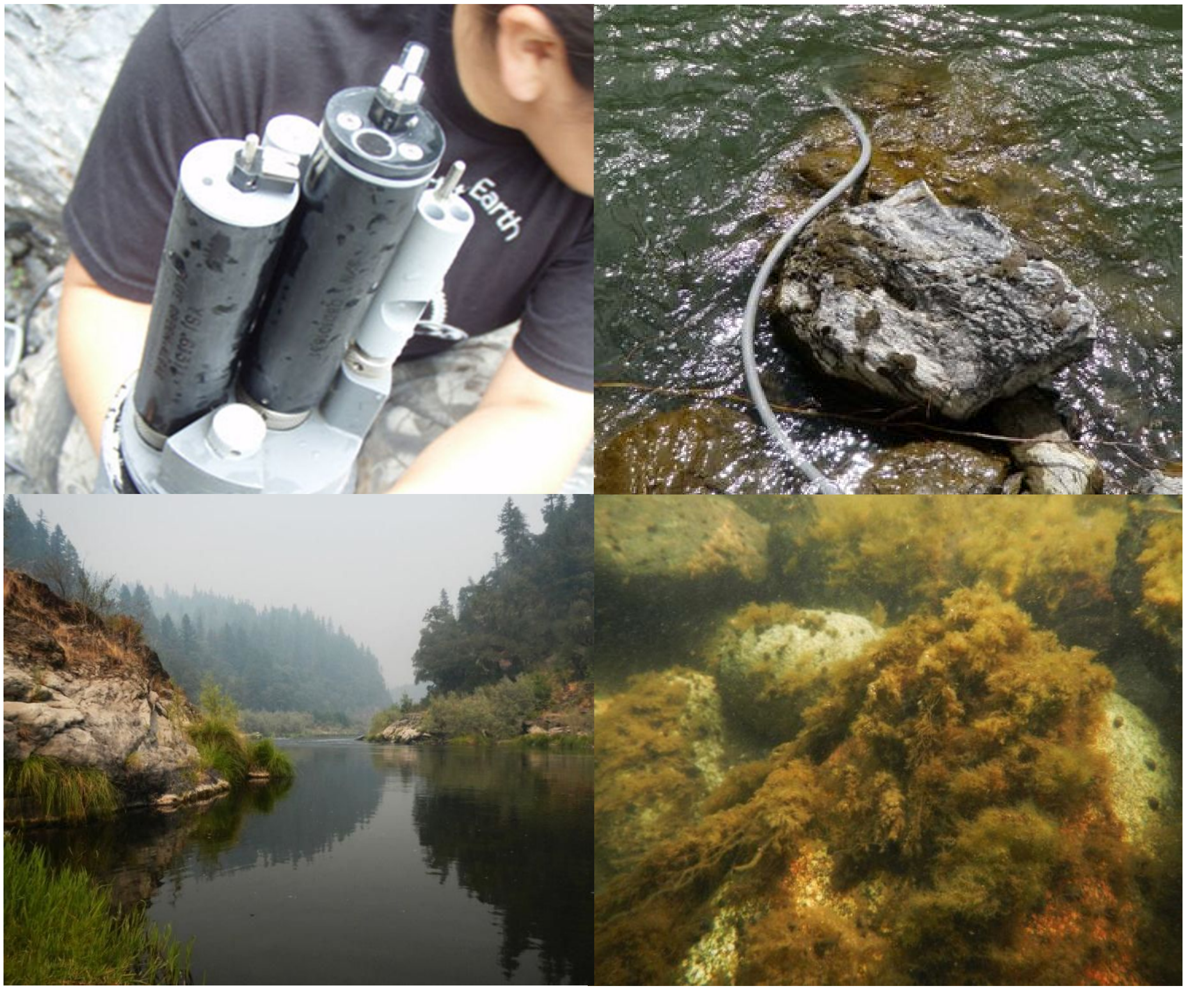
Synthesis of Continuous Water Quality Data for the Lower and Middle Klamath River, 2001-2011



PREPARED FOR THE

KLAMATH BASIN TRIBAL WATER QUALITY WORK GROUP

BY

ELI ASARIAN
KIER ASSOCIATES
EUREKA, CALIFORNIA

JACOB KANN, PH.D.
AQUATIC ECOSYSTEM SCIENCES LLC
ASHLAND, OREGON

SYNTHESIS OF CONTINUOUS WATER QUALITY DATA FOR THE LOWER AND MIDDLE KLAMATH RIVER, 2001-2011

THIS REPORT WAS PREPARED FOR THE

KLAMATH BASIN TRIBAL WATER QUALITY WORK GROUP

BY

ELI ASARIAN
KIER ASSOCIATES
EUREKA, CALIFORNIA
WWW.KIERASSOCIATES.NET

JACOB KANN, PH.D.
AQUATIC ECOSYSTEM SCIENCES LLC
ASHLAND, OREGON
WWW.AQUATIC-ECOSCIENCES.COM

MAY, 2013

Suggested citation:
Asarian, E. and J. Kann. 2013. Synthesis of Continuous Water Quality Data for the Lower and Middle Klamath River, 2001-2011. Prepared by Kier Associates and Aquatic Ecosystem Sciences for the Klamath Basin Tribal Water Quality Work Group. 50p. + appendices.

EXECUTIVE SUMMARY

This study analyzes water quality data collected in the years 2001 through 2011 with continuous multi-parameter probes in the lower and middle Klamath River (i.e., between Iron Gate Dam and Turwar, just upstream of the Klamath Estuary) in California, as well as the four major tributaries to this reach: the Shasta, Scott, Salmon, and Trinity rivers. Parameters analyzed included water temperature, dissolved oxygen (DO) concentration, DO as percent of saturation, and pH. Data were collected by the Karuk Tribe, Yurok Tribe, U.S. Fish and Wildlife Service (USFWS), and Quartz Valley Indian Reservation. Analyses included examination of longitudinal, seasonal, and inter-annual patterns as well as a preliminary assessment of the causal factors driving to those patterns.

The Klamath River and some of its tributaries are designated as impaired waterbodies under the Clean Water Act. Water quality is a concern in the Klamath River because it affects culturally and economically important salmon fisheries as well as public health. During the warm summer months, dissolved oxygen and pH followed a 24-hour cycle in which photosynthesis by aquatic plants and algae attached to the streambed (periphyton) elevated pH and dissolved oxygen concentrations during the day. Respiration at night by those same organisms had the reverse effect, depressing dissolved oxygen and pH. The resulting low nighttime DO and high daytime pH values observed in this study can be chronically stressful to fish, but were not acutely lethal.

Although variation occurred between years and stations, the seasonal water quality pattern was relatively consistent. From May through July, flow declined and air temperatures increased. Mean and maximum water temperature peaked in late July or early August, coincident with lowest minimum DO. The daily range (i.e., daily maximum minus daily minimum) of pH and DO followed a similar seasonal trajectory, driven by the daily cycles of photosynthesis and respiration and typically peaking between late July and early September.

As with the seasonal patterns, while there was variation in timing and magnitude, the overall longitudinal (i.e., upstream to downstream) patterns in water quality were relatively consistent from year-to-year. Percent exceedance of regulatory and biological thresholds for DO was higher in the upper half of the study area (i.e., Iron Gate Dam to Happy Camp) than in the lower half. Percent exceedance of pH thresholds was highest in the upper third of the study area (i.e., Iron Gate to Seiad Valley). In contrast to DO and pH, the lowest percent exceedances for water temperature occurred at Iron Gate Dam.

In contrast to the river processes which dominate water quality at sites downstream, water quality at Iron Gate Dam is driven by conditions directly upstream in Iron Gate Reservoir, which results in unique water quality conditions. For example, the magnitude of the 24-hour cycle of water temperature, DO, and pH is muted due to the thermal mass of the reservoir and the depth at which reservoir water is withdrawn (i.e., from light limited depths with little photosynthetic activity) for release into the river. Iron Gate Dam has lower minimum DO concentrations and these low values occur later in the season than at sites downstream, likely associated with the decomposition of blue-green algal biomass as seasonal blooms decline, and the breakdown of thermal stratification in the reservoir. Although other sites in the upper third of the study area (i.e., from Seiad Valley upstream) had daily maximum pH values that were similar to or higher than values observed at Iron Gate, high daily maximum pH values at Iron Gate were not due to large 24-cycles (i.e., daily range) and were correlated with high chlorophyll-*a* concentrations from upstream algal blooms.

Of the four monitored tributaries to the Klamath River, the Shasta River had the higher percent exceedances of water quality thresholds for every parameter as well as the most extreme individual measurements. The Salmon River had lowest summer water temperatures, followed closely by the Trinity River, but the Trinity River had higher DO. The Scott River was the only tributary with two monitoring stations (one at the USGS gage at the outlet of Scott Valley and another downstream at the bottom of the Scott River Canyon above the confluence with the Klamath River). A comparison of these two stations showed that 24-hour cycles in temperature, DO, and pH had lower magnitudes at the downstream site, likely due to tributary input between the stations as well as re-aeration of dissolved oxygen in the turbulent canyon.

The 2001-2011 study period analyzed in this report encompassed a wide range of hydrological, meteorological, and nutrient conditions with which to assess relationships among several important dependent and independent variables at mainstem and tributary sites. The correlation analyses contained in this report are intended to provide an initial exploration of factors influencing water quality, and to provide a basis for formulation of additional questions and analyses. Continued monitoring by Klamath Basin Tribes and their cooperators will provide additional years of data to increase sample size and encompass an increased range of conditions.

At mainstem and tributary sites, of all independent variables evaluated (e.g., flow, nutrient concentration, air temperature, and precipitation), flow had the strongest effect on water quality, likely due to multiple complex interacting physical, chemical, and biological pathways. The report includes a conceptual model and description of these pathways, which include effects of: 1) thermal mass and transit time where reduced flow makes water temperature more responsive to meteorological conditions; 2) water temperature on the solubility of oxygen in water and the growth rate of periphyton; 3) reduced flow and decreased mean water depth on the amplification of the effect of periphyton on water column DO and pH; 4) high flows in causing scour and sloughing of periphyton which could reduce periphyton biomass; and 5) increased water depth on reducing the amount of light reaching the stream bed which could limit periphyton growth. DO had stronger correlations with independent variables such as flow and temperature than pH did. Correlations between flow and pH daily range were much stronger than correlations between flow and pH maximum.

Correlation does not necessarily prove causation, and it is particularly difficult to untangle the relative contributions of multiple variables controlling water quality given that parameters such as flow, water temperature, and nutrient concentration tend to co-vary, especially in June and July (i.e., high flow is associated with low water temperature and low nutrient concentration). Additional multivariate statistical analyses beyond the scope of this report would help increase understanding of these observed patterns.

While the 2001-2011 study period encompassed a substantial portion of the flow variability contained in the 1961-2011 hydrologic period of record at Iron Gate Dam, it did not include the most extreme low flows that occurred in 1977 and the early 1990s. Given that water quality appears to be generally worse during relatively low-flow years than in relatively high-flow years, it is possible (or perhaps even likely) that if extreme low flows occur again in the future, water quality conditions would be worse than observed in the 2001-2011 study period.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 DESCRIPTION OF STUDY AREA

The Klamath River is one of the major salmon rivers of the western United States. Its uppermost tributaries originate in southern Oregon and drain into Upper Klamath Lake, the Link River and Lake Ewauna, where the Klamath River proper begins. From this point the mainstem river flows through a series of impoundments, including Keno, J.C. Boyle, Copco, and Iron Gate Reservoirs. Below Iron Gate Dam, the river flows 190 miles to the Pacific Ocean.

This study focuses on the lower and middle mainstem Klamath River (i.e., between Iron Gate Dam and Turwar, just upstream of the Klamath Estuary), as well as the four major tributaries to this reach: the Shasta, Scott, Salmon, and Trinity rivers (Figure 1).

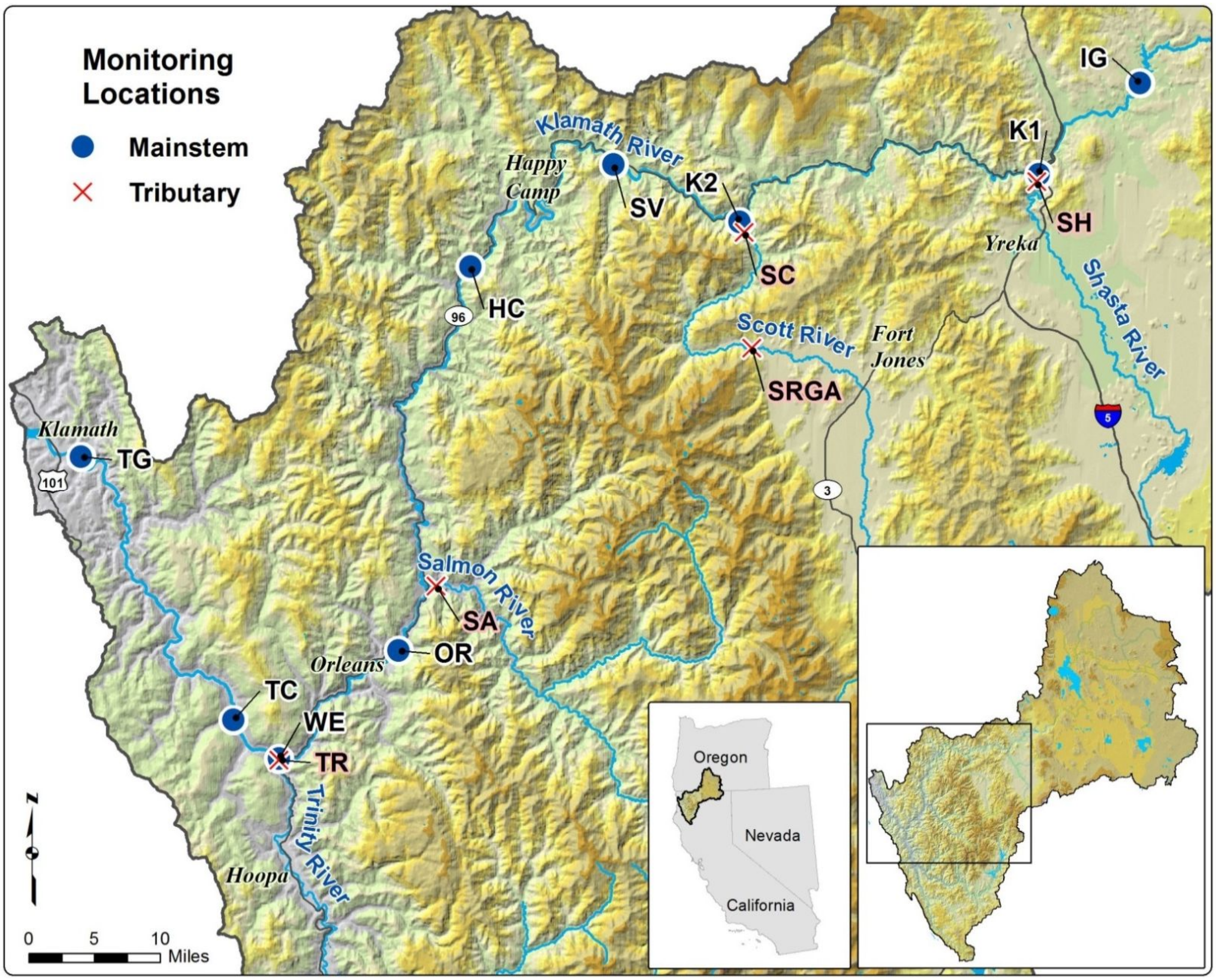


Figure 1. Location of monitoring stations on the mainstem Klamath River and tributaries.

1.2 BACKGROUND

The Klamath River and some of its tributaries are designated on the Clean Water Act (CWA) Section 303(d) list as impaired water bodies. The list of impairments varies by state and reaches within states, but includes pH (only in Oregon reservoirs), water temperature, nutrients, organic enrichment/low dissolved oxygen (DO), sedimentation/siltation, ammonia toxicity, microcystin, and chlorophyll-*a* (NCRWQCB 2010). Total Maximum Daily Loads (TMDLs) have developed for the river and its tributaries by the U.S. EPA, Oregon Department of Environmental Quality (ODEQ 2010) and the North Coast Regional Water Quality Control Board (NCRWQCB 2010). Copco and Iron Gate reservoirs have been the subject PacifiCorp relicensing of the Klamath Hydropower Project (KHP) with the Federal Energy Regulatory Commission, and State Water Board CWA section 401 water quality certification. The TMDLs have been completed but the other two processes have been put on hold pending potential implementation of two linked agreements: the Klamath Hydrologic Settlement Agreement (KHSA) and the Klamath Basin Restoration Agreement (KBRA). The KHSA is a multi-party agreement to remove J.C. Boyle, Copco and Iron Gate Dams. The KBRA is an agreement between Klamath Basin Tribes, irrigators, fishermen, environmental groups, counties, states, and federal agencies that aims to both restore Klamath Basin fisheries and provide stability to the local economies.

Water quality is a concern in the Klamath River because it affects culturally and economically important salmon fisheries as well as public health. During the warm summer months, dissolved oxygen and pH follow a 24-hour cycle in which photosynthesis by aquatic plants and algae attached to the streambed (periphyton) elevates pH and dissolved oxygen concentrations during the day. Respiration at night by those same organisms has the reverse effect, depressing dissolved oxygen and pH (Nimick et al. 2011). The resulting low nighttime DO and high daytime pH can exceed water quality standards and be stressful to fish (NCRWQCB 2010) (Figure 2).

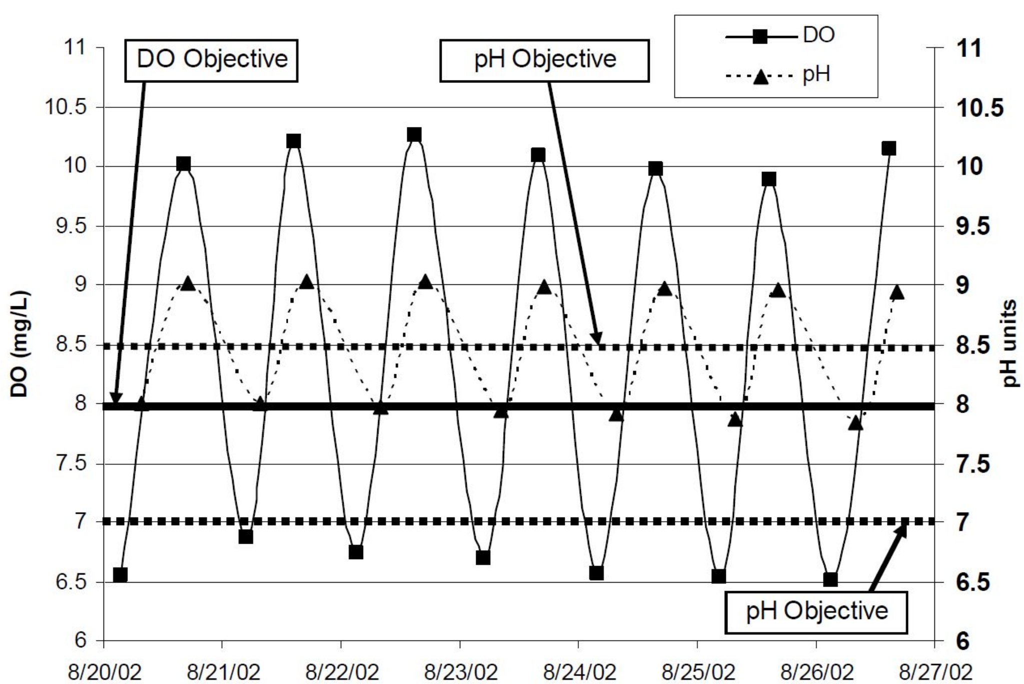


Figure 2. Example diel cycle of (24-hour) DO and pH in the Klamath River at Seiad Valley in August 2002. Figure from NCRWQCB (2010).

1.3 PREVIOUS AND CURRENT KLAMATH RIVER WATER QUALITY STUDIES

Continuous temperature, DO, and pH data have been collected in the lower and middle Klamath River[1] and tributaries for over a decade by various agencies and tribes; however, other than annual monitoring reports (Karuk Tribe 2007, 2008, 2010, 2011, 2012; Yurok Tribe 2004b, 2004c, 2005, 2010a, 2011a, 2012a), relatively few in-depth analyses have been performed on these data. Exceptions include Ward and Armstrong's (2010) calculation of community metabolism, the Hoopa Valley Tribe's development of nutrient criteria for the Klamath River (HVTEPA 2008), and the development of water quality models for the flow studies (Deas and Orlob 1999, Watercourse Engineering 2003), Klamath River TMDLs (NCRWQCB 2010) and KHP relicensing (PacifiCorp 2004, 2008).

In contrast, Klamath River nutrient dynamics have been studied to a greater degree, and include a computation of nutrient budgets for the free-flowing Klamath River reaches (Asarian et al. 2010, Asarian and Kann 2006) and for Iron Gate and Copco Reservoirs (Kann and Asarian 2005, 2007; Asarian et al. 2009), a high-frequency study of two short free-flowing Klamath River reaches (Deas 2008), two synthesis reports (Butcher 2008 and PacifiCorp 2006), development of plug-flow model (Armstrong and Ward 2008a), and calculation of nutrient loads (Armstrong and Ward 2008b).

This report is intended to provide a review of continuous water quality datasets collected by tribes and agencies in the lower and middle Klamath River and tributaries from 2001–2011. The report was prepared for the Klamath Basin Tribal Water Quality Work Group (Work Group) using funds awarded to the Work Group by the U.S. EPA Region 9 and administered by the Yurok Tribe. Data analysis and report writing were conducted by Kier Associates and Aquatic Ecosystem Sciences LLC.

1.4 STUDY GOALS

The overall goals of this study were to compile and analyze continuous water quality data for the Klamath River for the years 2001-2011. This included examination of longitudinal, seasonal, and inter-annual patterns as well as a preliminary assessment of the causal factors driving those patterns.

2 METHODS

2.1 CONTINUOUS WATER QUALITY DATA

2.1.1 Monitoring Locations, Parameters, and Equipment

Continuous water quality probes were deployed at nine mainstem stations from just below Iron Gate (river mile 189.73) to Turwar (river mile 5.79, just upstream of the Klamath Estuary), as well as in four tributaries (Shasta, Scott, Salmon, and Trinity rivers) near their confluences with the Klamath River and in the Scott River at the downstream end of Scott Valley. Three of the mainstem stations (Klamath above Shasta River, Klamath above Scott River, and Klamath River at Happy Camp) were monitored for a shorter subset of the years, and monitoring at the Scott Valley station did not begin until 2007. Sampling stations and station codes used for this study are shown in Table 1 and Figure

[1] Further upstream on the Klamath River in Oregon, the U.S. Bureau of Reclamation has been collecting continuous water quality probes for many years and these data have been used to develop an updated water quality model for Keno Reservoir (Sullivan et al. 2013).

1 and will be used throughout this report. Within the 2001-2011 study period, a few monitoring stations were relocated short distances due to logistical and access issues. In such cases, the most recent station location and code are used in this report to facilitate comparisons across years[2].

Data were collected by the Karuk Tribe, Yurok Tribe, U.S. Fish and Wildlife Service (USFWS), and Quartz Valley Indian Reservation (QVIR), with methodology and results described in the following reports: Karuk Tribe (2007, 2008, 2010, 2011, 2012), Yurok Tribe (2004b, 2004c, 2005, 2010a, 2011a, 2012a), Ward and Armstrong (2010), and QVIR (2008, 2009, 2011).

Measurements were recorded at 30 minute intervals. Parameters recorded included water temperature, pH, dissolved oxygen (DO) concentration, DO as percent of saturation, specific conductivity, and beginning in 2007, at select sites, phycocyanin[3]. The duration of the monitoring seasons varied by station and year, but generally occurred from May through October (Figure 3).

Equipment and procedures generally improved during the course of the study period. For example, at the beginning of the study period the Yurok Tribe, Karuk Tribe, and USFWS employed Hydrolab 4a probes utilizing the fouling-prone Clark's membrane method for (DO). Beginning in 2005 the Yurok Tribe upgraded to YSI 6600 EDS probes, and the Karuk Tribe and QVIR upgraded to YSI 6600 V2 probes in 2007. The YSI probes utilize an optical sensor for DO that is less prone to bio-fouling during multi-day deployments.

[2] The Yurok Tribeôs Klamath River below Trinity moved from Martinôs Ferry (RM 40.4) to Tully Creek (RM 38.5) in mid-2003, to below Trinity River (RM 42.5) in 2005, and then returned to Tully Creek in September 2007. The Yurok Tribeôs lowermost monitoring station moved from Klamath River at Turwar gage (RM 5.8) to above Turwar (RM 8.5) in 2005.

[3] Phycocyanin (a blue-green algal pigment) data were only available for a subset of years, so were excluded from most analyses in this report.

Table 1. Water quality monitoring stations on the mainstem Klamath River and tributaries.

	Station Description	Site ID	Station Code	River Mile	Latitude	Longitude	Drainage Area (km^2)	Elevation (ft)	Data Sources: Continuous WQ and Nutrient	Data Sources: Hydrology	Data Sources: Meteorology Location/ Source
Mainstem Stations	KR below Iron Gate	KR18973	IG	189.73	41.931083	-122.442200	11992	2169	USFWS 2001-2005, Karuk 2006-2011	USGS Iron Gate	Brazie Ranch/ CalFIRE
	KR above Shasta R.	KR17608	K1	176.08	41.831110	-122.591940	12553	2028	USFWS 2004-2005	USGS Iron Gate + accretions	Brazie Ranch/ CalFIRE
	KR above Scott R.	KR14261	K2	142.61	41.779360	-123.033110	13485	1535	USFWS 2003-2005	USGS Iron Gate + accretions	Oak Knoll/ USFS
	KR at Seiad Valley	KR12858	SV	128.58	41.842683	-123.218867	17975	1355	USFWS 2001-2003, Karuk 2004-2011	USGS Seiad	Oak Knoll/ USFS
	KR at Happy Camp	KR10066	HC	100.66	41.729667	-123.429583	20846	921	Karuk 2001-2005	USGS Seiad + accretions	Somes Bar/ USFS
	KR at Orleans	KR05912	OR	59.12	41.305600	-123.531583	21950	358	Karuk 2001-2011	USGS Orleans	Somes Bar/ USFS
	KR at Weitchpec (above Trinity R.)	KR04350	WE	43.5	41.185833	-123.705556	22611	194	Yurok 2001-2011	USGS Orleans+ accretions	Notcho/ Yurok Tribe
	KR above Tully Creek (below Trinity R.)	KR04250	MF/ KBW/ TC	42.5	41.192500	-123.717778	30457	183	Yurok 2001-2011	USGS Orleans + accretions + USGS Trinity	Notcho/ Yurok Tribe
	KR at Turwar	KR00579	KAT/ TG	5.79	41.516111	-123.999167	31339	22	Yurok 2001-2011	USGS Turwar	Notcho/ Yurok Tribe
Tributary Stations	Shasta R. near Klamath R.	SH00	SH00		41.823167	-122.595000	2054	2060	USFWS 2001-2005, Karuk 2006-2011	USGS Shasta	Brazie Ranch/ CalFIRE
	Scott R. at Johnson's Bar (near mouth)	SCM	SCM		41.768333	-123.026117	2107	1579	USFWS 2001-2002, Karuk 2003-2011	USGS Scott + accretions	Oak Knoll/ USFS
	Scott R. USGS gage	SCUS	SRGA		41.640690	-123.015037	1691	2639	QVIR 2007-2011	USGS Scott	Quartz Hill/ CalFIRE
	Salmon R. near Somes Bar	SA	SA		41.376950	-123.477217	1945	488	Karuk 2001-2011	USGS Salmon	Somes Bar/ USFS
	Trinity River near Weitchpec	TR	TR		41.184444	-123.705278	7685	192	Yurok 2001-2011	USGS Trinity + accretions	Hoopa/ Hoopa Tribe

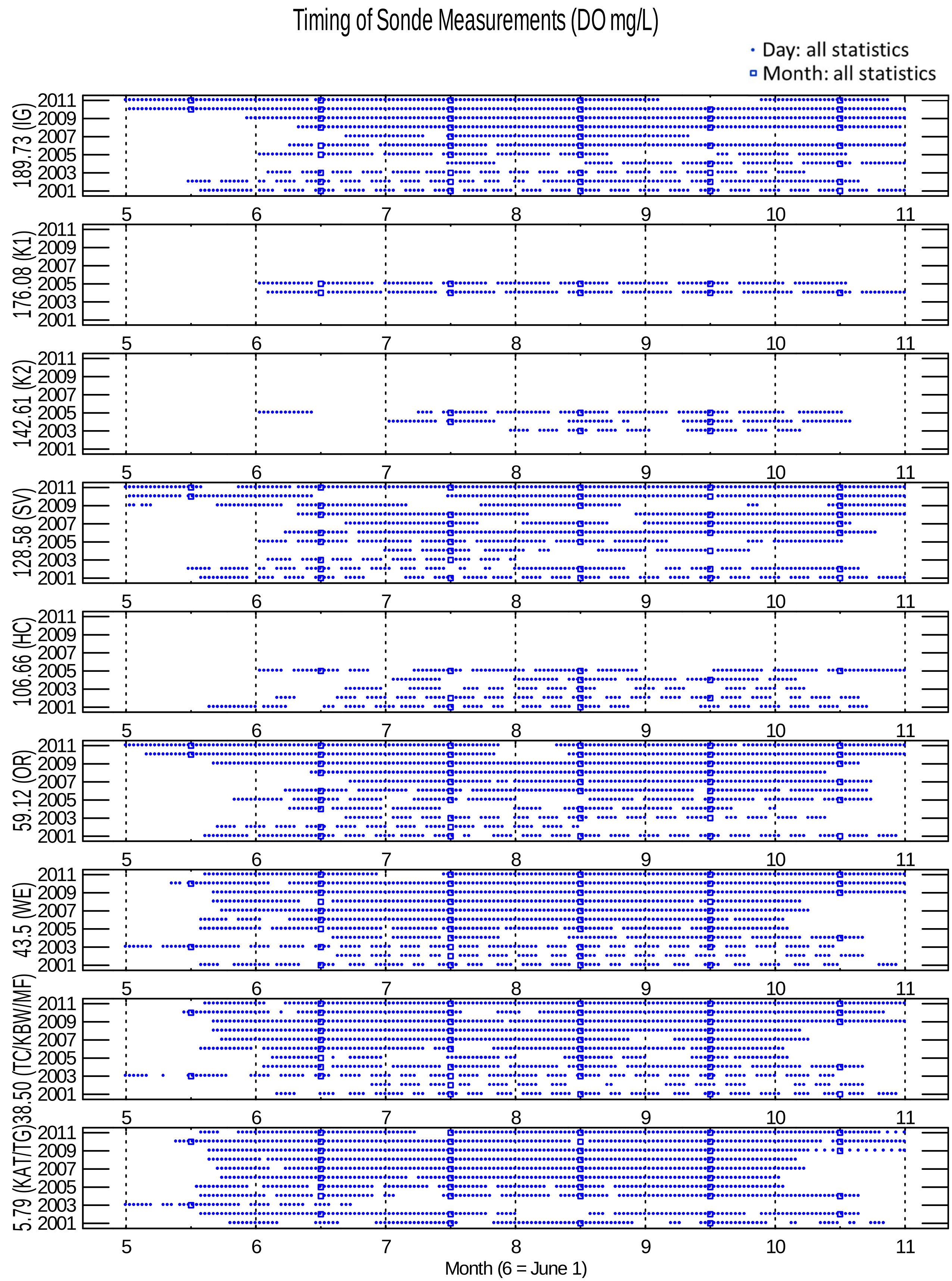


Figure 3. Days and months with sufficient DO measurements to calculate daily and/or monthly statistics (see section 2.1.3 for completeness criteria) for mainstem Klamath River sites. Sites are labeled by code and river mile. Monthly symbols (boxes) placed at center of month. Graphs for water temperature and pH are in Appendix A.

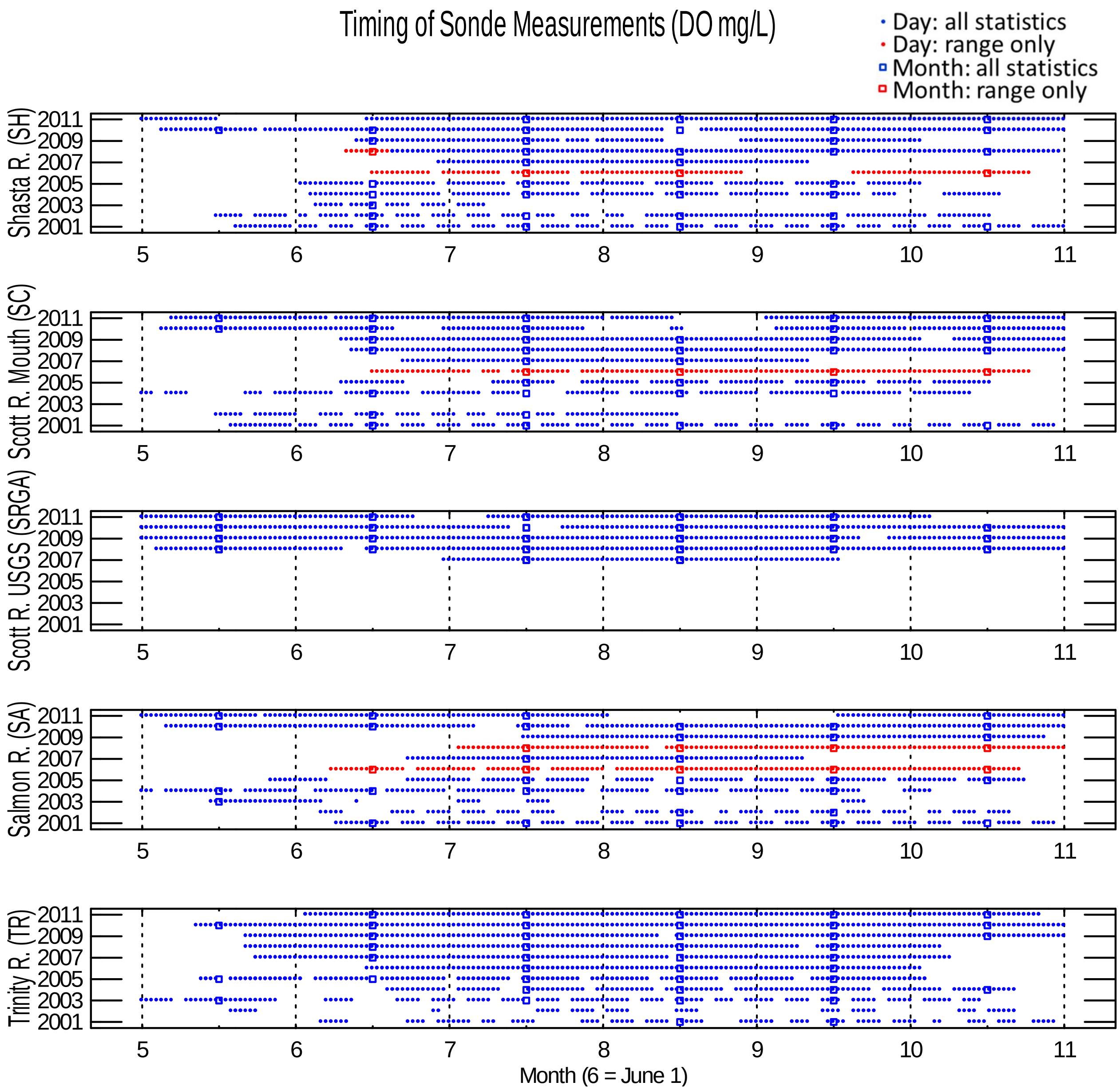


Figure 4. Days and months with sufficient DO measurements to calculate daily and/or monthly statistics (see section 2.1.3 for completeness criteria) for tributary sites. Sites are labeled by code and river mile. Monthly symbols (boxes) placed at center of month. Graphs for water temperature and pH are in Appendix A.

2.1.2 Data Compilation and Data Quality

Continuous water quality data for all stations in 2001-2005 and for three stations (IG, SV, OR) in 2006, were compiled and corrected by the USFWS and their contractors (Ward and Armstrong 2010). Data for each deployment were subjected to a labor-intensive process in which low quality data were removed and remaining data were corrected as necessary to address calibration drift and biofouling, resulting in an improved final dataset[4] utilized in the Ward and Armstrong (2010) report.

The 2006-2011 data were acquired from the Yurok Tribe (as a single Excel file), Karuk Tribe (as individual Excel files for each year and station), and QVIR (as individual Excel files for each year). The Yurok and Karuk Tribe enter their continuous water quality data, including QA/QC information such as pre-deployment and post-deployment measurements from a reference sonde, into the Yurok Environmental Data Storage System (YEDSS). For each deployment and parameter, YEDSS calculates data quality grades according to USGS protocols (Wagner et al. 2006) and automatically flags and removes values outside user-specified criteria (Karuk Tribe 2012). The Yurok Tribe applied corrections to their 2010 and 2011 data to address calibration drift and biofouling according to Wagner et al. (2006) procedures. The Karuk Tribe's 2006-2011 data (except IG, SV, and OR in 2006) were not corrected, nor were the Yurok Tribe's 2006-2009 data or QVIC's 2007-2011 data. Only those deployments where combined error from fouling and calibration drift exceeds data correction criteria[5] require correction (Wagner et al. 2006); thus, only a portion of the not yet corrected data actually warrants correction.

This report primarily relied on the QA/QC procedures of the USFWS for the 2001-2005 period and the Yurok Tribe, Karuk Tribe, and QVIR for the 2006-2011 period. Although formal quality control procedure was beyond the scope of this report, graphical inspections were made of all 30-minute continuous water quality data, and obvious erroneous data were removed from the dataset. Issues identified included 1) outliers at beginning and end of deployments (i.e., insufficient trimming of pre-deployment and post-deployment data), 2) calibration shifts between deployments, and 3) probe malfunctions resulting in excessively high or low values or excessive 24-hour cycles. Other information utilized in the data quality assessment included: 1) reviewing data grades for deployments, 2) flags and comments from YEDSS, 3) comments in Tribal annual data reports, and 4) reviewing other parameters, such as flow, to assess whether sudden shifts were due to equipment malfunction or appeared to be real.

Some datasets did not include DO as percent saturation[6] and the YSI datasondes were configured to output DO as percent saturation based on sea-level atmospheric pressure instead of the station's atmospheric pressure (which decreases as elevation increases upstream). Thus, we first calculated pressure from site elevation using equations from Water on the Web[7] and then calculated DO saturation based on pressure, water temperature, and conductivity (USGS 2011).

2.1.3 Data Summaries and Analyses

Daily statistics were calculated each site with at least 80% completeness (38 out of 48 individual 30-minute measurements present). Daily statistics included number of measurements, minimum, maximum, mean, and range. In addition, the percent of 30-minute measurements exceeding various biological or regulatory thresholds was calculated (Table 2). Data from deployments with minor, but readily apparent, calibration errors were only used for the calculation of daily range, not other statistics (because relative to other statistics, daily range is less affected by calibration errors).

---

[4] Available online at: http://www.fws.gov/arcata/fisheries/activities/waterQuality/klamathWQ_reports.html

[5] Data correction criteria from Wagner et al. (2006) are ± 0.2 ºC for temperature, ± 0.3 mg/L for DO concentration, and 0.2 pH unit for pH.

[6] Data from 2001-2005 and from QVIR 2007-2011 did not include DO percent saturation as one of the parameters.

[7] http://www.waterontheweb.org/under/waterquality/oxygen.html

Table 2. Regulatory and biological thresholds for percent exceedance calculations.

Threshold	Jurisdiction, Geographic Applicability, and/or Notes
DO <8 mg/L	Hoopa Valley Tribe (2008) objective: Klamath River at Hoopa Reservation Previous (NCRWCB 2001) objective: Klamath River Iron Gate Dam to estuary
DO <6 mg/L	Not an adopted objective. Used here as an indicator of DO conditions more severe than 8 mg/L. EPA (1986) described 6 mg/L as a Slight Production Impairment for salmonids.
DO saturation <90%	NCRWQCB (2010) and Karuk Tribe (2012) objective: Klamath River from Iron Gate to Scott River (October 1-March 31) Klamath River from Scott River to Hoopa boundary (year-round)
DO saturation <85%	NCRWQCB (2010) and Karuk Tribe (2012) objective: Klamath River from Iron Gate to Scott River (April 1 – September 30) Klamath River from Hoopa boundary to Turwar (year-round)
pH >8.5	NCRWQCB(2010), Hoopa Valley Tribe (2008), Karuk Tribe (2012), and Yurok Tribe (2004a) objective: Klamath River and tributaries
pH >9	Not an adopted objective. Used here as an indicator of pH conditions more severe than 8.5.
Temperature >22 °C	Not an adopted objective. When mainstem Klamath River exceeds 22 °C, juvenile salmonids move to thermal refugia (Strange 2010).

Monthly statistics were calculated from daily statistics for each site and month that had at least 18 days (60%) of daily statistics. July-September statistics were calculated from daily statistics for each site and month that had at least 60 days of daily statistics (65%). Monthly and July-September statistics included minimum, maximum, mean, median of the daily statistics as well as the percent of measurements exceeding thresholds (Table 2).

2.2 NUTRIENTS AND CHLOROPHYLL DATA

2.2.1 Sampling Locations and Parameters

Nutrient samples were collected at the same stations as the continuous water quality monitoring (Table 1 and Figure 1). Data were collected by a variety of entities, with methodology and results described in the following reports: Karuk Tribe (2007, 2008, 2010, 2011, 2012), Yurok Tribe (2004b, 2004c, 2005, 2007, 2008, 2009, 2010b, 2011b, 2012b), QVIR (2008, 2009, 2011), Armstrong and Ward (2005), ARFO (2005), Raymond (2008, 2009, 2010), Deas (2008), Watercourse Engineering (2011a, 2011b, 2012), Kann and Asarian (2007), and Asarian et al. (2009).

Sampling frequency varied by station and year, but generally occurred monthly or bi-weekly for 2001-2005, and bi-weekly for 2007-2011. Parameters analyzed include ammonia (NH3), nitrate-plus-nitrite (NO3+NO2), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), total organic carbon (TOC), chlorophyll-a (CHLA), and phaeophytin (PHEO). Total inorganic nitrogen (TIN) was computed as NH3 plus NO3+NO2; organic nitrogen (ON) was computed as TN minus NH3 minus NO3+NO2; and particulate phosphorus (PP) was calculated as TP minus SRP. Some data collection entities did not analyze TN, in which case TN was calculated as Total Kjeldahl Nitrogen (TKN)+ NO3+NO2. In this report, nutrient concentrations are expressed in units of mg/L as N or mg/L as P.

2.2.2 Data Compilation and Quality Assurance

Nutrient data for the years 2001-2004 from many entities were compiled by Asarian and Kann (2006). That document contains details of the data sources and information about data quality. For the 2001-2004 data, reporting limits for nitrogen parameters were sometimes excessively high and therefore most non-detect nitrogen samples in 2003-2004 were not used[8].

The 2005-2008 nutrient data were compiled by Asarian and Kann (2010). Nutrient data for 2009-2012 were obtained from the Yurok Tribe, Karuk Tribe, Hoopa Valley Tribe, and QVIR and compiled as part of this database. Tribal samples from mid-2005 through 2011 were processed by Aquatic Research Inc., which utilized lower reporting limits than those used by laboratories between 2001 through mid-2005. Nutrient data from PacifiCorp for 2005-2010 were also utilized in the analysis.

In order to compare to data summaries computed for the continuous water quality data, similar monthly and seasonal statistics were computed for the nutrient and chlorophyll parameters.

2.3 HYDROLOGIC DATA

Streamflow data for the Klamath River gages listed in Table 1 were obtained online from the USGS Water Resources National Water Information System[9].

Because not all nutrient samples were taken at USGS stream gages, discharge was estimated at some locations using a watershed area accretion method similar to that used by PacifiCorp (2004), Tetra Tech (2009), and Asarian et al. (2009 and 2010). The total watershed area contributing to the ungaged accretions (areas of gaged tributaries were excluded) between each mainstem USGS gage (Iron Gate, Seiad, Orleans, and Turwar) was determined using GIS, and the ratios of individual areas to the total accretion area were calculated. Five-day moving averages of all gages were calculated and accretions for the reaches between the mainstem gages were developed by calculating the difference between the five-day moving averages of the upstream gage, downstream gage, and any gaged tributaries within the reach[10]. The accretion volume was then distributed to the nutrient sampling stations in proportion to their watershed area.

Monthly and seasonal statistics were computed for the discharge data in order to compare to similar data summaries computed for the continuous water quality data.

[8] Although it is typically possible to increase accuracy by using a method such as Kaplan-Meier estimation or regression order statistics (Bonn 2008) to address non-detect samples, in this case the detection limits were exceedingly high (e.g., TKN 0.5 mg/L in 2004 and 1.0 mg/L in 2003, see Asarian and Kann 2006 for details) such that a very high percentage were non-detect. This issue primarily affects only the years 2003-2004 (a small subset of the entire 2001-2011 period), so is unlikely to alter study results and conclusions.

[9] http://waterdata.usgs.gov/usa/nwis

[10] The five-day moving averages were used to avoid the negative calculated accretion values that occasionally resulted from the combination of transit time and rapid changes in flow (i.e., storm events and/or dam releases) at gages. PacifiCorp (2004) and TetraTech (2009) used seven-day moving averages, but for the May-October period analyzed here, a five-day average was sufficient.

2.4 METEOROLOGICAL DATA

Meteorological data for several Remote Automated Weather Stations (RAWS) were obtained from the Western Regional Climate Center's (WRCC) RAWS USA Climate Archive[11]. Parameters utilized included mean air temperature, precipitation, and mean wind speed. Solar radiation data were not utilized for analysis due to data quality issues[12]. A meteorological station was assigned to each water quality monitoring station according to proximity (longest distance was 30 miles) and elevation (Table 1). Aside from removing data readily identifiable as completely erroneous[13] we did not attempt to adjust or correct the meteorology data.

2.5 CORRELATION BETWEEN VARIABLES

Spearman rank correlation was used to explore the effect of hydrologic, meteorological, nutrient, and algal variables on inter-annual differences in water quality metrics. Spearman's rank correlation is a non-parametric alternative to correlation that does not rely on assumptions of normality and is less sensitive to outliers than standard Pearson correlation. Input values (monthly means of various daily summary statistics) were converted to ranks and then a correlation analysis was performed on the ranks. The resulting Spearman's correlation coefficient (Spearman's rho) ranges from -1 to 1 according to whether variables are positively or negatively correlated (positive rho indicates positive correlation and a negative rho indicates negative correlation). The associated p-value provides a test of statistical significance.

3 RESULTS AND DISCUSSION

3.1 FLOW

Monthly average discharge data at four mainstem Klamath River locations and four tributary locations for the April-October periods in calendar years 2001-2011 shows substantial variation among locations, seasons, and years (Figure 5). Discharge increases with downstream distance due to accretion from springs and tributaries. The ratio between early spring and summer/fall flows is often lower at Iron Gate than sites downstream, especially in dry years, due to a combination of dam-regulated flows and groundwater-dominated hydrology from porous volcanic geology upstream. In summer, the Shasta River exhibits high day-to-day variability due to dynamic irrigation diversions. Flows were generally highest at most stations in 2006, 2010, and 2011. Summer flows were generally lowest in 2001, 2002, and 2004, except at Iron Gate where 2001 flows remained high due to dam releases.

A comparison of the study period (2001-2011) with the period of record for the Klamath River at Iron Gate Dam (1961-2011) and Klamath (1911-1926 and 1951-2011) indicates that flows during the study period encompass a substantial portion of the variability contained in the period of record; however, it did not include the most extreme low flow periods such as those occurring in 1918, 1920, 1924, 1926, 1977, and the early 1990s (Figure 6). The wide range of hydrologic conditions occurring across the study period provided an opportunity to evaluate the effects of flow on water quality (see section 3.4.2).

---

[11] http://www.raws.dri.edu/

[12] Major solar radiation data quality issues included apparently erroneous spikes, shifts in calibration (i.e., differences in unobstructed insolation among years), and data gaps. Ward and Armstrong (2010) describe methods for correcting insolation data, but that was outside the scope of this project.

[13] For example: Air temperature flatlined at -35.5 °C.

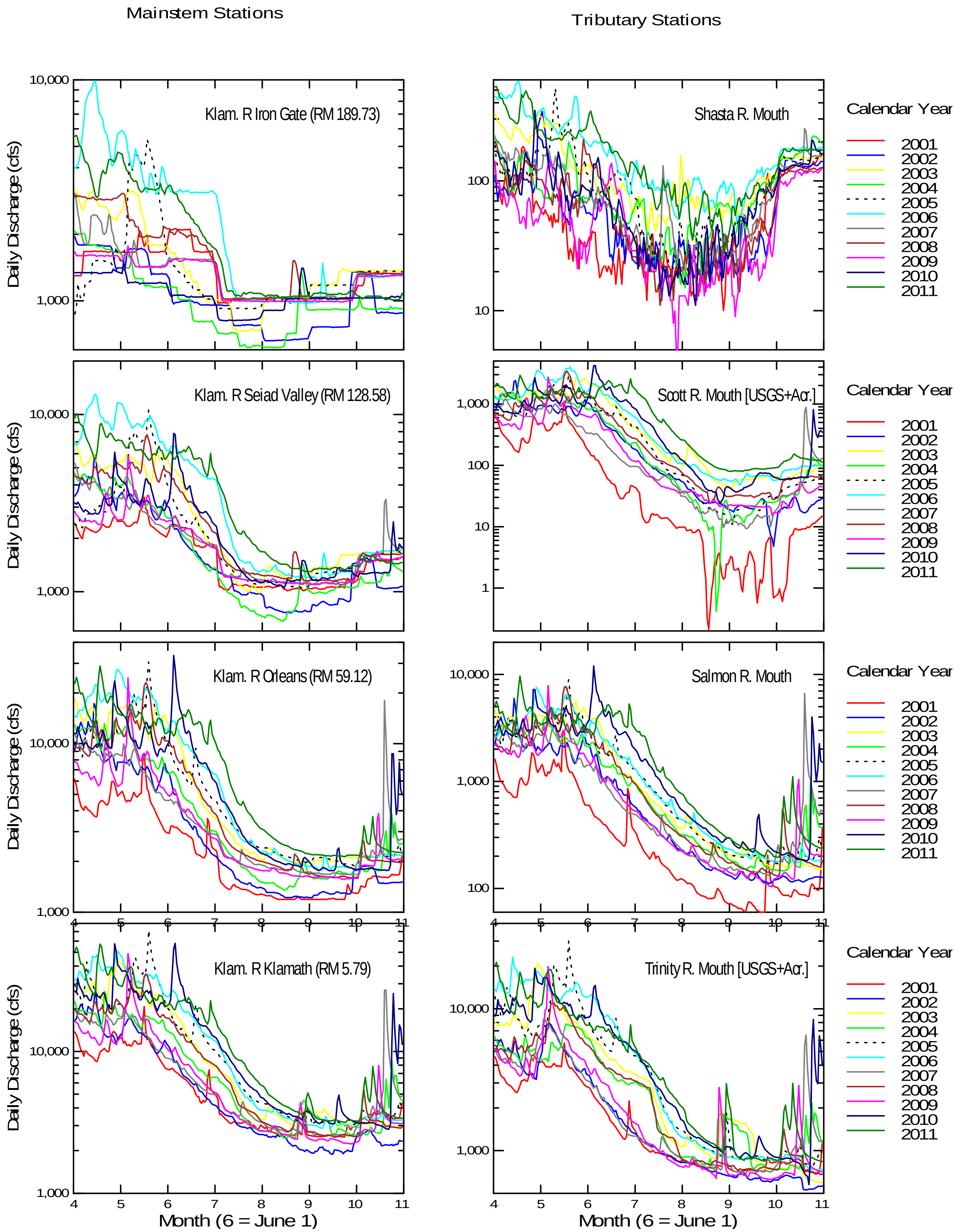


Figure 5. Daily mean flow for the April-October periods of calendar years 2001-2011 for selected sites on the mainstem Klamath River and the mouths of the major tributaries. Note: y-axis varies and has logarithmic scale.

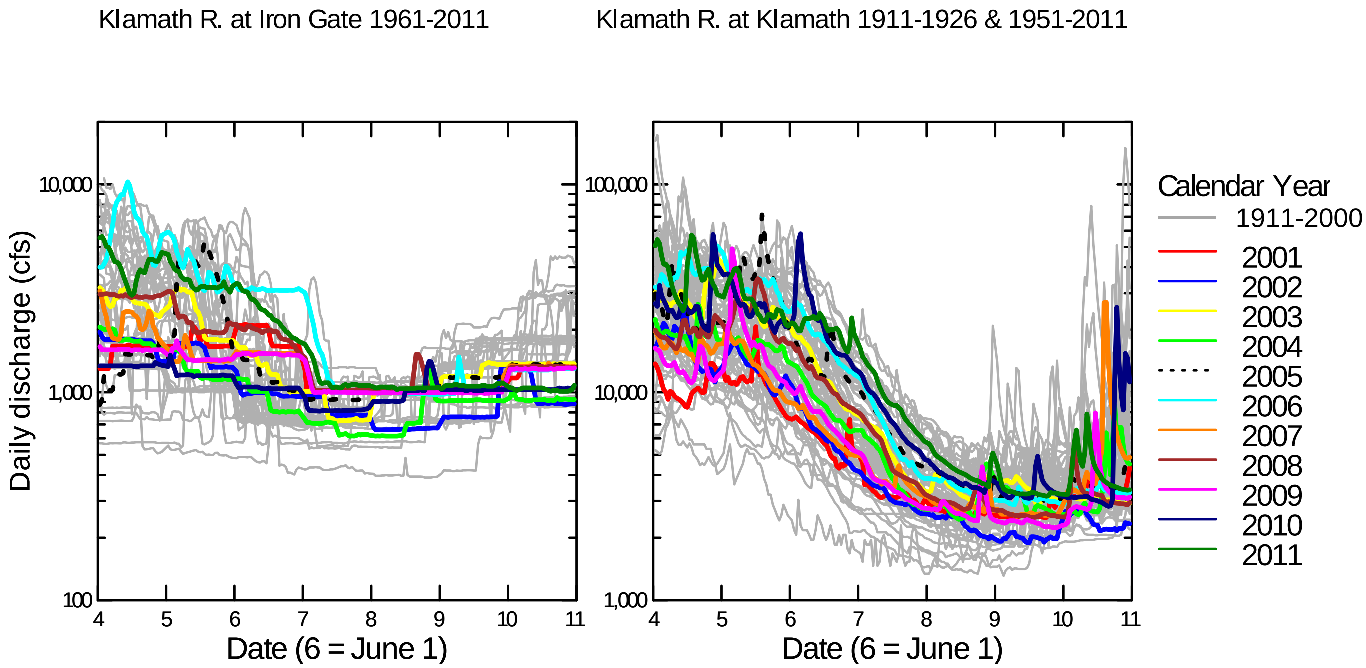


Figure 6. Comparison of April-October flows during the 2001-2011 study period with the available period of record for the Klamath River at Iron Gate Dam (1961-2011) and Klamath (1911-1926 and 1951-2011).

3.2 CONTINUOUS WATER QUALITY DATA

3.2.1 Spatial and Seasonal Patterns

As noted in the methods section above, six primary mainstem stations were consistently monitored through the 2001-2011 period, and three additional stations (K1, K2, and HC) were monitored for several years between 2001-2005. A series of contour plots illustrate the overall longitudinal and seasonal trends in DO, pH, and water temperature for the primary mainstem Klamath River Sites for 2001-2011 (Figure 7), and for a shorter period that provides additional spatial resolution by including all stations (primary and supplemental) for 2004-2005[14] (Figure 8). These contour plots average the daily statistics over many years[15] and interpolate between stations; therefore, they show overall longitudinal and seasonal trends, but not the most acute water quality values occurring at any particular station or time. The most extreme individual 30-minute measurements for each mainstem site are shown in Figure 9.

Mean and maximum water temperature peaked in late July or early August (Figure 7 and Figure 8, bottom panels). Water temperatures also showed a tendency to warm with distance downstream from Iron Gate Dam (Figure 7 and Figure 9, bottom panels), with the plot depicting greater longitudinal resolution indicating that the highest daily mean water temperatures occurred in the middle section of the river between the Above Scott River (site K2) and Happy Camp stations (Figure 8). The zone of highest maximum daily water temperatures also includes Above Shasta River

[14] The only years for which all nine stations were available.
[15] Individual measurements were collected every 30 minutes, then daily statistics are calculated (e.g., the minimum dissolved oxygen at Seiad Valley on August 1, 2008) as described in section 2.1.3. The contour plots average all years together for a particular day (e.g., average of each year's August 1 daily minimum dissolved oxygen at Seiad Valley).

(K1) due to high diel fluctuations at that site. Water temperatures decrease at Orleans and sites downstream. This decreased temperature is likely due to the influence of cooler coastal air temperatures as well as input from colder tributaries such as the Salmon and Trinity rivers.

The seasonal pattern of minimum DO is the inverse of water temperature, reaching its lowest value in July and August when water temperatures are highest (Figure 7 top panel). Maximum pH rises in July, peaks in August, and then drops through the end of October. At Iron Gate Dam, pH peaks later (early September) than at sites downstream, presumably due to the timing of phytoplankton blooms in the impoundment upstream. The seasonal trends in daily pH and DO range were very similar, with peaks occurring in mid-August (Figure 7 top and middle panels). DO minimum and pH maximum, as well as their daily ranges, reach their most extreme values from below Iron Gate to around the Seiad Valley area (Figure 7 and Figure 9), with some of the more extreme values occurring at the Above Shasta River station (K1)(for minimum DO and range, and maximum pH and range), at the Above Scott River station (K2)(for minimum DO and range, but not pH), and Happy Camp (for minimum DO only) (Figure 8).

At tributary stations, the most extreme annual values for maximum pH, minimum DO and maximum water temperature generally occurred at Shasta River mouth (SH) and Scott River valley (SRGA), with intermediate values at Scott River mouth (SC), and least extreme values at the mouths of the Salmon (SA) and Trinity (TR) rivers (Figure 10).

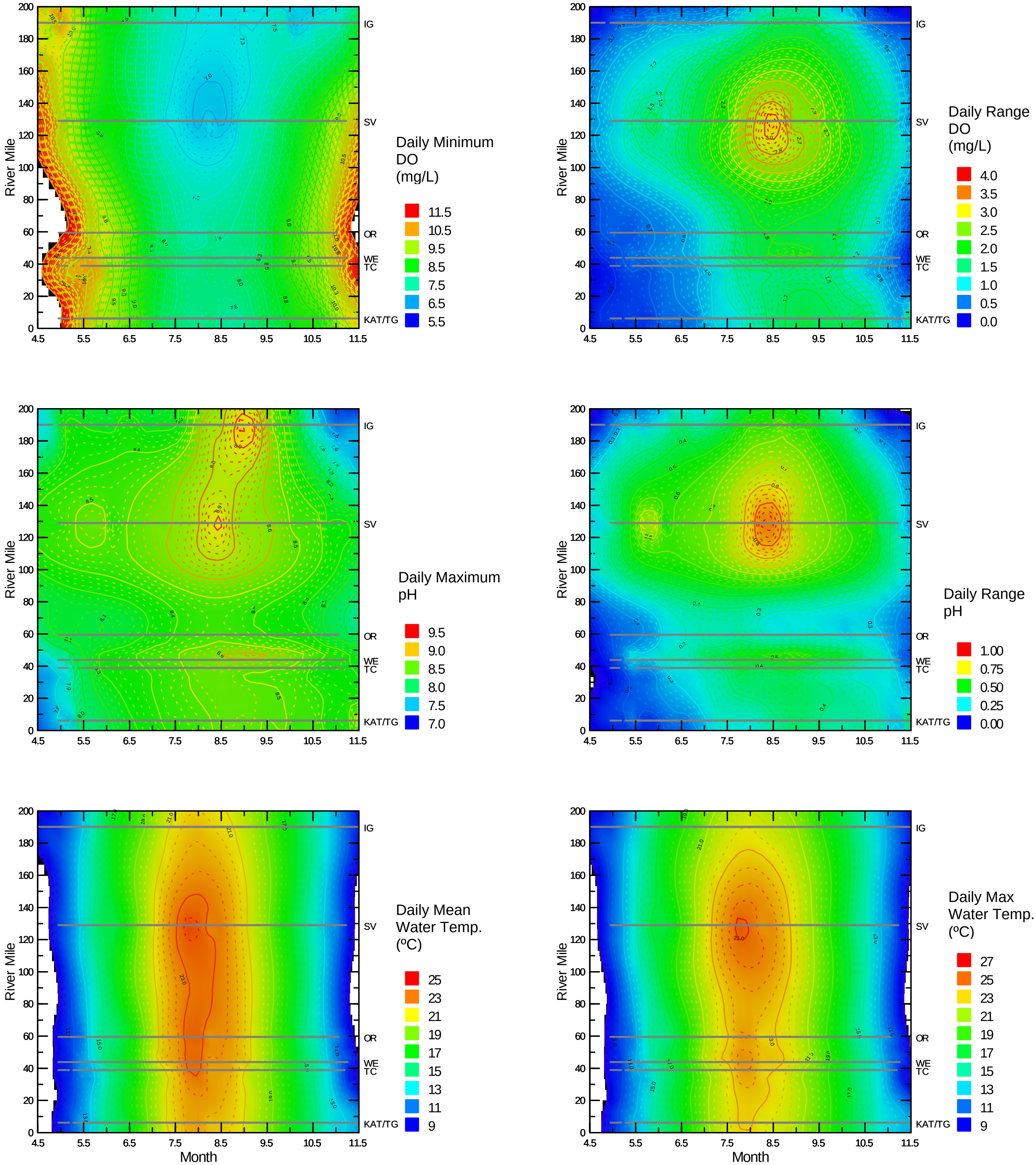


Figure 7. River mile-date (7.5=July 15) distribution of isopleths showing daily metrics of DO (minimum and range), pH (maximum and range), and water temperature (mean and maximum) for the primary mainstem Klamath sites, 2001-2011. Horizontal grey lines are days with measurements, indicating the beginning and end of the monitoring season as well as gaps; data outside the monitoring season (i.e., left of first line or right of last line) are extrapolated and not meaningful, as are data above river mile 190 and below river mile 5.

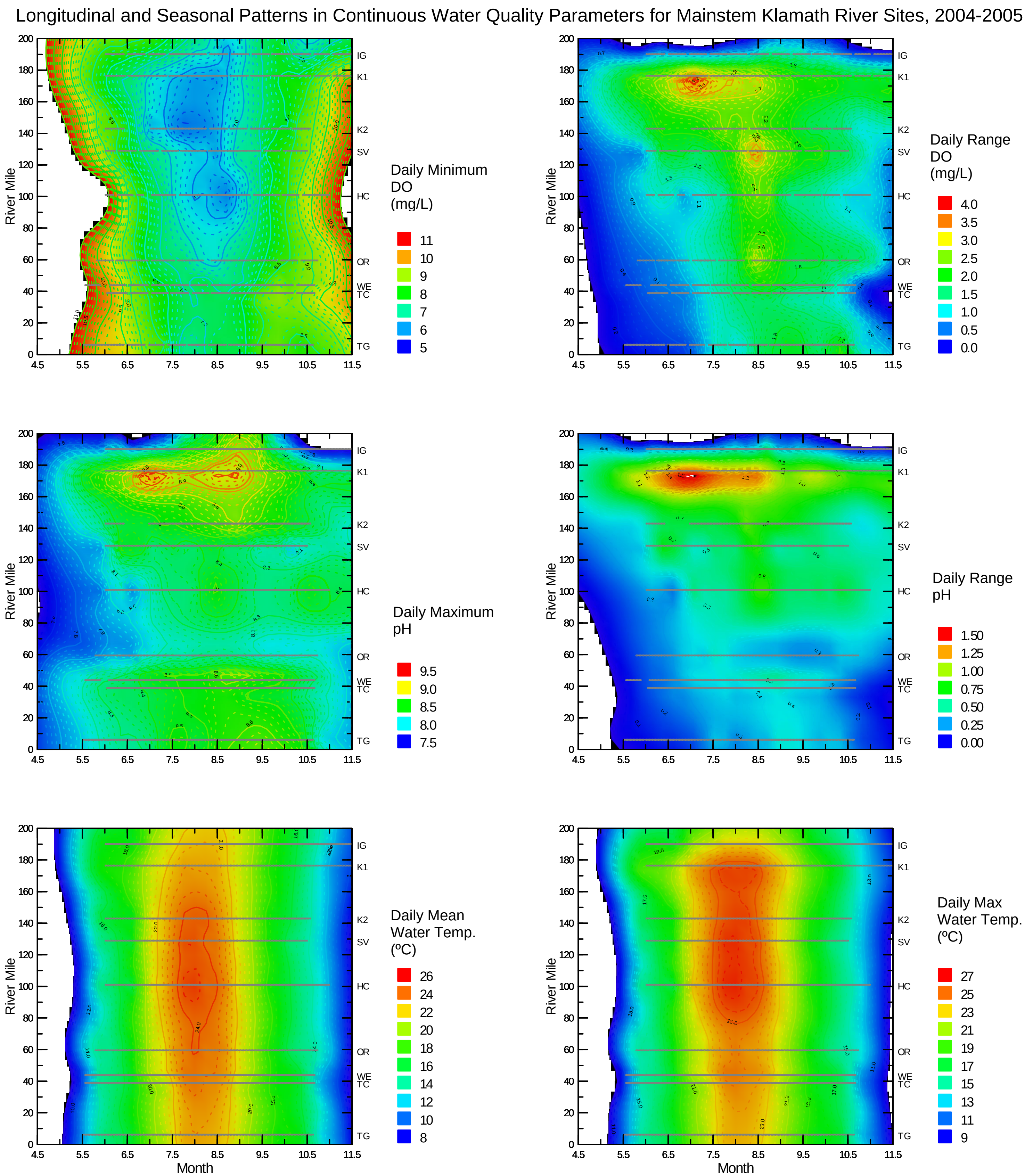


Figure 8. River mile-date (7.5=July 15) distribution of isopleths showing daily metrics of DO (minimum and range), pH (maximum and range), and water temperature (mean and maximum) for nine mainstem Klamath sites, 2004-2005 (the only years in which all nine stations were monitored). Horizontal grey lines are days with measurements, indicating the beginning and end of the monitoring season as well as gaps; data outside the monitoring season (i.e., left of first line or right of last line) are extrapolated and not meaningful, as are data above river mile 190 and below river mile 5.

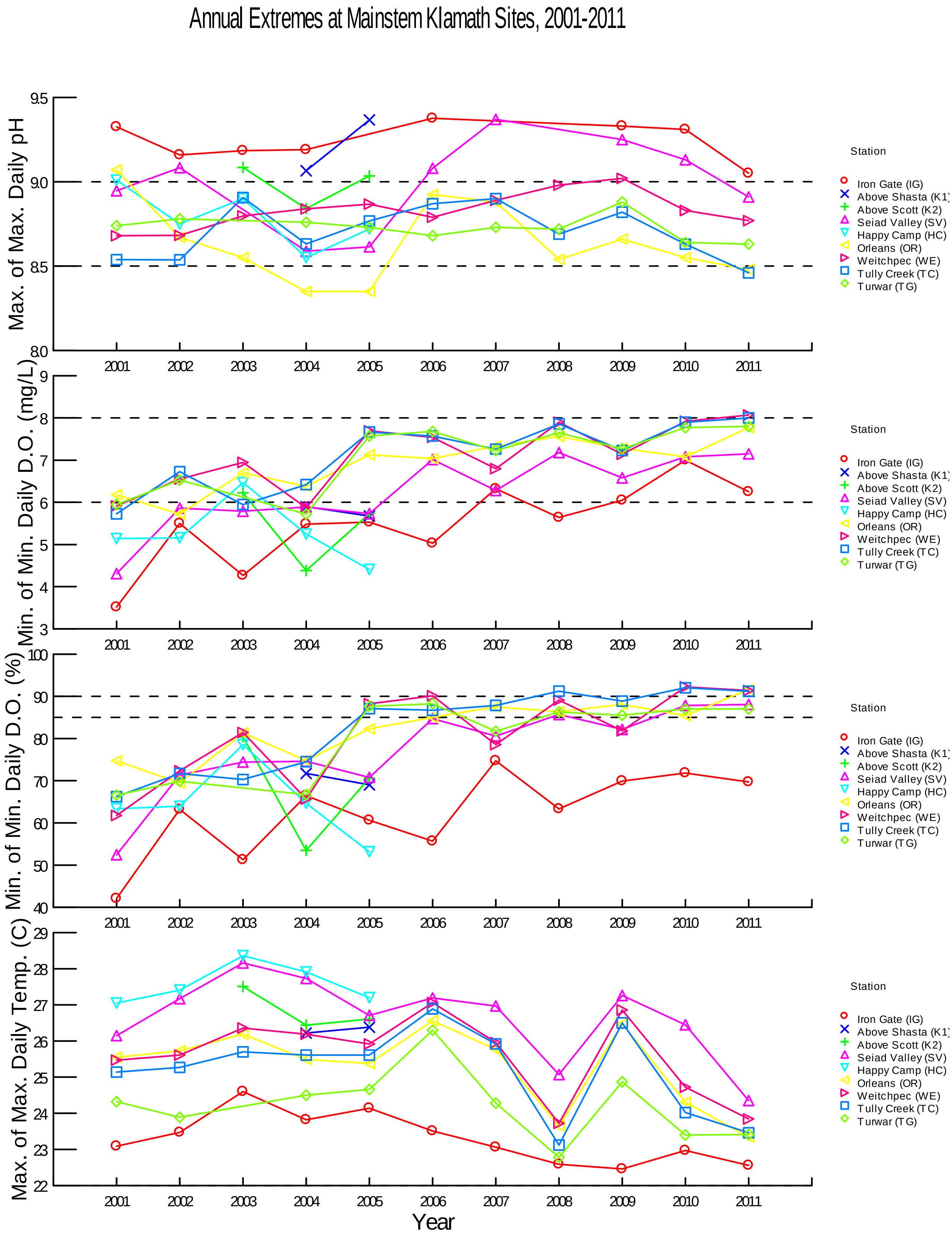


Figure 9. Maximum or minimum instantaneous measurement of pH, DO, and water temperature for mainstem Klamath River sites for each year 2001–2011. These values are the extreme of the individual 30-minutes measurements made at each site for each year. If a site/year had substantial gaps during months when annual extreme values were typically observed then it was excluded from the graph.

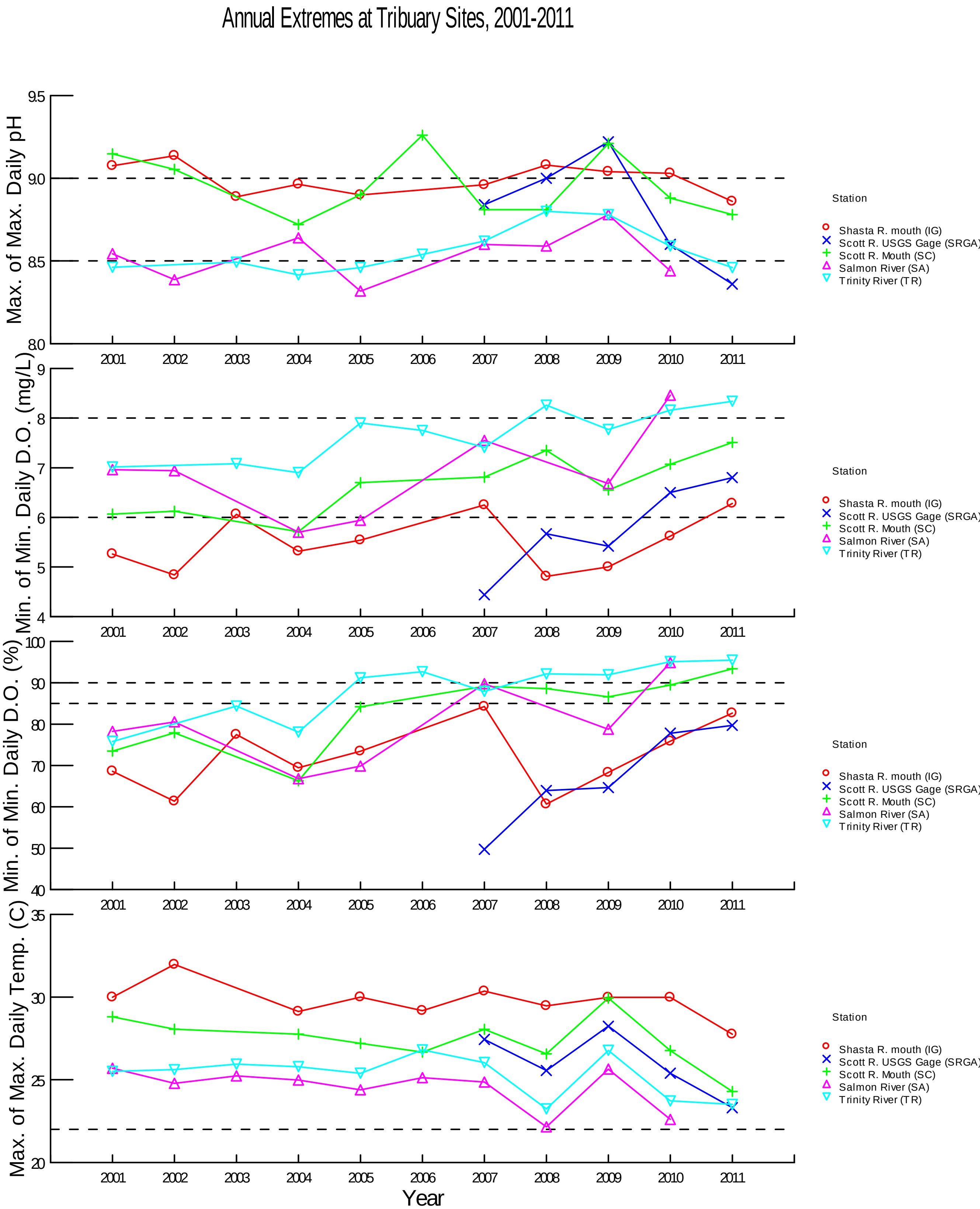


Figure 10. Maximum or minimum instantaneous measurement of pH, DO, and water temperature for tributaries to the Klamath River for each year 2001–2011. These values are the extreme of the individual 30-minutes measurements made at each site for each year. If a site/year had substantial gaps during months when annual extreme values were typically observed then it was excluded from the graph.

3.2.2 Exceedance of Regulatory and Biological Thresholds

Percent exceedance of thresholds of regulatory or biological significance generally decreased with distance downstream from Iron Gate Dam for pH and DO, but water temperature followed a different pattern with the lowest exceedances occurring at Iron Gate Dam (Figure 11 and Table 3).

DO was the parameter most frequently exceeding water quality thresholds. The percent of DO measurements less than 8 mg/L for June–October at mainstem sites ranged from a low of 11.4% at Tully Creek (TC) near the mouth to a high of 48% at Iron Gate (IG). At tributary stations, the Salmon River (SA) showed the lowest percent of measurements less than 8 mg/L (8%) while the highest was 49% (Shasta River (SH) (Table 3). Seasonally, percent of DO measurements less than 8 mg/L were greatest in July and August, coincident with the highest water temperatures of the season. In contrast, the highest frequency of DO saturation measurements less than 85% and 90% also included September at many stations. A notable exception to this temporal pattern was Iron Gate Dam where low DO concentrations (62% <8 mg/L and 11% <6mg/L) and DO percent saturation (74% <90% saturation, 61% <85% saturation) were most severe in October (Table 3).

pH exceedances (e.g., values >8.5) followed a similar patterns as DO values less than 8 mg/L (Table 3). On the mainstem, percent exceedances of pH were generally higher in the upper reaches of the river (i.e., from Seiad upstream) than in the middle and lower reaches. As with DO, percent exceedances for pH were higher at the Shasta River than other tributaries stations. Specifically, the mean percent of June–October measurements greater than pH 8.5 ranged from 11% (Orleans) to 35% (Above Shasta - K1) at mainstem stations, and 3% (Salmon River) to 60% (Shasta River) at tributary stations (Table 3). Seasonally, percent exceedance of pH greater than 8.5 was highest in August and September at most stations (Table 3 and Figure 11 top panel). Exceedance of pH greater than 9.0 was rare (<0.1%) at mainstem stations below Seiad Valley (SV) but occurred more frequently upstream at Iron Gate (9% for September), Above Shasta (8% for August), and Seiad Valley (6 % for August), as well as in the Shasta and Scott Rivers (Table 3).

Exceedance of 22 °C water temperature occurred most frequently in July and August (Table 3) and at Above Scott River, Seiad Valley, and Happy Camp.

3.3 NUTRIENT CONCENTRATION

Nutrient and chlorophyll concentrations during June–October were highest at Iron Gate Dam and decreased with distance downstream (Figure 12). This same pattern was noted by Asarian et al. 2010), who attributed the nutrient reductions to retention dynamics as well as tributary dilution.

Inter-annual variability in nutrient concentration was evident during the 2001-2011 study period (Figure 13). The lowest phosphorus (both TP and SRP) concentrations occurred during the high flow years of 2006, 2010, and 2011 and the moderate flow year of 2005. Highest TP concentrations occurred in the low flow years of 2001-2004. Nitrate showed substantial variability among years that was somewhat different from phosphorus, with highest concentrations in 2001, 2005, and 2008 and lowest in 2002, 2004, 2010, and 2011. Total nitrogen (TN) concentrations were highest in the low flow year 2001 and lowest in the high flow year 2011. Highest chlorophyll concentrations occurred in 2007 and 2008 at Iron Gate Dam. Complete time series of individual samples for selected nutrient parameters are available in Appendix D.

Nutrient concentrations are generally much lower in the tributaries (Figure 14) than in the mainstem Klamath River (Figure 13). Exceptions include TP, TN, and SRP in the Shasta River and TN and NO3+NO2 in the Scott River at the USGS gage (station SRGA, at outlet of Scott Valley), although concentrations downstream at the Scott River's mouth (station SC) are substantially reduced relative to SRGA due to dilution from mountain tributaries in the Scott River canyon.

Table 3. Percent of measurements by month that exceed regulatory or biological thresholds at monitoring stations on the mainstem Klamath River and tributaries, 2001-2011. Rows marked as month '6 to 10' are percent exceedances for the five-month June through October period. Months with significant data gaps (see Figure 3, Figure 4 and Appendix A) are excluded. Supplemental stations have fewer years of data (1 to 5) than primary stations (4 to 11) and the month of October has fewer years with data than other months. Not all 0 values are actually zeroes; some are very low frequency of exceedances rounded to zero. Cells are color-coded by % exceedance

0 | >0.001 to ≤10 | >10 to ≤25 | >25 to ≤50 | >50 to ≤100

Threshold	Month	Percent of Measurements Exceeding Thresholds													
		Mainstem									Tributaries				
		Primary Stations						Supplemental Stations			Primary Stations				Supp.
		RM 189.73 Iron Gate (IG)	RM 128.58 Seiad Valley (SV)	RM 59.12 Orleans (OR)	RM 43.50 Weit-chpec (WE)	RM 42.50 Tully Creek (TC)	RM 5.79 Tur-war (TG)	RM 176.08 Above Shasta (K1)	RM 142.61 Above Scott (K2)	RM 100.66 Happy Camp (HC)	Shasta (SH)	Scott Mouth (SC)	Salmon (SA)	Trinity (TR)	Scott Gage (SRGA)
D.O. <90%	6	13	19	4	6	0	7	36		5	37		10	0	6
	7	20	28	14	13	15	23	46	55	42	49	16	18	6	24
	8	24	34	14	14	11	18	52	43	55	41	25	30	11	42
	9	39	28	10	15	8	17	38	39	50	21	22	29	11	44
	10	74	14	6	6	5	16	25		0	1	11	13	14	36
	6 to 10	**33**	**25**	**10**	**12**	**8**	**16**	**41**	**45**	**42**	**33**	**17**	**21**	**8**	**31**
D.O. <85%	6	5	3	0	3	0	2	17		0	17	2	1	0	1
	7	12	13	1	4	6	12	34	42	12	33	4	6	0	13
	8	14	18	3	7	4	7	41	21	32	20	16	10	1	32
	9	24	10	1	7	1	8	11	12	14	4	11	7	1	29
	10	61	3	0	2	1	5	0		0	0	3	0	2	12
	6 to 10	**22**	**9**	**1**	**5**	**2**	**7**	**23**	**23**	**19**	**17**	**7**	**5**	**1**	**18**
D.O. <8 mg/L	6	20	21	5	6	0	3	36		1	50	12	5	0	5
	7	53	50	33	25	26	28	61	79	75	74	36	24	12	32
	8	55	51	26	23	20	21	69	66	74	67	51	35	17	46
	9	50	29	9	13	4	11	38	35	40	26	20	13	3	37
	10	62	1	0	1	1	3	1		0	0	0	0	1	5
	6 to 10	**48**	**31**	**16**	**16**	**11**	**14**	**46**	**56**	**56**	**49**	**25**	**17**	**8**	**27**
D.O. <6 mg/L	6	0	0	0	0	0	0	0		0	3	0	0	0	0
	7	1	1	0	0	0	0	0	9	0	9	0	0	0	3
	8	3	0	0	0	0	0	3	3	3	2	0	0	0	2
	9	6	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	11	0	0	0	0	0	0		0	0	0	0	0	0
	6 to 10	**4**	**0**	**0**	**0**	**0**	**0**	**1**	**3**	**1**	**3**	**0**	**0**	**0**	**1**
pH >8.5	6	6	16	2	5	2	3	29		0	65	25	0	1	1
	7	10	30	9	18	13	7	41	14	6	53	35	4	5	7
	8	53	40	19	34	23	17	47	38	21	68	39	4	9	18
	9	47	32	12	36	19	24	35	24	8	73	36	3	8	10
	10	6	11	10	23	3	14	6	15	2	38	34	0	11	3
	6 to 10	**23**	**26**	**11**	**24**	**14**	**13**	**35**	**25**	**11**	**60**	**34**	**3**	**6**	**9**
pH >9.0	6	0	0	0	0	0	0	2		0	0	0	0	0	0
	7	0	1	0	0	0	0	5	0	0	0	0	0	0	1
	8	3	6	0	0	0	0	8	0	0	1	3	0	0	3
	9	9	1	0	0	0	0	2	0	0	0	4	0	0	0
	10	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	6 to 10	**2**	**2**	**0**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**1**	**0**	**0**	**1**
Water Temp. >22 C	6	0	7	5	3	1	1	9	6	2	29	5	0	1	1
	7	22	69	59	59	48	41	53	76	82	68	41	24	40	18
	8	21	65	65	60	54	37	53	67	75	48	42	21	46	21
	9	0	4	5	7	1	2	7	5	8	4	6	2	2	1
	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6 to 10	**9**	**31**	**28**	**29**	**24**	**17**	**27**	**38**	**49**	**31**	**20**	**10**	**21**	**10**

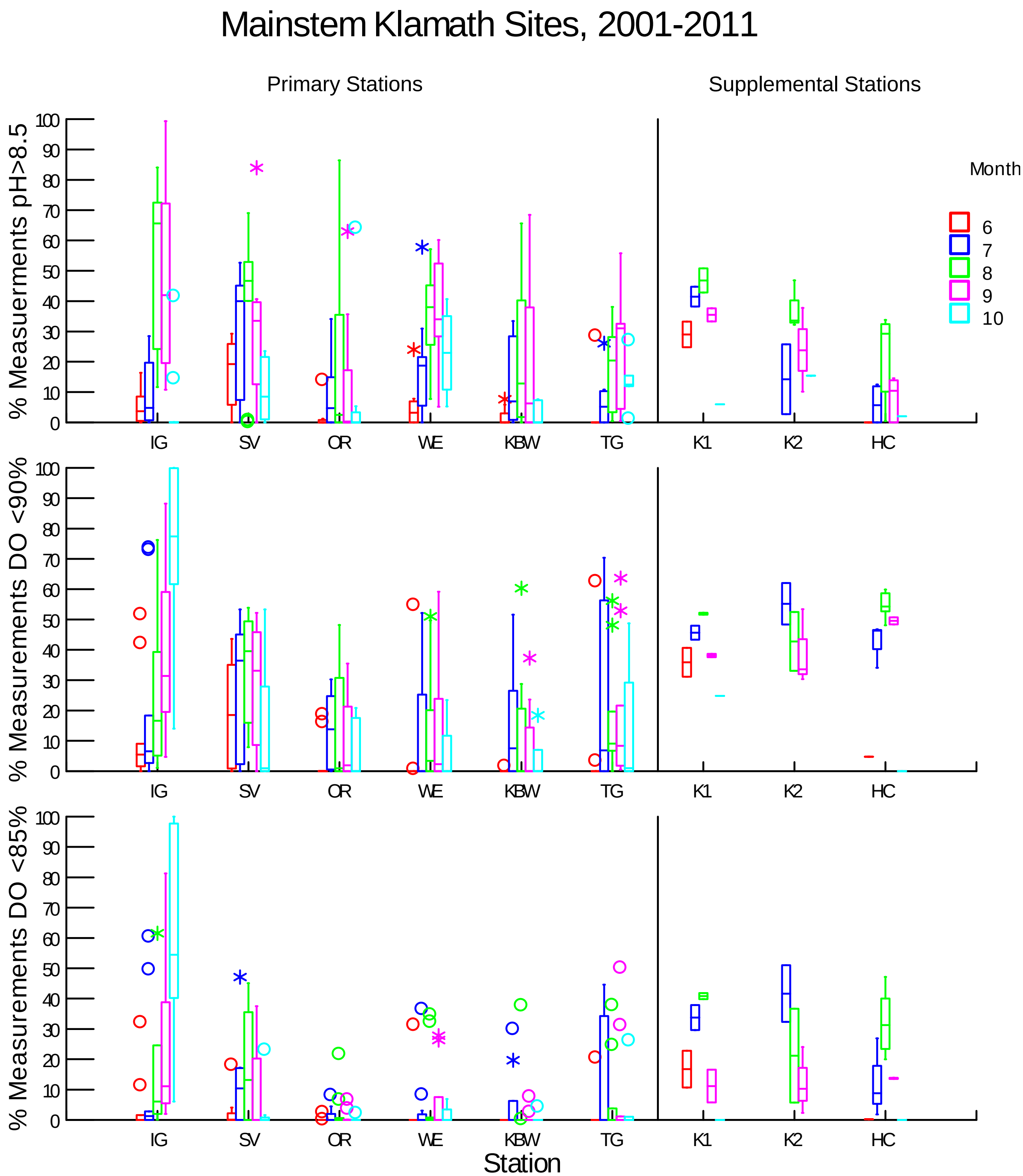


Figure 11. Boxplot of percent of 30-minute measurements per month exceeding thresholds of regulatory or biological significance at mainstem Klamath River monitoring stations, 2001-2011. Months with significant data gaps (see Figure 3 and Appendix A) are excluded. Supplemental stations have fewer years of data (1 to 5) than primary stations (4 to 11) and the month of October has fewer years with data than other months. Details of boxplot format: 1) horizontal line inside each box is the median and the edges of each box are the 25th and 75th percentiles, 2) whiskers show the range of values within 1.5 times the interquartile (75th-25th) range, 3) values more than 1.5 times the interquartile range past the box edges are plotted as asterisks while those more than 3 times the interquartile range past the box edges are plots as open circles.

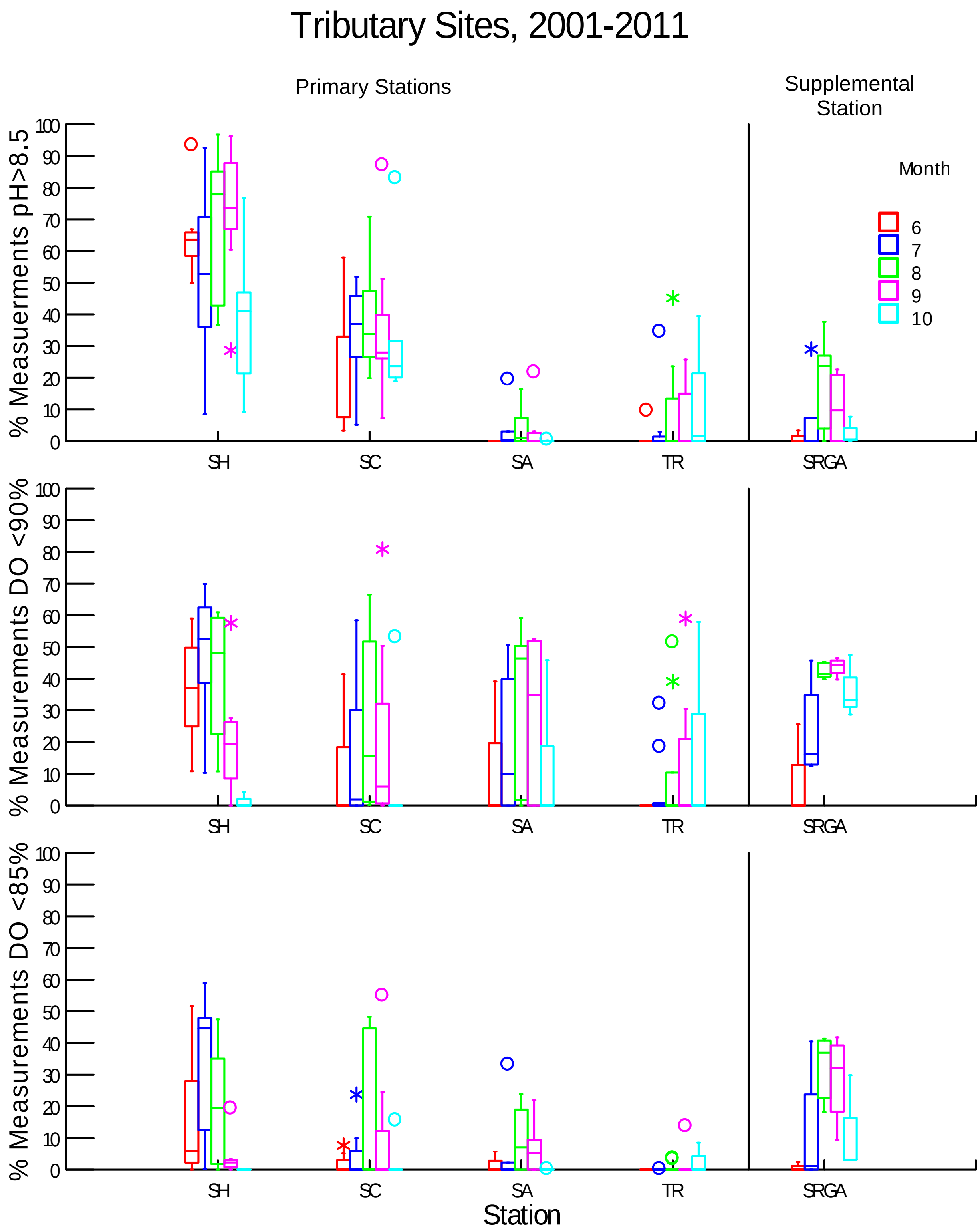


Figure 12. Boxplot of percent of 30-minute measurements per month exceeding thresholds of regulatory or biological significance at tributary monitoring stations, 2001-2011. Months with significant data gaps (see Figure 3 and Appendix A) are excluded. Supplemental stations have fewer years of data (1 to 5) than primary stations (4 to 11) and the month of October has fewer years with data than other months. Refer to Figure 11 caption for details of boxplot format.

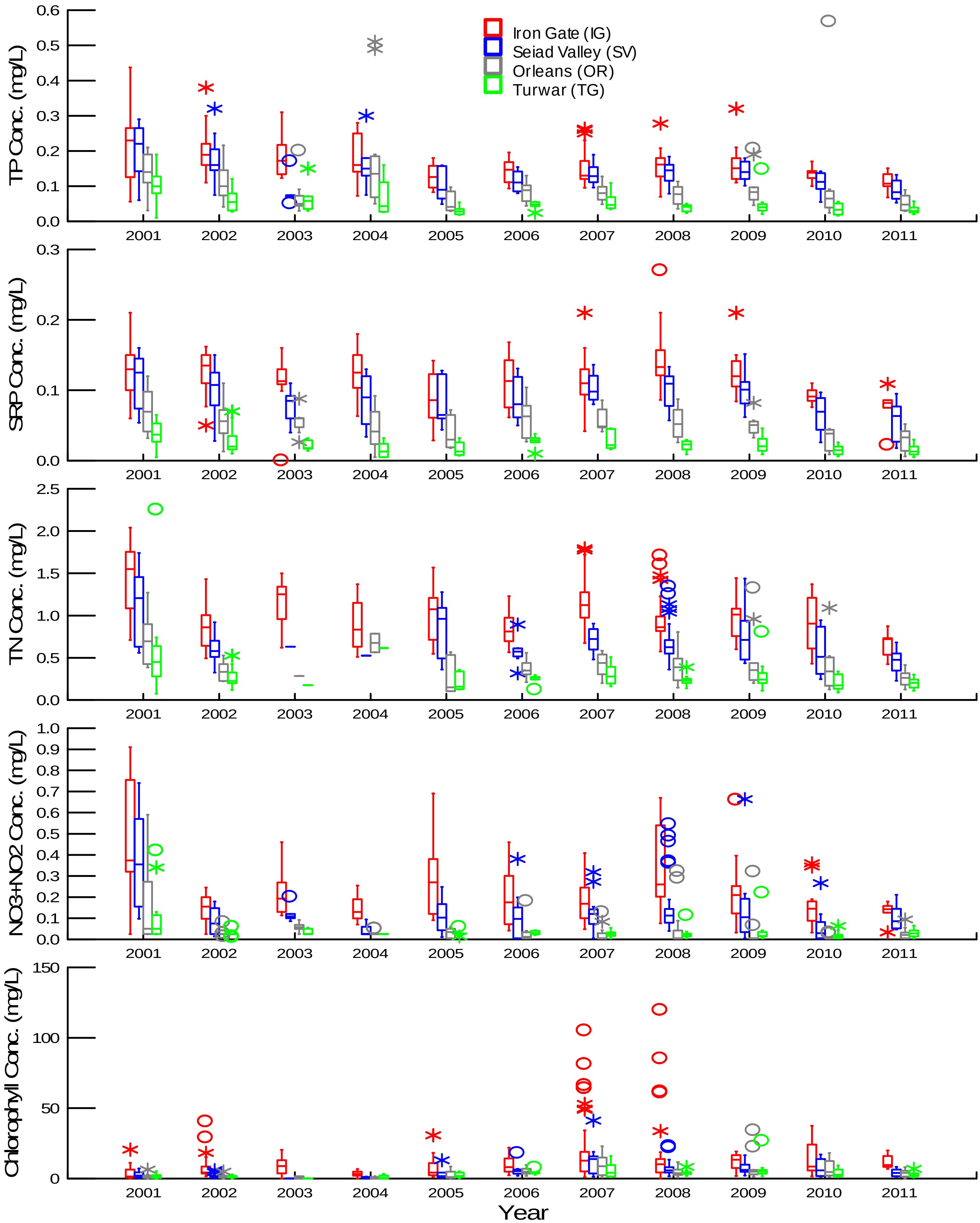


Figure 13. Boxplot of concentrations for nutrients and chlorophyll-*a* for the June–October periods of 2001–2011, by year at four mainstem Klamath River sites. Parameters shown: total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), nitrate+nitrite nitrogen (NO3+NO2), and chlorophyll-a. Refer to Figure 11 caption for details of boxplot format.

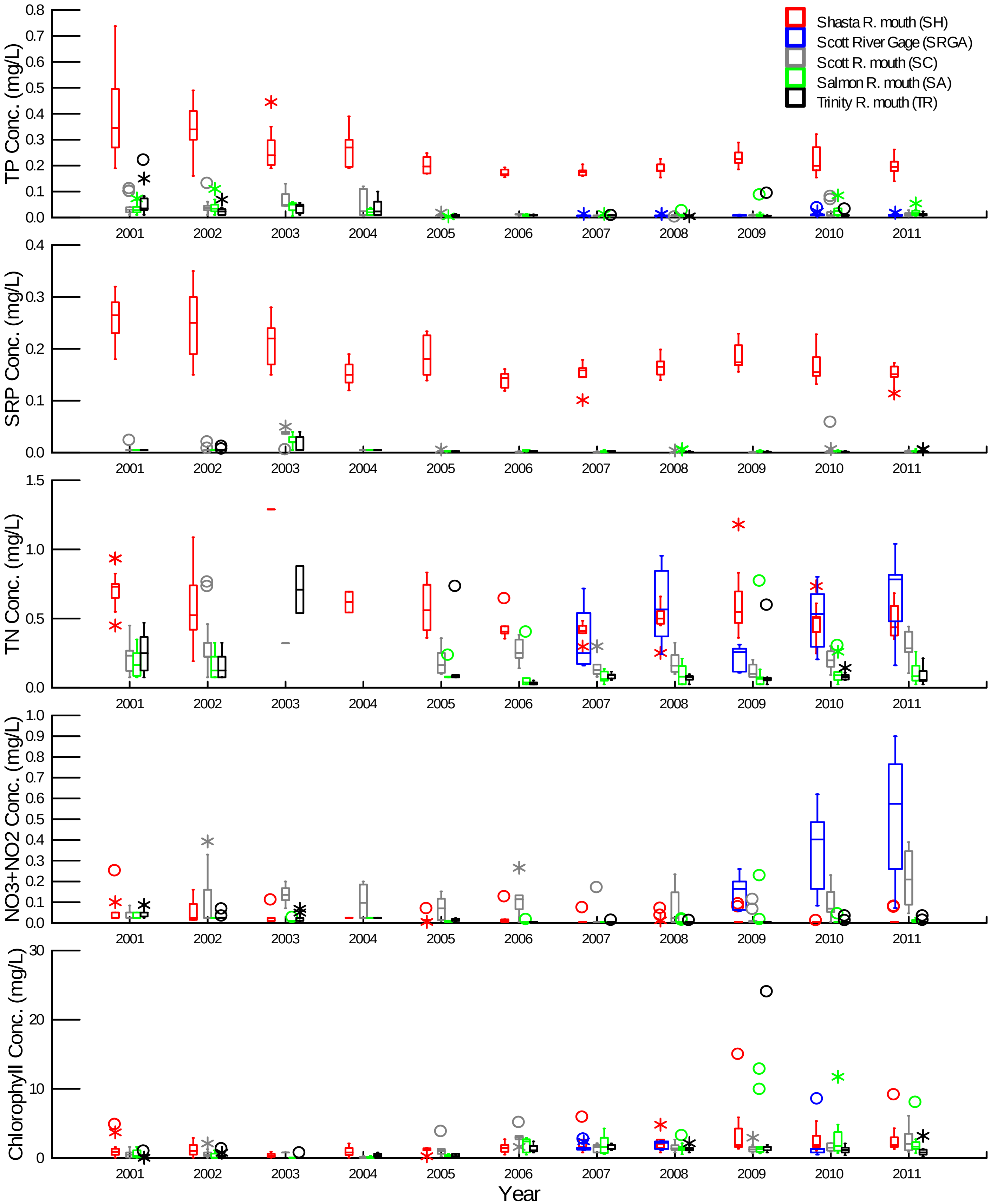


Figure 14. Boxplot of concentrations for nutrients and chlorophyll-a for the June–October periods of 2001–2011, by year at tributaries to the Klamath River. Parameters shown: total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), nitrate+nitrite nitrogen (NO3+NO2), and chlorophyll-a. Refer to Figure 11 caption for details of boxplot format.

3.4 RELATIONSHIPS BETWEEN VARIABLES

3.4.1 General Seasonal Patterns

At mainstem Klamath River sites, most hydrologic, meteorological, dissolved nutrient, algal, and continuous water quality parameters follow a similar seasonal trend, although there is variation in timing and magnitude among years and sites. Figure 15 illustrates seasonal patterns for Seiad Valley as an example of a typical pattern for the mainstem Klamath River (similar graphs for other sites are available in Appendix C). Solar radiation peaks in late June with the summer solstice but is lower in May and early June than in July, likely due to a higher frequency of cloud cover (Figure 16). Flow declines through the spring to reach an annual minimum from late July through mid-September and then rises through October (Figure 15 top panel).

Water temperature follows air temperature closely, although there is a temporal lag in which water temperatures are slightly lower than air for May-July but higher than air in September-October (Figure 15 top panel). This temporal lag, which is highest at Iron Gate Dam and dissipates with distance downstream (Appendix C), is likely due to the thermal mass of Iron Gate Reservoir upstream[16].

SRP concentrations (Figure 15 top panel) rise from May-October while total inorganic nitrogen (TIN: ammonia plus nitrate+nitrite) remains stable in May-August and then rises in September and October (Figure 15 middle panel). Chlorophyll-*a* declines in May/June, then climbs in July/August before declining in September and October (Figure 15 middle panel).

Phycocyanin, a blue-green algal pigment, is low from May through early August before climbing to a peak in early September and then declining to low levels by the end of October (Figure 15 middle panel). The seasonal pattern of mean DO is the inverse of water temperature, reaching a low in July and August in when water temperatures are highest (Figure 15 bottom panel). Mean pH rises in July to a peak in August and then declines through the end of October. Daily pH range and daily DO range track each other very closely, peaking in mid-August (Figure 15 bottom panel). The mid-August peak in these ranges occurs while solar radiation and water temperatures are still near (but slightly past) their peaks, SRP has just reached a plateau near its seasonal maximum, water-column chlorophyll is beginning to approach (but has not yet reached) its seasonal maximum, and several weeks after the lowest flows (which last for several months) are reached.

[16] Computer simulations of Klamath River water temperatures indicate that Iron Gate Reservoir causes a temperature lag (Bartholow et al. 2004, PacifiCorp 2004, Perry et al. 2011).

Seasonal Patterns: Klamath R. at Seiad Valley (SV) 2001-2011

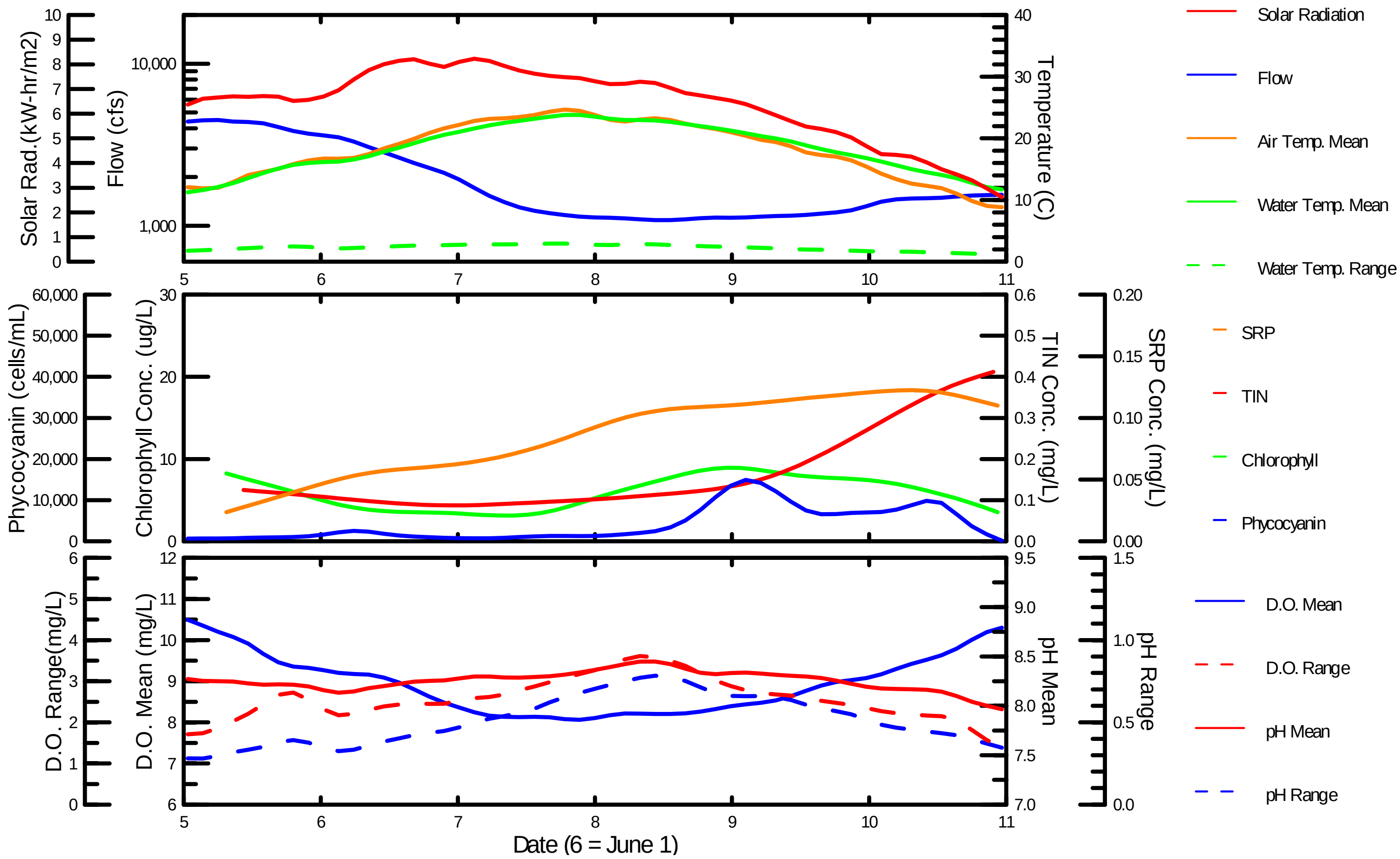


Figure 15. General seasonal trends for sixteen hydrologic (flow), meteorological (solar radiation and air temperature)[top panel], dissolved nutrients (TIN and SRP), algal (chlorophyll-*a* and phycocyanin) [middle panel], and continuous water quality (water temperature [top panel], DO, and pH [lower panel]) variables for May-October periods of 2001-2011 at Seiad Valley (SV). Each line is a distance-weight least squares (DWLS) smoother fit to daily means. Note: Phycocyanin data are only from 2008-2011, whereas the rest of the parameters generally contain data for each year in the entire 2001-2011 period.

3.4.2 Inter-Annual Patterns and Correlation Analyses

The Seiad Valley daily time series of hydrologic, meteorological, dissolved nutrient, algal, and continuous water quality parameters (Figure 16) illustrates the substantial inter-annual variability occurring at most stations (Appendix D). For example, examination of the 2001-2011 daily time series at Seiad Valley indicates that the minimum daily DO concentration appears to be substantially higher in years with high flow (e.g., 2006, 2010, and 2011) than in years with low flow (e.g., 2001 and 2002) (Figure 16). Plotting the monthly mean of the minimum DO concentration versus monthly mean flow supports this observation (Figure 17), as does a plot of daily minimum DO versus daily mean flow (Figure 18). However, flow appears to exert less influence on DO during the months of September and October.

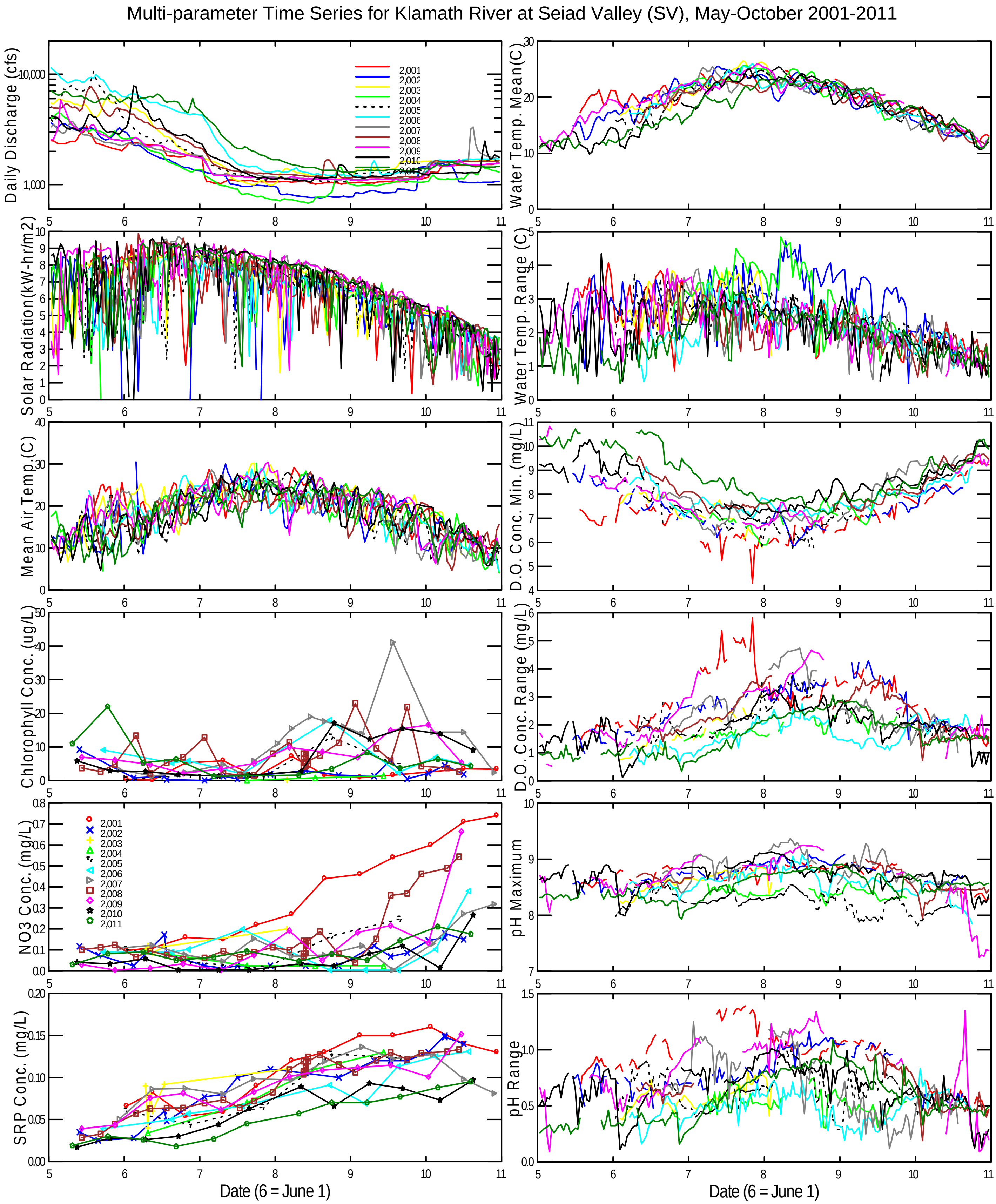


Figure 16. Daily time series of hydrologic, meteorological, dissolved nutrient, algal, and continuous water quality parameters for May-October periods of 2001-2011 at Klamath River at Seiad Valley.

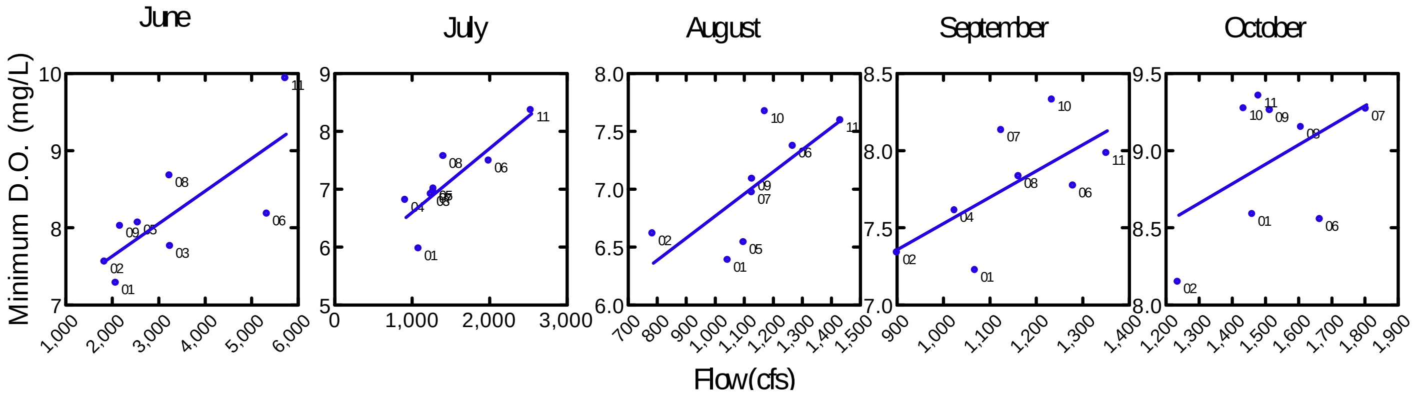


Figure 17. Monthly mean of daily minimum DO concentration vs. monthly average flow, by month for mainstem Klamath River at Seiad Valley 2001-2011. Spearman's rho values are: 0.79 for June (p=0.02), 0.95 for July (p<0.001), 0.89 for August (p=0.007), 0.62 for September (not significant), and 0.12 for October (not significant). Points are labeled with 2-digit year and a regression line is drawn as visual aid.

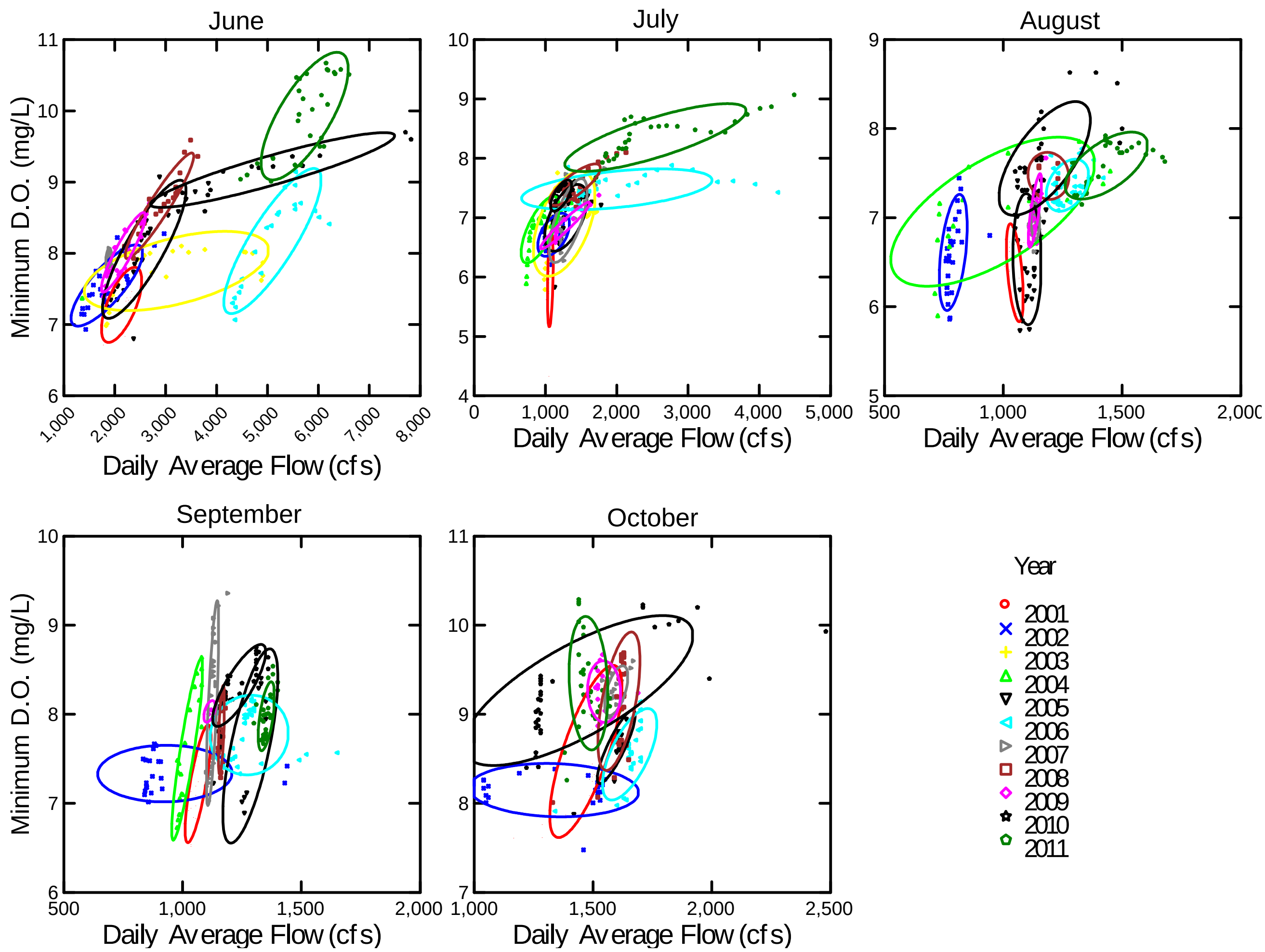


Figure 18. Daily minimum DO concentration vs. daily average flow, by month for the mainstem Klamath River at Seiad Valley 2001-2011. Markers are individual days and years are differentiated by color with a 95% confidence ellipse drawn around each year's points as visual aid.

We used Spearman's rank correlation tests to further evaluate inter-annual variability in 5 important water quality variables (monthly mean of: daily minimum DO concentration, daily DO concentration range, daily maximum pH, daily pH range, and mean daily water temperature). Spearman's rho and associated significance values were calculated for the correlation between these 5 dependent variables and 12 independent variables (monthly mean of: daily mean flow, daily mean water temperature[17], daily water temperature range, daily mean air temperature, daily mean precipitation, daily mean wind speed, alkalinity, and concentrations of TP, SRP, TN, NO_3+NO_2, and chlorophyll) for each month at each mainstem and tributary station.

To facilitate comparisons and to indicate independent variables that may explain inter-annual variations in water quality, Spearman correlation matrix[18] results were summarized by the number of site-month combinations with significance values of $p<0.05$ (Figure 19 and Figure 20).

Across all the dependent variables, flow had the highest number of overall statistically significant correlations at mainstem and tributary stations (Figure 19), with strongest relations occurring in June and July although they occurred in other months as well (Figure 20, Figure 21[19]). In the mainstem Klamath River, correlation between flow and water quality showed a strong longitudinal pattern: non-existent at Iron Gate, present for some parameters and months at Seiad Valley, and then strengthening with distance downstream. Iron Gate Dam was the only mainstem site where there were no significant relationships between flow and any dependent water quality variable for any month (Figure 19). In contrast to the river processes which dominate water quality at sites downstream, the lack of relationship at Iron Gate Dam is likely due to the domination of water quality by conditions in the upstream Iron Gate Reservoir. The negative correlations between flow and DO range were particularly strong and consistent at sites from Orleans to Turwar, with significant relationships at all four sites for June through September and two sites for October (Figure 21). Positive correlations between flow and DO minimum were weaker than for DO range at sites from Orleans to Turwar but stronger at Seiad Valley (Figure 21). Flow also had strong correlations with DO minimum, pH range, and mean water temperature at tributary stations. In addition, the Scott River USGS gage (SRGA), there were strong significant correlations between flow and maximum pH for June through September (Figure 19 and Appendix E), although this station has only been monitored for five years (compared with eleven years for the primary stations) so has relatively low sample size.

Water temperature was negatively correlated with DO minimum and generally positively correlated with DO and pH range, although these relationships were generally weaker than those for flow (Figure 19, Figure 20, Figure 21, and Figure 22). Indicating a seasonal shift and possible interaction between temperature and flow, at mainstem stations water temperature was correlated with flow in June and July (Figure 21 bottom panel) but correlated with air temperature in September (Figure 20 bottom panel and Figure 23). Overall, both higher flow and lower temperature were associated with a higher DO minimum and a narrower daily D.O range (i.e. 24-hour cycles). At tributary stations, water temperature appeared to be more affected by flow (Figure 21 bottom panel) than by air

[17] Daily mean water temperature was used as both a dependent and independent variable, because it is affected by flow and air temperature but then indirectly affects both DO and pH (through influence on growth of periphyton and phytoplankton) as well as directly affecting DO (though influence on oxygen solubility).
[18] The matrix consists of 3300 individual Spearman test combinations (5 dependent x 12 independent variables x 11 stations x 5 months).
[19] Note that this figure allows evaluation of both the strength of the relationship (the *rho* value) and the significance level (filled bars are statistically significant at the $p<0.05$ level; hollow bars are $p\geq0.05$) as well as the direction (positive or negative correlation).

temperature (Figure 23), with exceptions including the Shasta River in all months and the Scott River mouth (SC) and Salmon River (SA) in July.

At mainstem stations, TP and TN were negatively correlated with DO minimum and positively correlated with DO range, with the number of months with significant relationships varying by site (Figure 19, Figure 24, and Figure 25) and with July and August showing higher frequency of significant results as well as stronger relationships (Figure 20 and Figure 24). Nutrient limitation of periphyton is a possible explanation for these relationships, but most of these sites/months also have significant relationships between DO and flow (Figure 21); thus, these relationships could also be explained by covariance with flow, rather than nutrient effects on periphyton. An exception is Orleans, where despite no significant relationship between DO minimum and flow for July through September, there were relationships between DO minimum and TP (all three months) and TN (August and September); given the relative lack of relationships at this site between DO range and TP or TN (only July for TN)[20], the apparent relationships between DO minimum and TN and TP at Orleans could be affected by covariance with water temperature and the significant relationships between DO minimum and water temperature present in July and August. TN was also correlated with pH range for one month each at Seiad Valley, Tully Creek, and Turwar (Figure 24).

Some of the significant correlations between nutrients (i.e., TP,SRP, TN, and NO3+NO2) and DO and pH (Figure 19) have directions opposite of the expected and thus may be artifacts of co-variation with other variables, rather than causal relationships between nutrients and DO and pH. For example, at the Trinity River TP, SRP, and NO3+NO2 are negatively correlated with pH maximum (i.e., when pH is high, nutrients are low) (Appendix E). Other examples include negative correlation between pH maximum and TP in the Shasta River, and NO3+NO2 at Weitchpec (Appendix E).

Relative to the other water quality metrics, pH had the least number of significant correlations with independent variables (Figure 19). Chlorophyll had the highest number of significant correlations with maximum pH but only at three mainstem sites: Iron Gate (August/September), Weitchpec (June/July) and Tully Creek (July/August) (Figure 26). At Iron Gate, the likely explanation is that for the August and September months where the pH-chlorophyll relationships occurred, blue-green algal blooms in the reservoir upstream as well as entrainment of cells to the IG station are at seasonal maxima. The reasons for the relationship at Weitchpec and Tully Creek are less certain, and would require further analysis of phytoplankton data at these stations. There were also significant positive correlations between chlorophyll and maximum pH in the Trinity River (August and September) and Shasta River (September) (Figure 26). At the Scott River USGS gage (SRGA), there were strong significant correlations between flow and pH (daily range or maximum) for June through September (Figure 22 and Appendix E).

Previous studies have noted that alkalinity is relatively low in the Klamath River and thus does not provide much buffer against pH fluctuations (NCRWQCB 2010, ODEQ 2010). The results of this study support those descriptions of the low influence of alkalinity on Klamath River pH because the vast majority (five of six site-months) of significant correlations between alkalinity and pH range were positive (i.e., higher pH range when alkalinity was higher) (Figure 27), which is the opposite of what would occur if differences in alkalinity were a dominant factor in explaining year-to-year differences in pH range.

[20] The presumed mechanism linking nutrients to DO would be periphyton, which should affect DO range.

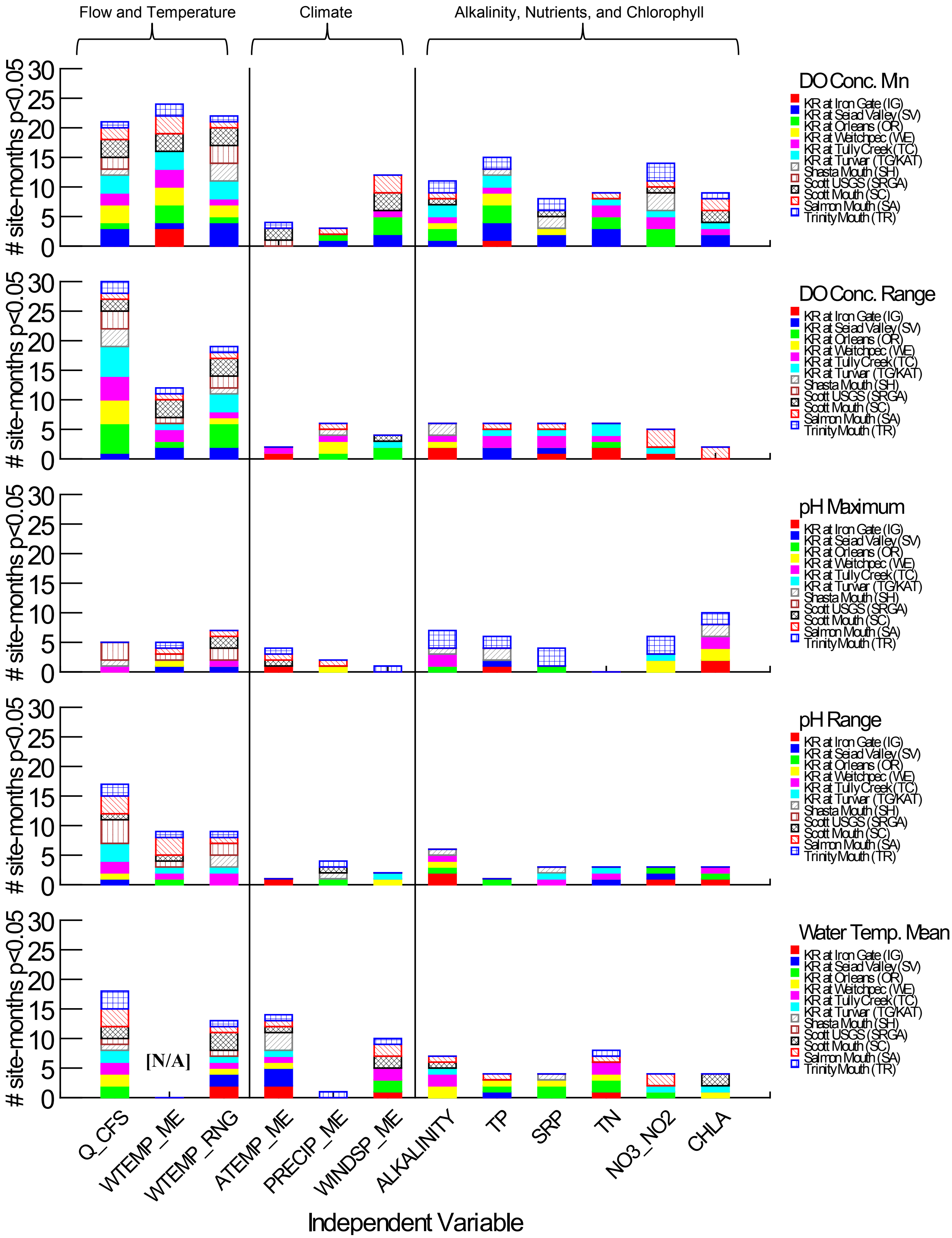


Figure 19. Frequency of significant (p <0.05) Spearman's rank correlation tests by site and parameter. Colors denote sites and the height of stacked bars is the number of months and sites (June through October 2001-2011) with statistically significant (p <0.05) relationship between the dependent and independent variable. Solid fills are mainstem sites and patterned fills are tributary sites.

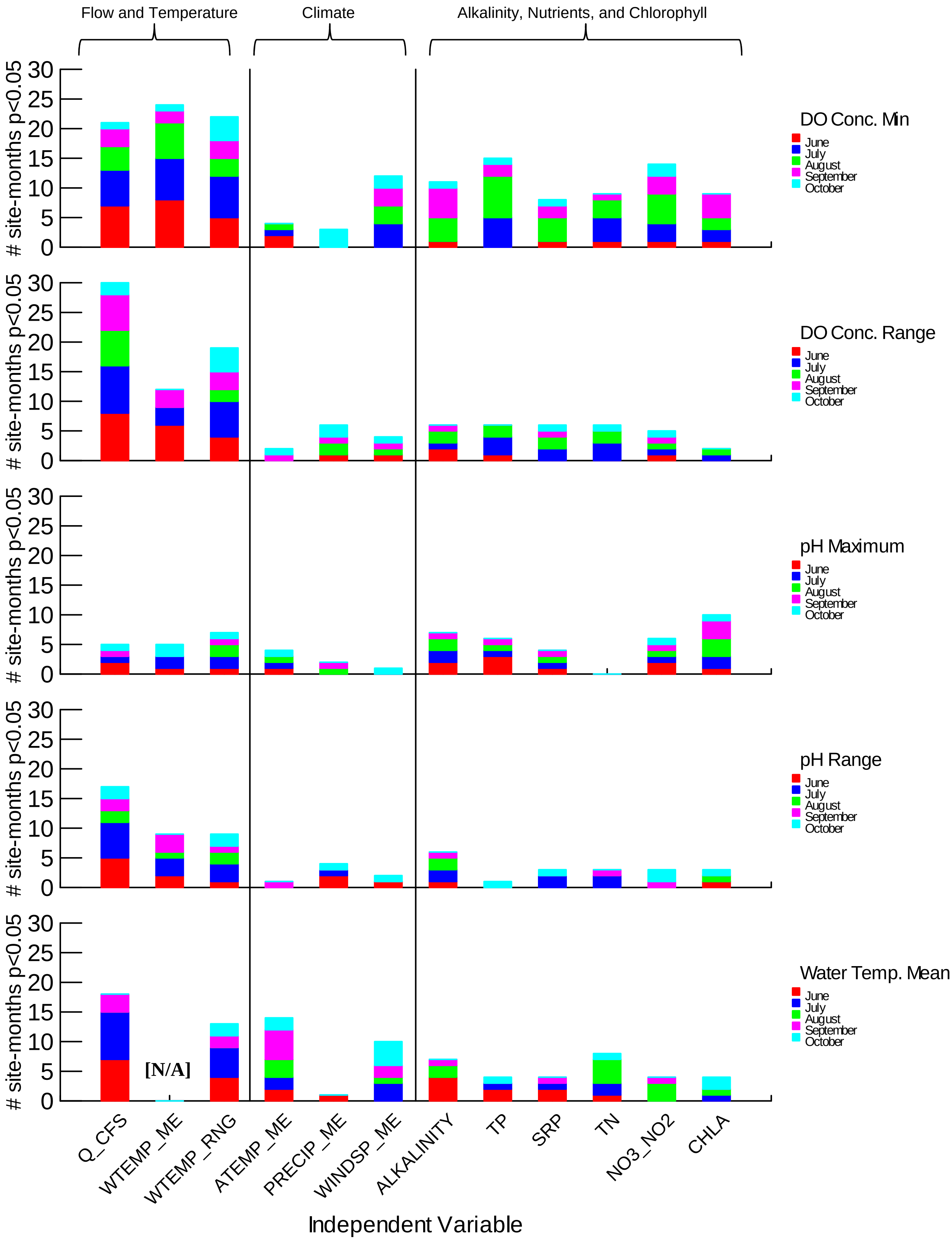


Figure 20. Frequency of significant (p <0.05) Spearman's rank correlation tests by month and parameter. Colors denote months and the height of stacked bars is the number of months and sites (June through October 2001-2011) with a statistically significant (p <0.05) relationship between the dependent and independent variable.

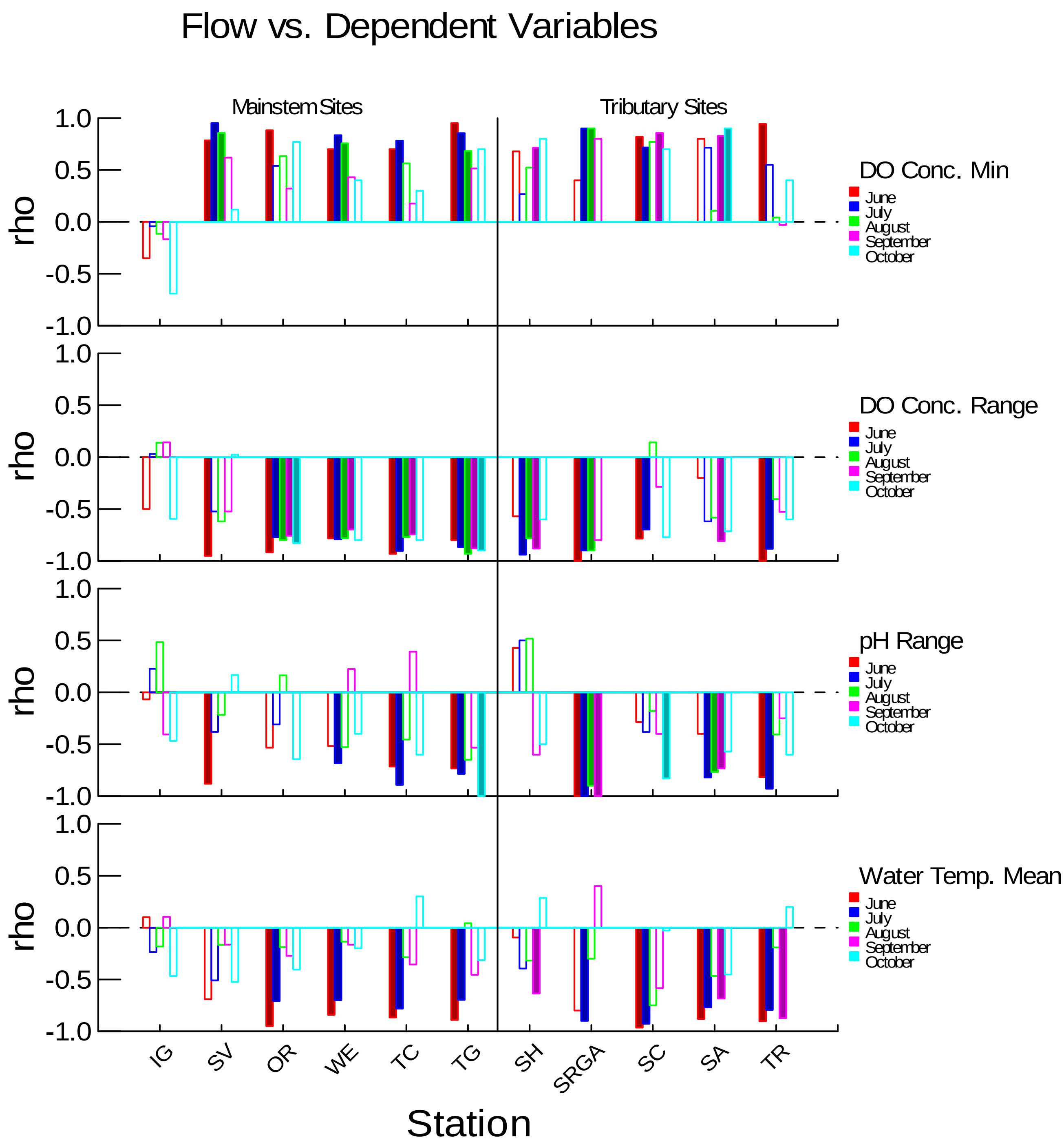


Figure 21. Spearman's rho values for the correlation between mean monthly flow and mean monthly DO minimum, DO range, pH range, and mean water temperature, for each station and month. Positive rho values denote positive correlations, while negative values denote negative correlations. Filled bars are statistically significant ($p < 0.05$) rho values; hollow bars are not significant ($p \geq 0.05$).

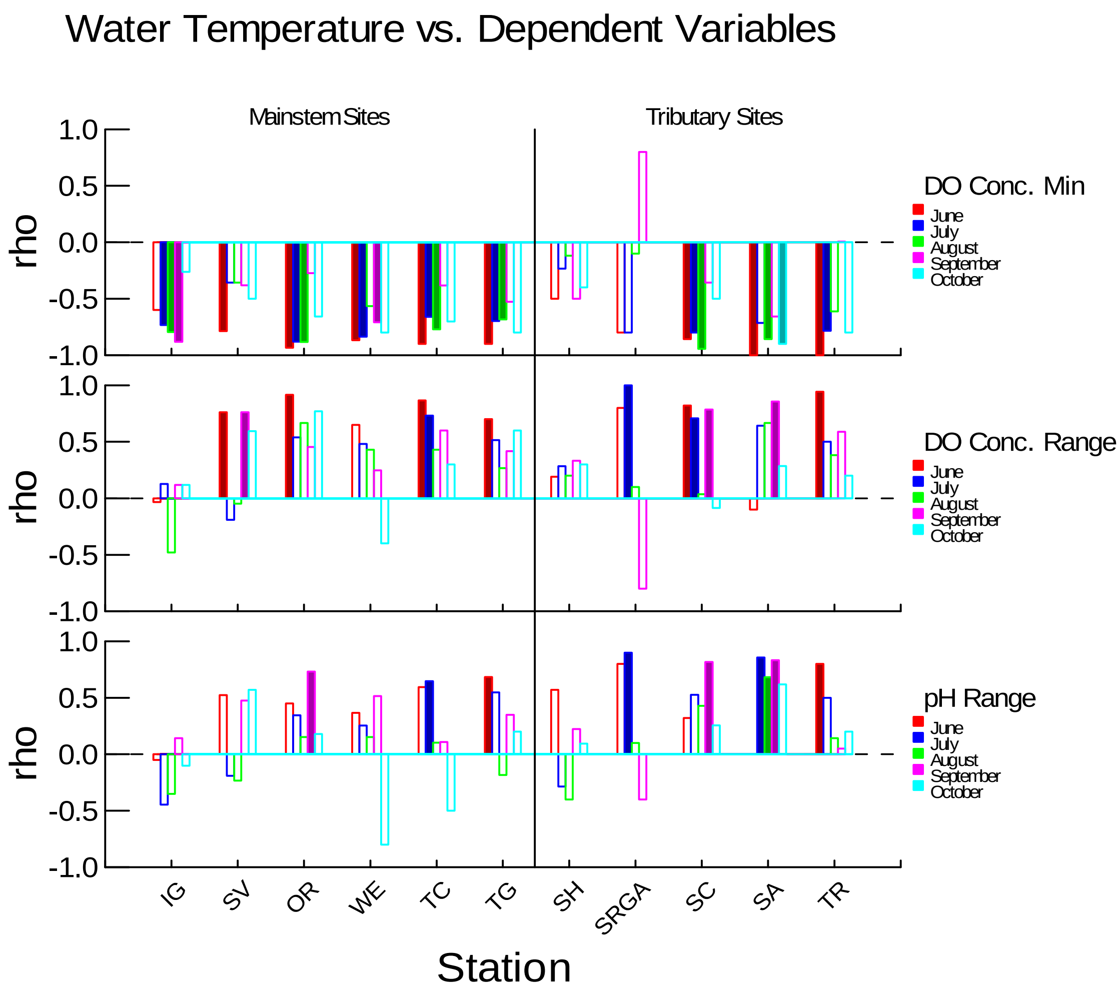


Figure 22. Spearman's rho values for the correlation between mean monthly water temperature and mean monthly DO minimum, DO range, and pH range for each station and month. Positive rho values denote positive correlations, while negative values denote negative correlations. Filled bars are statistically significant ($p < 0.05$) rho values; hollow bars are not significant ($p \geq 0.05$).

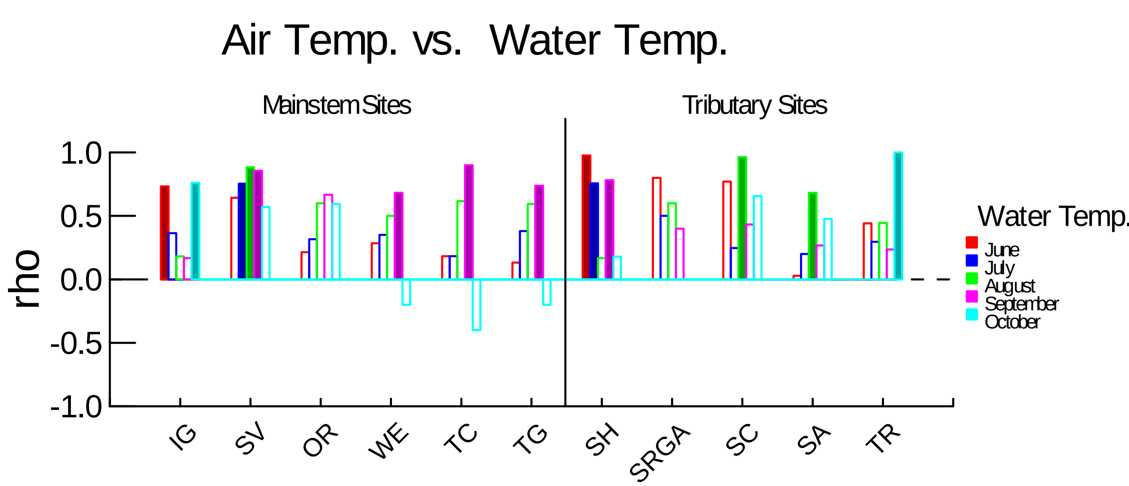


Figure 23. Spearman's rho values for the correlation between monthly mean air temperature and monthly mean water temperature, for each mainstem station and month. Positive rho values denote positive correlations, while negative values denote negative correlations. Filled bars are statistically significant ($p < 0.05$) rho values; hollow bars are not significant ($p \geq 0.05$).

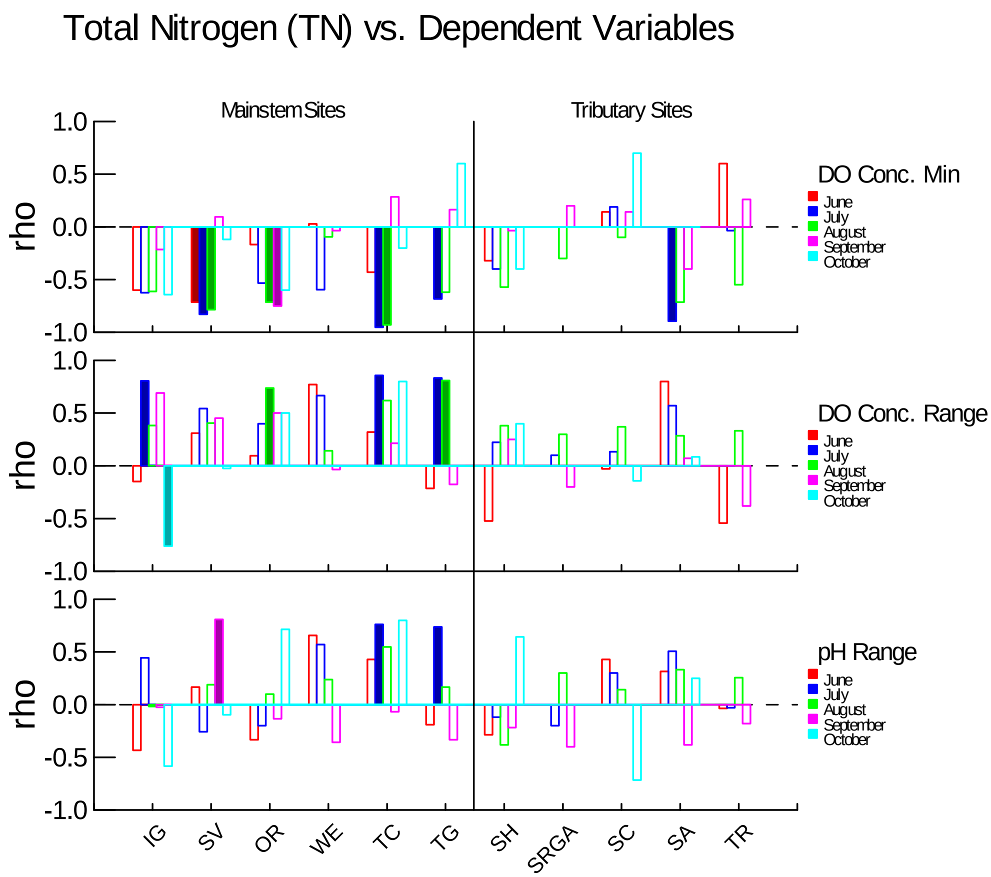


Figure 24. Spearman's rho values for the correlation between monthly mean total nitrogen (TN) and monthly mean of daily DO minimum, DO range, and pH range for each mainstem station and month Positive rho values denote positive correlations, while negative values denote negative correlations. Filled bars are statistically significant ($p < 0.05$) rho values; hollow bars are not significant ($p \geq 0.05$).

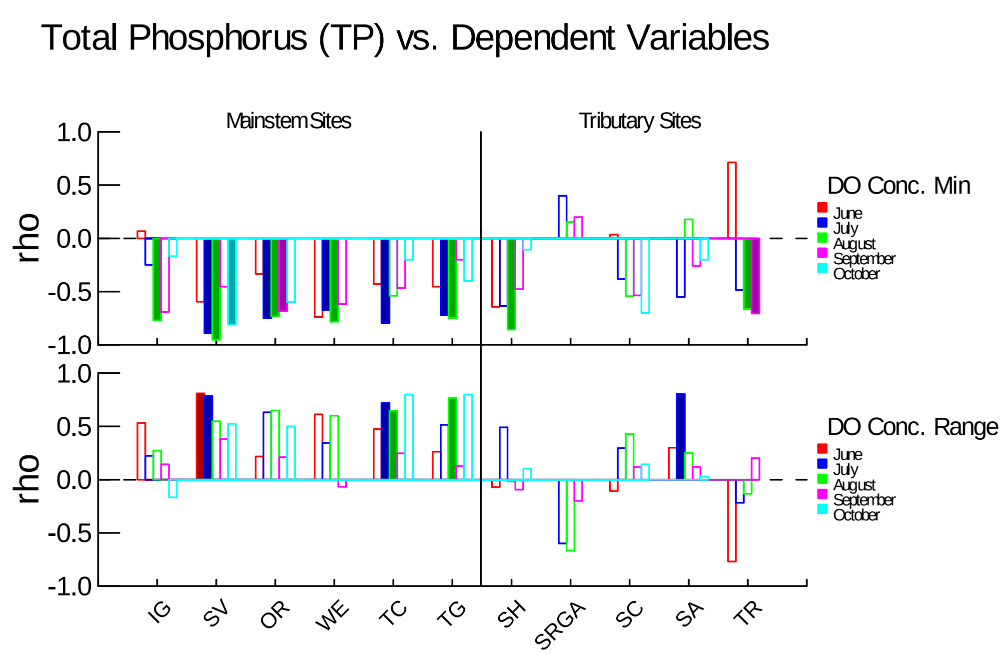


Figure 25. Spearman's rho values for correlation between total phosphorus (TP) and monthly mean of daily DO minimum and DO range for each station and month. Positive rho values denote positive correlations, while negative values denote negative correlations. Filled bars are statistically significant ($p < 0.05$) rho values; hollow bars are not significant ($p \geq 0.05$).

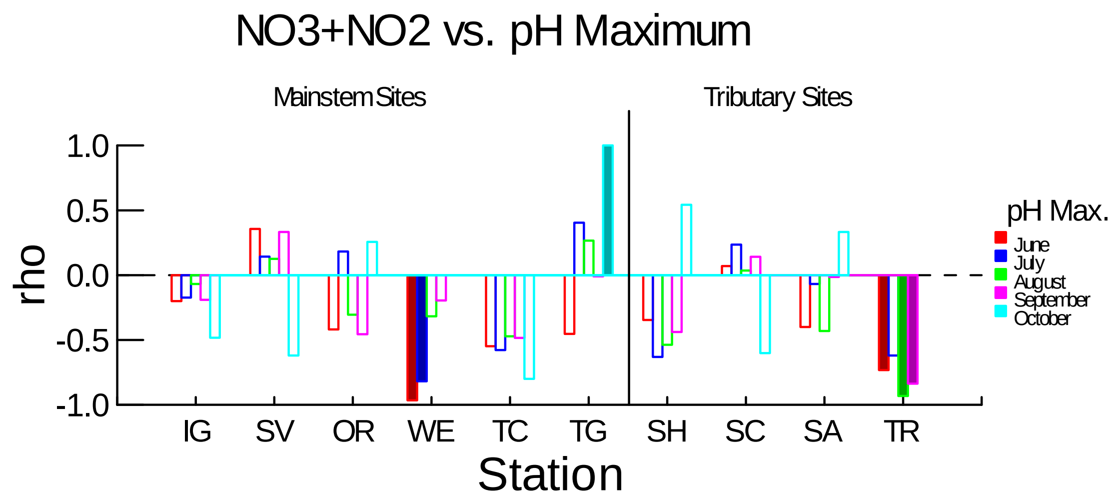


Figure 26. Spearman's rho values for the correlation between mean monthly chlorophyll concentration and monthly mean of daily pH maximum, for each station and month. Positive rho values denote positive correlations, while negative values denote negative correlations. Filled bars are statistically significant ($p < 0.05$) rho values; hollow bars are not significant ($p \geq 0.05$). Station SRGA is not included due to lack of chlorophyll data.

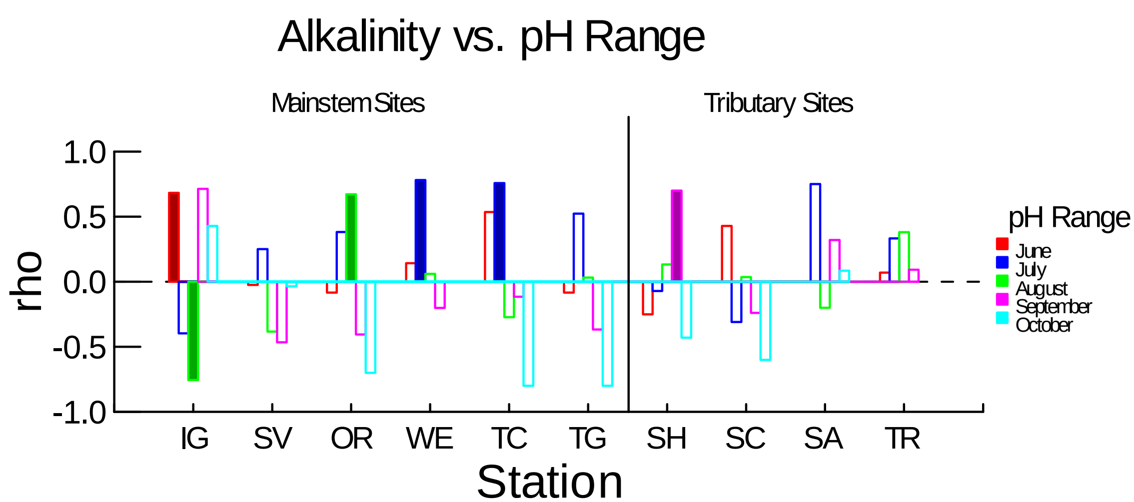


Figure 27. Spearman's rho values for the correlation between monthly mean alkalinity concentration and monthly mean of daily pH range, for each station and month. Positive rho values denote positive correlations, while negative values denote negative correlations. Filled bars are statistically significant ($p < 0.05$) rho values; hollow bars are not significant ($p \geq 0.05$). Station SRGA is not included due to lack of alkalinity data.

3.4.3 Discussion Regarding the Effect of Flow on Water Quality

It is well known that river water quality is related to spatiotemporal variation in climate and flow regime (e.g., Nilsson and Renöfält 2008; Garvey et al. 2007), and the Klamath River is no exception. Analyses in section 3.4.2 indicate that flow is significantly correlated with water temperature, DO, and pH in the Klamath River. This is likely due to multiple interacting pathways which include both direct and indirect effects, as illustrated by a conceptual model (Figure 28). These pathways can be differentiated into two groups: 1) pathways based entirely on physics and chemistry, and 2) pathways with complex biological, biochemical, and ecological intermediaries (e.g., periphyton and phytoplankton). Such complex interactions were illustrated by Garvey et al. (2007) where these authors showed that season, flow (and gradient), temperature, geomorphology, organic enrichment (and primary production/decomposition), and oxygen demand by macro-organisms, formed a hierarchical model to explain DO dynamics.

A strictly physical/chemical pathway occurs, for example, as flow is reduced, water temperature becomes more responsive to local meteorological conditions such as solar radiation and air temperature due to reduced thermal mass and increased transit time (due to lower water velocity) (Basdekas and Deas 2007). This can lead to either decreased or increased water temperature, depending on incoming water temperature and local meteorological conditions. Furthermore, because warmer water holds less oxygen (Wetzel 2001), increased water temperature also leads to reduced DO concentration and can be associated with lower flow (as shown above by the negative correlations between flow and water temperature, e.g., Figure 21 lower left panel).

Benthic diatom assemblages (a biological pathway) are strongly affected by channel morphology parameters (a physical pathway) such as wetted channel width and thalweg depth (e.g., Pan et al 2006). Although both wetted channel width and thalweg depth are affected by flow, decreased flow amplifies the relative water quality effect of a given periphyton biomass because as flow and water depth decrease there is a disproportionate change in the channel attributes such that the ratio between cross-sectional area and water depth decreases (i.e., mean depth decreases). The water quality effect of the decreased mean depth stems from the fact that remaining periphyton biomass[21] would have proportionally greater effect on the water column, and thus would magnify diel cycles of pH and DO. We verified that mean depth increases with flow using channel cross sections from USGS mainstem and tributary stream flow gages data as well as 57 Klamath River channel cross-sections surveyed by Ayers Associates (1999) (Appendix F). For example, when flow drops from 2100 cfs to 1600 cfs at Happy Camp, mean depth decreases 7.1% while wetted width decreases only 1.4% (Figure 29). This phenomenon is affected by cross-sectional channel shape, and is more pronounced in reaches with steeper channel margins.

Flow can affect periphyton biomass through several other mechanisms as well. First, higher water velocity caused by higher flow can result in sloughing of periphyton (Biggs 2000), and very high energy flows can cause scour and bed turnover (Holmquist-Johnson and Milhous 2010). Such flow perturbations can also reduce algal species richness depending on whether river beds are armored or unarmored (e.g., Biggs and Smith 2002). Second, higher flows also increase water depth, which when combined with the humic-colored water of the Klamath River (and to a lesser extent, organic

[21] Periphyton grow attached to the riverbed and exert their influence on the water column chemistry by impacting diel cycles of photosynthesis and respiration in the overlying water column. Although periphyton would also decrease as the wetted channel area declines, because the ratio of cross-sectional area:width decreases with decreased flow, periphyton would decrease at a lower rate relative to water column depth changes.

particulates) may reduce light reaching the streambed and subsequent periphyton growth (and conversely, lower flows would decrease depth and increase light)[22]. Numerous studies have also shown the effects of light, as well as the interaction of light and nutrient concentration on periphyton dynamics (e.g., Hill et al. 2009; Von Schiller et al. 2007). Hilton et al. (2006) also indicate that interaction of hydraulic drag and light limitation can be a strong determinant of benthic and filamentous algal domination.

Third, flow can either increase or decrease water temperature, according to ambient conditions (i.e., meteorology and incoming water temperature, as discussed above). When lower flow leads to warmer water temperature, periphyton growth rates can increase (Biggs 2000). Fourth, flow can affect nutrient concentration, depending on the source of water. For example, nutrient concentration in tributaries of the Klamath River is much lower (with the exception of the Shasta River) than in the mainstem Klamath River, so a decreased contribution of tributary flows relative to mainstem flow would increase nutrient concentration, which could increase periphyton growth in reaches of the Klamath River that are nutrient-limited[23]. Biggs and Close (2007) note that hydrological factors contribute at least equally with nutrients to the differences in periphyton biomass in gravel-bed study rivers. Analyses of available Klamath River periphyton data could help assess the degree to which the relationships between flow, temperature, and nutrients described in this paragraph, derived from other systems, also apply to the Klamath River (see section 4.8).

In addition to affecting periphyton, flow has been shown to be an important determinant of riverine phytoplankton populations. For example, both planktonic diatom and blue-green blooms were associated with extended low flow (generally <200 cfs) and or stratified conditions in Australian rivers (Mitrovic et al 2011; Mitrovic et al. 2008; Mitrovic et al. 2003). In general, low flow, stable conditions are required for planktonic blooms to occur in riverine systems, and due to turbulent, higher velocity conditions, free-flowing reaches of the mainstem Klamath River do not provide a favorable environment for phytoplankton growth. However, under extreme low flows it is possible that phytoplankton could increase to the extent that they further impact pH and DO.

The 2001-2011 study period encompassed a substantial portion of the flow variability contained in the 1961-2011 hydrologic period of record at Iron Gate Dam, but did not include the most extreme low flows that occurred in 1977 and the early 1990s (Figure 5). Given that water quality appears to be generally worse during relatively low-flow years than in relatively high-flow years, it is possible (or perhaps even likely) that if extreme low flows occur again in the future, water quality conditions could be worse than observed in the 2001-2011 study period.

[22] The degree to which light limits periphyton growth in the Klamath River is uncertain and likely varies by reach (more likely to occur in the lower reaches of the river where depths are higher).
[23] The degree to which nutrients limit periphyton growth in the Klamath River is uncertain and likely varies by reach (more likely to occur in the lower reaches of the river where nutrient concentrations are lower).

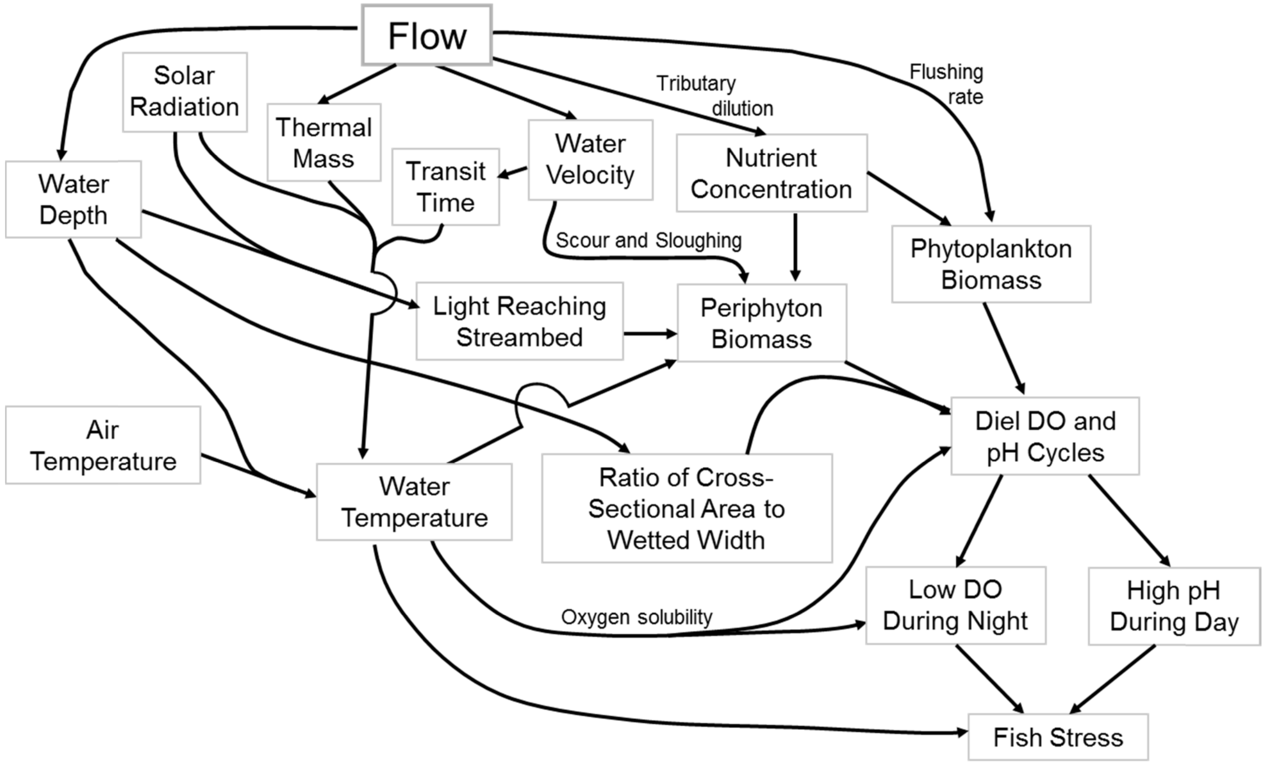
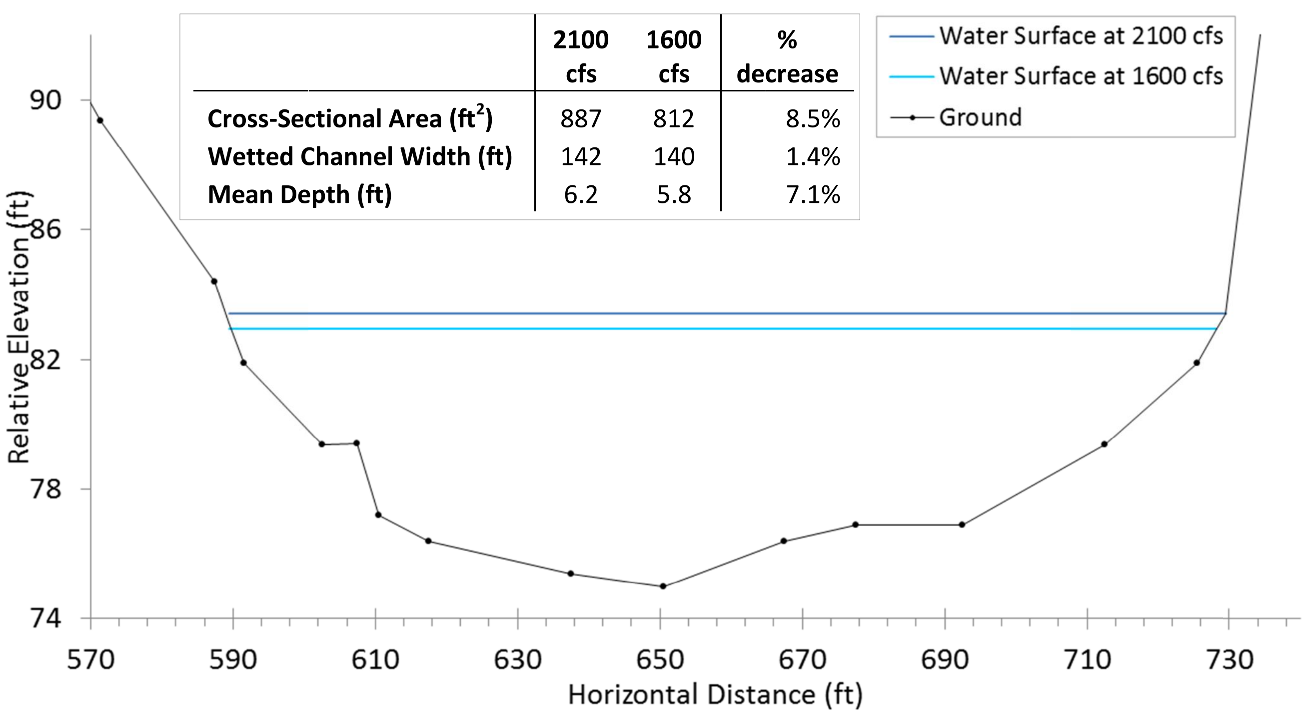


Figure 28. Conceptual model for the effect of flow on water quality in the mainstem Klamath River. By design, the model does not show all factors that affect water quality, just those most relevant to flow.



	2100 cfs	1600 cfs	% decrease
Cross-Sectional Area (ft^2)	887	812	8.5%
Wetted Channel Width (ft)	142	140	1.4%
Mean Depth (ft)	6.2	5.8	7.1%

Figure 29. Example Mainstem Klamath River channel cross section at river mile 106 near Happy Camp. Chart created from data in Ayres Associates (1999) for site number 3, cross section number 5. For clarity, the vertical scale is stretched approximately 4x relative to horizontal scale.

4 RECOMMENDATIONS

In this section, we present recommendation for additional monitoring and analyses.

4.1 CONTINUED MONITORING

Continued monitoring in future years is essential for better understanding Klamath River water quality and providing information to guide management of fish and water. Each year has its own unique set of hydrologic, meteorological, nutrient, and water quality conditions and building a long-term monitoring dataset makes it possible to evaluate relationships among these variables. Each additional year of data increases the sample size available for analysis and increases the strength of the conclusions that can be drawn. Years with extreme conditions, such as very low flows, are especially valuable scientifically although they may be detrimental to aquatic resources. As noted by Adams et al. (2002), long-term data sets incorporating a variety and range of endpoints are needed to improve our understanding of natural variability in streams and to provide a baseline against which disturbance and recovery processes can be evaluated.

4.2 RESUME MONITORING OF SUPPLEMENTAL MAINSTEM STATIONS

The 2001-2005 data indicate that some of the worst water quality (e.g., highest temperature, highest pH, and lowest DO) occurred at the supplemental mainstem Klamath River stations (K1 – Above Shasta River, K2 – Above Scott River, and HC – Happy Camp), which were not monitored in the years 2006-2011. If resources are available, monitoring should resume at these sites. During development of this report, we discussed this issue with the Karuk Tribe, the entity that monitors water quality between Iron Gate Dam and Orleans, and the Tribe operated a sonde at Above Shasta River in 2012 and is in the process of attempting to obtain equipment to operate a sonde at Happy Camp for the 2013 monitoring season (Crystal Bowman, pers. comm.). There are no current plans for monitoring at the Above Scott River station.

4.3 CORRECTION OF 2006-2011 DATA

While we excluded any obviously erroneous data from our analyses, most of the 2006-2011 continuous water quality dataset (the exception is the Yurok Tribe's 2010-2011 data) has not yet been corrected to address calibration drift and biofouling, as noted in the Section 2.1.2 above. Data correction is only warranted when combined error from fouling and calibration drift exceeds data correction criteria (Wagner et al. 2006). Analyses spanning the entire 2001-2011 study period, such as the correlations between variables presented in Section 3.4.2, could be affected by the improvements in the quality of equipment that occurred over the study period. As noted in the methods section above, the switch from Hydrolab to higher quality YSI probes occurred in 2005 for the Yurok Tribe and 2007 for the Karuk Tribe. However, the YSI probes are less prone to calibration drift and biofouling and thus warranted corrections to the 2006-2011 data would likely not be as significant as the corrections that were applied to the 2001-2005 data

We recommend that remaining 2006-2011 data be evaluated and corrected where justified. Applying corrections where necessary to the 2006-2011 dataset and then re-running the analyses would solidify confidence in the results presented in this report.

4.4 CALCULATION OF COMMUNITY METABOLISM

Ward and Armstrong (2010) calculated community metabolism (production and respiration) using the 2001-2005 continuous water quality dataset. It would be beneficial to run a similar analysis on the entire 2001-2011 dataset, which contains a wider range of hydrologic conditions than the relatively low-flow 2001-2005 period, to see if the patterns observed in the earlier analysis are confirmed in the longer dataset.

4.5 RELATIVE CONTRIBUTIONS OF THE BENTHOS AND WATER COLUMN

The relative contributions of the benthos (i.e., streambed periphyton and macrophytes) and water column (i.e., free-floating phytoplankton and decaying particulate organic matter) to diel and seasonal cycles are not well understood in the Klamath River. Laurel Genzoli, a graduate student at the University of Wyoming, conducted field experiments on this subject in 2012 for her Master's thesis research. Since the results are not yet available for review, it is unclear if further work on this subject is warranted. This is relevant for understanding how water quality dynamics would change following dam removal.

4.6 ADDITIONAL STATISTICAL ANALYSES

The statistical analyses conducted for this report were only a preliminary step in the evaluation of this rich eleven year (and counting) dataset. Additional analyses should be conducted to further elucidate causes of inter-annual variations in water quality. In addition, statistical analysis of longitudinal (i.e., between sites) variation in water quality and potential controlling factors is also recommended.

4.7 EXAMINE EFFECTS OF PULSE FLOWS

Natural and human-caused summer pulse flows may affect water quality in the Klamath River during the summer season. Events with coinciding continuous water quality data available for analysis include: 1) a summer storm event in late June 2001 that elevated flows in the Salmon and Trinity rivers and mainstem Klamath sites downstream, and 2) each year starting in 2003, pulse flows were released from either Iron Gate Reservoir or Trinity Lake in late August or early September. Examining the DO and pH data before, during, and after these events could provide information on how these pulse flows affect periphyton biomass and the effect of periphyton on water quality. For example, diel range of pH and DO may be reduced for several weeks as periphyton biomass recovers from sloughing and scour that may have occurred during pulse flows.

4.8 ANALYZE KLAMATH RIVER PERIPHYTON DATA

The Yurok and Karuk Tribes have been collecting periphyton samples in the Klamath River since 2004 but these data have yet not been comprehensively analyzed. Later this year, we will be completing a report summarizing patterns in the 2004-2012 periphyton data, including relationships with other variables such as flow, temperature, and nutrients.

5 CONCLUSIONS

This report summarizes the seasonal, longitudinal, and inter-annual patterns in continuous water quality variables in the lower and middle Klamath River and tributaries for the years 2001-2011. Analysis of the multi-year dataset provided confirmation, clarity, and additional insight on the seasonal, longitudinal, and inter-annual patterns in continuously monitored water quality data collected by a variety of agencies and tribes. This initial effort also provides a foundation upon which additional analysis can be conducted.

While there is variation in timing and magnitude, the overall longitudinal (i.e., upstream to downstream) patterns in water quality are relatively consistent from year-to-year. Percent exceedance of thresholds of regulatory or biological significance generally decreased with distance downstream from Iron Gate Dam for pH and DO, but water temperature followed a different pattern with the lowest exceedances occurring at Iron Gate Dam.

The 2001-2011 study period analyzed in this report encompassed a wide range of hydrological, meteorological, and nutrient conditions with which to assess relationships among several important dependent and independent variables. The non-parametric correlation analyses contained in this report are intended to provide an initial exploration of factors influencing water quality, and to provide a basis for formulation of additional questions and analyses. Continued monitoring by Klamath Basin Tribes and their cooperators will provide additional years of data to increase sample size and encompass an increased range of conditions.

Of all independent variables evaluated, flow had the strongest effect on water quality, likely due to multiple complex interacting physical, chemical, and biological pathways illustrated in Section 3.4.3. Flow had a stronger correlation with DO and temperature than it did with pH. Correlation does not necessarily prove causation, and it is particularly difficult to untangle the relative contributions of multiple variables controlling water quality given that parameters such as flow, water temperature, and nutrient concentration tend to co-vary, especially in June and July (i.e., high flow is associated with low water temperature and low nutrient concentration). Additional statistical analyses beyond the scope of this report would help increase understanding of these observed patterns.

6 ACKNOWLEDGEMENTS

The report was prepared for the Klamath Basin Tribal Water Quality Work Group (Work Group) using funds awarded to the Work Group by the U.S. EPA Region 9 and administered by the Yurok Tribe. We thank all the entities who contributed data to this report, particularly the Yurok Tribe, Karuk Tribe, and Quartz Valley Indian Reservation. In addition, we thank the following people for providing comments on a draft version of this report: Maia Singer of Stillwater Sciences, Rick Carlson of the U.S. Bureau of Reclamation, Kim Mattson of the Quartz Valley Indian Reservation, Crystal Bowman of the Karuk Tribe Department of Natural Resources, and Matt Hanington of the Yurok Tribe Environmental Program.

7 LITERATURE CITED

Adams, S. M., W. R. Hill, M. J. Peterson, M. G. Ryon, J. G. Smith, and A. J. Stewart. 2002. Assessing Recovery in a Stream Ecosystem: Applying Multiple Chemical and Biological Endpoints. *Ecological Applications,* 12: 1510-1527.

Arcata Fish and Wildlife Office (ARFO). 2005. Protocol for Collection of Nutrient Grab Samples. Arcata Fish and Wildlife Office, Arcata, CA. Available online at: <http://www.ccfwo.r1.fws.gov/fisheries/reports/wq/2004_grab_protocol_pzedits_nea_comments.pdf> Accessed 2005 1 April.

Armstrong, N.E. and G.E Ward. 2005. Review of the AFWO Klamath River Grab Sample Water Quality Database. University of Texas, Austin, TX.

Armstrong, N.E and G.E. Ward. 2008a. Coherence of Nutrient Loads and AFWO Klamath River Grab Sample Water Quality Database. Report to US Fish & Wildlife Service, Arcata, CA. 86 pp. Available online at: <http://www.fws.gov/Arcata/fisheries/activities/waterQuality/reports/KlamathRiver/NutrientsAndSondeData/Task%202%20Nutrient%20Loading%20Final%20Report%20Final%2011082008.pdf> Accessed 25 November 2012. 86 pp.

Armstrong, N.E and G.E. Ward. 2008b. Evaluation of Constituent Loading. Prepared for the U.S. Fish and Wildlife Service, Arcata, CA. 78 pp. Available online at: <http://www.fws.gov/Arcata/fisheries/activities/waterQuality/reports/KlamathRiver/NutrientsAndSondeData/Task%202%20Nutrient%20Loading%20Final%20Report%20Final%2011082008.pdf> Accessed 25 November 2012.

Asarian, E. and J. Kann. 2006. Klamath River Nitrogen Loading and Retention Dynamics, 1996-2004. Kier Associates Final Technical Report to the Yurok Tribe Environmental Program, Klamath, California. 56pp + appendices. Available online at: <http://elibrary.FERC.gov/idmws/file_list.asp?accession_num=20060811-5089> Accessed 09 November 2006.

Asarian, E. J. Kann, and W. Walker, 2009. Multi-year Nutrient Budget Dynamics for Iron Gate and Copco Reservoirs, California. Final Technical Report to the Karuk Tribe Department of Natural Resources, Orleans, CA. 55pp + appendices. Available online at: <http://www.riverbendsci.com/reports-and-publications-1/Cop_IG_Budget_may05dec07_report_final.pdf>

Asarian, E., J. Kann, and W. Walker. 2010. Klamath River Nutrient Loading and Retention Dynamics in Free-Flowing Reaches, 2005-2008. Final Technical Report to the Yurok Tribe Environmental Program, Klamath, CA. 59pp + appendices. <http://www.riverbendsci.com/reports-and-publications-1/Klamath0508_nutrient_dynamics_final_report_revised.pdf>

Bartholow JM, Campbell SG, Flug M. 2004. Predicting the thermal effects of dam removal on the Klamath River. *Environmental management* 34:856–874.

Basdekas, L. and Deas, M. 2007. Technical Memorandum No. 7 Temperature and flow dynamics of the Klamath River. Submitted to the Bureau of Reclamation Klamath Basin Area Office. Cramer Fish Sciences. Available online at: http://www.fishsciences.net/projects/klamathcoho/tech_memo_7.php

Biggs, B. J. F. And Close, M. E. (1989), Periphyton biomass dynamics in gravel bed rivers: the relative effects of flows and nutrients. Freshwater Biology, 22: 209–231

Biggs, B.J.F. 2000. New Zealand Periphyton Guideline: Detection, Monitoring, and Managing Enrichment of Streams. Prepared for Ministry of Environment. NIWA, Christchurch. Accessed online 11/4/20008 at: http://www.mfe.govt.nz/publications/water/nz-periphyton-guide-jun00.pdf

Biggs, B. J. F., and R. A. Smith. 2002. Taxonomic richness of stream benthic algae: Effects of flood disturbance and nutrients. *Limnol. Oceanogr.*, 47(4): 1175–1186

Bonn, B.A., 2008, Using the U.S. Geological Survey National Water Quality Laboratory LT-MDL to evaluate and analyze data: U.S. Geological Survey Open-File Report 2008-1227, 73p.

Butcher, J. 2008. Nutrient Dynamics in the Klamath River. Report to US EPA Region IX, San Francisco, CA. 26 pp.

Crystal Bowman. Personal communication. Water Resources Coordinator, Karuk Tribe.

Deas, M.L. and G.T. Orlob. 1999. Klamath River Modeling Project. Project #96-HP-01. Assessment of Alternatives for Flow and Water Quality Control in the Klamath River below Iron Gate Dam. University of California Davis Center for Environmental and Water Resources Engineering. Report No. 99-04. Report 236 pp. Available online at: http://www.krisweb.com/biblio/klamath_ucd_deasorlab_1999_wq.pdf

Deas, M. 2008. Nutrient and Organic Matter Fate and Transport in the Klamath River: June to September 2007. Prepared for PacifiCorp by Watercourse Engineering, Inc., Davis, CA.

Garvey JE, Whiles MR, Streicher D. 2007. A hierarchical model for oxygen dynamics in streams. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 1816-1827.

Hill, W. R., S. E. Fanta, and B. J. Roberts. 2009. Quantifying phosphorus and light effects in stream algae. Limnol. *Oceanogr.*, 54(1): 368-380.

M. O'Hare, M.J. Bowes, and J.I. Jones. 2006. How green is my river? A new paradigm of eutrophication in rivers. *Sci Total Environ.* 15; 365(1-3):66-83

Holmquist-Johnson CL, Milhous RT. 2010. Channel Maintenance and Flushing Flows for the Klamath River Below Iron Gate Dam, California. United States Geological Survey Open File Report 2010-1086. Available from: http://pubs.usgs.gov/of/2010/1086/

Hoopa Valley Tribe Environmental Protection Agency (HVTEPA). 2008. Water Quality Control Plan Hoopa Valley Indian Reservation. Approved September 11, 2002, Amendments Approved February 14, 2008. Hoopa Tribal EPA. Hoopa, CA. 285 p.

Kann, J. and E. Asarian. 2005. 2002 Nutrient and Hydrologic Loading to Iron Gate and Copco Reservoirs, California. Kier Associates Final Technical Report to the Karuk Tribe Department of Natural Resources, Orleans, California. 59pp + appendices. Available online at: <http://www.krisweb.com/ftp/KlamWQdatabase/Copco_IG_Budgets.zip> Accessed 2006 12 February.

Kann, J., and E. Asarian. 2007. Nutrient Budgets and Phytoplankton Trends in Iron Gate and Copco Reservoirs, California, May 2005 – May 2006. Final Technical Report to the State Water Resources Control Board, Sacramento, California. 81pp + appendices. Available online at: <http://www.klamathwaterquality.com/documents/Copco_IG_Budget_may2005may2006_final_revised4.pdf> Accessed 2010 21 June.

Karuk Tribe. 2012. Water Quality Control Plan. Karuk Tribe Department of Natural Resources, Orleans, CA.

Karuk Tribe. 2007. Water Quality Assessment Report 2007. Karuk Tribe Department of Natural Resources, Orleans, CA. 64 p. <http://karuk.us/dnr/pdf/wqdocuments/2007WQReport_Final.pdf> Accessed 2009 21 December.

Karuk Tribe. 2008. Water Quality Assessment Report 2008. Karuk Tribe Department of Natural Resources, Orleans, CA. 75 p. <http://www.klamathwaterquality.com/documents/2009/2008_WQReport_Karuk.pdf> Accessed 2009 21 December.

Karuk Tribe of California. 2010. Water Quality Report for the mid-Klamath, Salmon, Scott, and Shasta Rivers: May-Dec 2009. Karuk Tribe Department of Natural Resources, Orleans, CA. 21 p. <http://www.klamathwaterquality.com/documents/Karuk_2010_WQ_Report_2009.pdf> Accessed 2012 22 October.

Karuk Tribe of California. 2011. Water Quality Assessment Report 2010, Klamath River, Salmon River, Scott River, Shasta River, and Bluff Creek. Karuk Tribe Department of Natural Resources, Orleans, CA. 23 p. <http://www.klamathwaterquality.com/documents/Karuk_2011_WQ_Report_2010.pdf> Accessed 2012 22 October.

Karuk Tribe of California. 2012. Water Quality Assessment Report 2011. Klamath River, Salmon River, Scott River, Shasta River, and Bluff Creek. Karuk Tribe Department of Natural Resources, Orleans, CA. 27 p. <http://www.karuk.us/karuk2/images/docs/wqdocuments/2011WQAR.pdf> Accessed 2012 22 October.

Mitrovic, S., Oliver, R.L., Rees, C., Bowling, L.C. & Buckney, R.T. 2003. Critical flow velocities for the growth and dominance of Anabaena circinalis in some turbid freshwater rivers. *Freshwater Biology*, 48: 164-174.

Mitrovic, S., Chessman, B., Davie, A.W., Avery, E.L. & Ryan, N. 2008. Development of blooms of Cyclotella meneghiniana and Nitzschia spp. (Bacillariophyceae) in a shallow river and estimation of effective suppression flows. *Hydrobiologia*, 596: 173-185.

Mitrovic, S., Hardwick, L. & Dorani, F. 2011. Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia. *Journal of Plankton Research*, 33: 229-242.

Nilsson, C., and B. Malm Renöfält. 2008. Linking flow regime and water quality in rivers: a challenge to adaptive catchment management. Ecology and Society 13(2): 18

Nimick DA, Gammons CH, Parker SR. 2011. Diel biogeochemical processes and their effect on the aqueous chemistry of streams: A review. *Chemical Geology* 283:3–17.

North Coast Regional Water Quality Control Board. 2001. Water Quality Control Plan for the North Coast Region. Staff report adopted by the North Coast Regional Water Quality Control Board on June 28, 2001. Santa Rosa, CA. 124 p. Available online at: http://www.krisweb.com/biblio/ncc_swrcb_ncrwqcb_2001_wqcontrolplan.pdf

North Coast Regional Water Quality Control Board (NCRWQCB). 2010. Final Staff Report for the Klamath River Total Maximum Daily Loads (TMDLs) Addressing Temperature, Dissolved Oxygen, Nutrient and Microcystin Impairments in California, the Proposed Site Specific Dissolved Oxygen Objectives for the Klamath River and California, and the Klamath River and Lost River Implementation Plans. NCRWQCB, Santa Rosa, CA.

Oregon Department of Environmental Quality. 2010. Upper Klamath and Lost River subbasins; total maximum daily load (TMDL) and water quality management plan (WQMP). Oregon Department of Environmental Quality, Portland, OR. Available online at http://www.deq.state.or.us/WQ/TMDLs/klamath.htm

PacifiCorp. 2004. Final License Application for the Klamath River Hydroelectric Project (FERC Project No. 2082). Portland, OR.

PacifiCorp. 2006. Appendix B: Causes and Effects of Nutrient Conditions in the Upper Klamath River, Klamath Hydroelectric Project (FERC Project No. 2082). PacifiCorp, Portland, Oregon.

PacifiCorp. 2008. Application for Water Quality Certification Pursuant to Section 401 of the Federal Clean Water Act for the Relicensing of the Klamath Hydroelectric Project (FERC No. 2082) in Siskiyou County, California. PacifiCorp, Portland, Oregon. 265pp.

Pan, Y., B. H. Hill, P. Husby, R. K. Hall, and P. R. Kaufmann. 2006. Relationships Between Environmental Variables and Benthic Diatom Assemblages in California Central Valley Streams (USA). *Hydrobiologia* 561:119-130.

Perry, R.W, Risley, J.C., Brewer, S.J., Jones, E.C., Rondorf, D.W. 2011. Simulating daily water temperatures of the Klamath River under dam removal and climate change scenarios. U.S. Geological Survey Open-File Report 2011-1243:78pp. Available online at: http://pubs.usgs.gov/of/2011/1243/

Quartz Valley Indian Reservation (QVIR). 2008. Water Quality Monitoring and Assessment Report 2007. By Crystal Bowman, Environmental Director, QVIR, Fort Jones, CA. 59 p. <http://www.klamathwaterquality.com/documents/Final%20QVIRWaterQuality_2008.pdf> Accessed 2012 25 November.

Quartz Valley Indian Reservation (QVIR). 2009. Water Quality Monitoring and Assessment Report 2008. By Crystal Bowman, Environmental Director, QVIR, Fort Jones, CA. 65 p. <http://www.klamathwaterquality.com/documents/qvir_2009_wq_monitor_report_2008.pdf> Accessed 2012 25 November.

Quartz Valley Indian Reservation (QVIR). 2011. Water Quality Monitoring and Assessment Report 2011. QVIR, Fort Jones, CA. 65 p. <http://www.qvir.com/uploads/2/8/6/9/2869254/2011_water_quality_assessment_report_final.pdf> Accessed 2012 25 November.

Raymond, R. 2008. Water Quality Conditions During 2007 in the Vicinity of the Klamath Hydroelectric Project. Prepared for PacifiCorp Energy by E&S Environmental Chemistry, Inc., Corvallis, Oregon. 34pp + appendices. http://www.pacificorp.com/content/dam/pacificorp/doc/Energy_Sources/Hydro/Hydro_Licensing/Klamath_River/Water_Quality_Conditions_During_2007_in_the_Vicinity_of_the_Klamath_Hydroelectric_Project.pdf

Raymond, R. 2009. Water Quality Conditions During 2008 in the Vicinity of the Klamath Hydroelectric Project. Prepared for PacifiCorp Energy by E&S Environmental Chemistry, Inc., Corvallis, Oregon. 66pp. http://www.pacificorp.com/content/dam/pacificorp/doc/Energy_Sources/Hydro/Hydro_Licensing/Klamath_River/Water_Quality_Conditions_During_2008_in_the_Vicinity_of_the_Klamath_Hydroelectric_Project.pdf

Raymond, R. 2010. Water Quality Conditions During 2009 in the Vicinity of the Klamath Hydroelectric Project. Prepared for PacifiCorp Energy by E&S Environmental Chemistry, Inc., Corvallis, Oregon. 74pp.

Schiller, D. V., Martí, E., Riera, J. L. And Sabater, F. (2007), Effects of nutrients and light on periphyton biomass and nitrogen uptake in Mediterranean streams with contrasting land uses. *Freshwater Biology*, 52: 891–906

Strange, J. 2010. Salmonid Use of Thermal Refuges in the Klamath River: 2010 Annual Monitoring Study. Yurok Tribal Fisheries Program, Hoopa, CA. Available online at: http://www.yuroktribe.org/departments/fisheries/documents/thermal_refguia_report_FINAL_2010_YTFP_000.pdf

Sullivan, A.B., Rounds, S.A., Asbill-Case, J.R., and Deas, M.L., 2013, Macrophyte and pH buffering updates to the Klamath River water-quality model upstream of Keno Dam, Oregon: U.S. Geological Survey Scientific Investigations Report 2013-5016, 52 p.

Tetra Tech. 2009. Model Configuration and Results – Klamath River Model for TMDL Development. Prepared for U.S. EPA Region 10, U.S. EPA Region 9, Oregon Department of Environmental Quality, and North Coast Regional Water Quality Control Board. December 2009. Tetra Tech, Inc., Fairfax, VA. http://www.swrcb.ca.gov/northcoast/water_issues/programs/tmdls/klamath_river/100427/Appendix_06_KlamathRiverModelingReport.pdf Accessed 2010 6 June.

U.S. Environmental Protection Agency (USEPA). 1986b. Quality Criteria for Water. Office of Water. EPA 440/5-86-001. 477pp. Available at: <http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/2009_01_13_criteria_goldbook.pdf>

U.S. Geological Survey. 2011. Change to solubility equations for oxygen in water: Office of Water Quality Technical Memorandum 2011.03. Available online at: <http://water.usgs.gov/admin/memo/QW/qw11.03.pdf> Accessed 2012 25 November.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, 51 p. + 8 attachments; accessed April 10, 2006, at http://pubs.water.usgs.gov/tm1d3

Ward GH, Armstrong NE. 2010. Assessment of Community Metabolism and Associated Kinetic Parameters in the Klamath River. Prepared for the U.S. Fish and Wildlife Service, Arcata Office. <http://www.fws.gov/arcata/fisheries/activities/waterQuality/reports/KlamathRiver/KlamathProductionFinal_08062010.pdf> Accessed 2012 22 October.

Watercourse Engineering, Inc. 2003. Klamath River Water Quality 2000 Monitoring Program - Project Report. Prepared for U.S. Bureau of Reclamation with support from PacifiCorp. Watercourse Engineering, Inc., Napa, CA.

Watercourse Engineering, Inc., 2011a. Klamath River Baseline Water Quality Sampling, 2009 Annual Report. Prepared for the KHSA Water Quality Monitoring Group. Watercourse Engineering, Inc., Davis, CA. 42pp. Available online at: <http://www.kbmp.net/images/stories/pdf/KHSA/KHSA_WQ_Basline_Monitoring_Report_2009.pdf>

Watercourse Engineering, Inc., 2011b. Klamath River Baseline Water Quality Sampling, 2010 Annual Report. Prepared for the KHSA Water Quality Monitoring Group. Watercourse Engineering, Inc., Davis, CA. 25pp plus appendices. Available online at: <http://www.kbmp.net/images/stories/pdf/KHSA/KHSA_WQ_Baseline_Monitoring_Report_2010_v2.pdf>

Watercourse Engineering, Inc., 2012. Klamath River Baseline Water Quality Sampling, 2012 Annual Report. Prepared for the KHSA Water Quality Monitoring Group. Watercourse Engineering, Inc., Davis, CA. 24pp plus appendices. Available online at: <http://www.kbmp.net/images/stories/pdf/KHSA/2011_KHSA_WQ_Baseline_Final_Report_revised_092512.pdf>

Wetzel RG. 2001. *Limnology: Lake and River Ecosystems*. Academic Press, San Diego, CA.

Yurok Tribe Environmental Program. 2004a Water Quality Control Plan For the Yurok Indian Reservation. Yurok Tribe Environmental Program, Klamath, CA. 37 p. <http://www.klamathwaterquality.com/documents/Yurok_Res_WQ_Plan_08-24-04.pdf> Accessed 2012 22 October.

Yurok Tribe Environmental Program. 2004b. Yurok Tribe Water Year 2002 (WY02) Report October 1, 2001 – September 30, 2002. Prepared by Kevin McKernan, Lori McKinnon, Ken Fetcho, and Eric Brunton. YTEP, Klamath, CA. 160 pp. <http://www.yuroktribe.org/departments/ytep/documents/WY02.pdf> Accessed 2012 22 October.

Yurok Tribe Environmental Program. 2004c. Yurok Tribe Water Year 2003 (WY03) Report October 1, 2002 – September 30, 2003. Prepared by Kevin McKernan, Lori McKinnon, Ken Fetcho, Eric Brunton, and Laura Mayo. YTEP, Klamath, CA. 538 pp. <http://www.yuroktribe.org/departments/ytep/documents/FinalWY03Report.pdf> Accessed 2012 22 October.

Yurok Tribe Environmental Program. 2005. Yurok Tribe Water Year 2004 (WY04) Report October 1, 2003 – September 30, 2004. Prepared by Kevin McKernan, Lori McKinnon, Ken Fetcho, Eric Brunton, Laura Mayo, Jessica Hackman, Monica Hiner, Micah Gibson, and Seafha Blount. YTEP, Klamath, CA. 207 pp. <http://www.yuroktribe.org/departments/ytep/documents/WY04.pdf> Accessed 2012 22 October.

Yurok Tribe Environmental Program. 2007. Final 2007 Klamath River Nutrient Summary Report. Prepared by Scott Sinnott, YTEP, Klamath, CA. 37 p. <http://www.klamathwaterquality.com/documents/Yurok_2007NutrientReport.pdf> Accessed 2009 21 December.

Yurok Tribe Environmental Program. 2008. Final 2008 Klamath River Nutrient Summary Report. YTEP Water Division, Klamath, CA. 37 p. <http://www.klamathwaterquality.com/documents/2009/Yurok_FINAL_2008_Nutrient_Report_040609.pdf > Accessed 2009 21 December.

Yurok Tribe Environmental Program. 2009. Final 2006 Klamath River Nutrient Summary Report. Prepared by Scott Sinnott, YTEP, Klamath, CA. 33 p. <http://www.yuroktribe.org/departments/ytep/documents/Final_2006_Nutrient_Report_033009.pdf> Accessed 2009 21 December.

Yurok Tribe Environmental Program. 2010a. Final 2009 Klamath River Continuous Water Quality Monitoring Summary Report. Prepared by Scott Sinnott. YTEP Water Division, Klamath, CA. 65 p.

Yurok Tribe Environmental Program. 2010b. Final 2009 Klamath River Nutrient Summary Report. . Prepared by Scott Sinnott. YTEP Water Division, Klamath, CA. 50 p.

Yurok Tribe Environmental Program. 2011a. Final 2010 Klamath River Continuous Water Quality Monitoring Summary Report. Prepared by Scott Sinnott. YTEP Water Division, Klamath, CA. 54 p.

Yurok Tribe Environmental Program. 2011b. Final 2010 Klamath River Nutrient Summary Report. Prepared by Scott Sinnott. YTEP Water Division, Klamath, CA. 54 p.

Yurok Tribe Environmental Program. 2012a. Final 2011 Klamath River Continuous Water Quality Monitoring Summary Report. Prepared by Scott Sinnott. YTEP Water Division, Klamath, CA. 57 p.

Yurok Tribe Environmental Program. 2012b. Final 2011 Klamath River Nutrient Summary Report. Prepared by Scott Sinnott. YTEP Water Division, Klamath, CA. 50 p.