MULTI-YEAR NUTRIENT BUDGET DYNAMICS FOR IRON GATE AND COPCO RESERVOIRS, CALIFORNIA

PREPARED FOR THE

KARUK TRIBE, DEPARTMENT OF NATURAL RESOURCES

BY

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EXECUTIVE SUMMARY

Copco and Iron Gate Reservoirs are mainstem reservoirs on the Klamath River in northern California, one of the major salmon rivers of the western United States. The Klamath River in California is listed as an impaired water body on the Clean Water Act (CWA) section 303(d) list for temperature, nutrients and dissolved oxygen. The North Coast Regional Water Quality Control Board is in the process of developing a Total Maximum Daily Load (TMDL) for the Klamath River. PacifiCorp Energy, the owner and operator of the Klamath Hydroelectric Project (Project) is also in the process of relicensing the Project with the Federal Energy Regulatory Commission. The Karuk Tribe of California initiated a sampling program to determine longitudinal, temporal, and depth trends in physical and chemical water quality in Copco and Iron Gate Reservoirs from May 2005 to December 2007. The overall goals of this study were to 1) collect and analyze detailed nutrient and hydrologic data for Copco and Iron Gate Reservoirs, and 2) construct mass-balance nutrient budgets to evaluate potential effects of the reservoirs on nutrient dynamics in the Klamath River.

Hydrologic (riverine discharge and reservoir volume data) and nutrient (riverine and in-reservoir concentrations of total nitrogen and total phosphorus) data were collected and/or assembled for inflow, outflow, and in-reservoir stations for both Copco and Iron Gate Reservoirs. Nutrient samples were collected approximately bi-weekly during the primary May-November sampling period, but were sampled less frequently during the winter period. Hydrologic data were obtained from USGS stream gages, PacifiCorp, and other agencies. These nutrient concentration and hydrologic data were used to compute nutrient loading for reservoir inflow/outflow and in-reservoir change in mass on a daily basis. These daily values were summarized to represent both sample period and whole season or annual dynamics and to account for travel time through the reservoir complex. Budgets were summarized for Copco and Iron Gate both separately and combined (to evaluate the net effect of both reservoirs in tandem) for 1) sample periods (~biweekly), 2) the approximate reservoir algal growing season (mid-May to end of September), 3) the study start through turnover (mid-May to mid-December), 4) annually (mid-May to mid-May), and 5) the winter/early spring period (mid-December to mid-May).

Several methodological improvements were made to the calculation of the nutrient budgets compared with the previous Kann and Asarian (2007) report that summarized the first year of the study's results (May 2005 – May 2006). These improvements included: adjusting Klamath River above Copco nutrient concentrations to account for the effects of hydropower peaking (recommendation for timing of future sampling are also included in this report), accounting for ungaged inflows, more accurately representing discharge for tributaries, improving calculation of reservoir-wide nutrient concentrations to better represent the anoxic zone of elevated nutrient concentration that exists at the sediment-water interface, and use of a flow- and season based multiple regression model (as opposed to interpolation only) for estimating daily nutrient concentrations that allows for uncertainty estimation in nutrient loads and retention.

Both reservoirs thermally stratified during the warm summer months, with the deeper waters (hypolimnion) in both reservoirs exhibiting low levels of dissolved oxygen as well as high concentrations of ammonia and soluble reactive phosphorus. The upper water column layers (epilimnion) in both reservoirs hosted large blooms of phytoplankton (as evidenced by chlorophyll *a*) and had elevated pH. Concentrations of total nitrogen (TN) were consistently lower at Klamath

River below Iron Gate than Klamath River above Copco for the July through October period, while total phosphorus (TP) concentrations were lower at Klamath River below Iron Gate for the mid-July through August period in 2005 and 2007, and from mid-July through September in 2006. This is likely due to 1) nutrient storage in the water column and sediments of the reservoirs, 2) penstock intakes that draw water from intermediate depths where concentrations are lower, and 3) possible atmospheric losses through denitrification (for nitrogen only). Higher TP concentrations were generally observed below Iron Gate than above Copco for the September-November period, likely reflecting internal loading and residence time.

Based on mass-balance nutrient budgets, the combined retention of Iron Gate and Copco Reservoirs was 9±4% of TP inflow over the entire 31-month study period (May 2005-December 2007). For the two years where May to May data were available, the total combined TP retention was 11% (9±6% for May 2005-May 2006, 13±7% for May 2006-May 2007), with a majority of that retention occurring in the winter and spring period of high flow when the percent of TP comprised of particulate P was high. During the main reservoir phytoplankton growing season (May 18-September 30 for 2005, 2006 and 2007) the total combined TP retention was -8% (-12% in 2005, -8% in 2006, -4% in 2007), while for the period encompassing turnover (May 18-December 11 for 2005, 2006 and 2007) it was 0% (-8±8% in 2005, 1±8% in 2006, 3±8% in 2007). The relatively low TP retention during the growing season period is likely due to a combination of two factors: 1) a high percentage of the incoming phosphorus load was in dissolved form, which is less likely to settle than particulate phosphorus, and 2) in many reservoirs, internal phosphorus loading commonly occurs during the type of low and prolonged dissolved oxygen conditions observed in this study. The pattern of flow-weighted average TP concentrations (calculated by dividing total load by total flow for both inputs and outputs to the combined complex of Iron Gate and Copco Reservoirs, including tributaries to account for dilution) was similar to that of retention, with outflow TP concentrations ranging from 73% to 104% of flow-weighted inflow concentrations across the various summary periods. In two of three years, outflow TP concentrations during the May-December periods that encompass turnover were slightly higher than flow-weighted inflow, and were within 10% of flow-weighted inflow concentrations for each of the three May-September periods.

Over the entire study period (May 2005-December 2007), the combined retention of Iron Gate and Copco Reservoirs was 13±3% of TN inflow. For the two May to May years, combined TN retention was 12% (12±4% for May 2005 to May 2006, 12±5% for May 2006 to May 2007). For the main reservoir phytoplankton growing season (May 18-September 30 for 2005, 2006 and 2007) total combined TN retention was 23% (22% in 2005, 23% in 2006, 25% in 2006), while for the period encompassing turnover (May 18-December 11 for 2005, 2006 and 2007) it was 15% (10±5% in 2005, 14±5% in 2006, 18±5% in 2007). Higher percent retention during summer months may reflect settling of inflow organic matter and in-reservoir algal material, and/or denitrification. The pattern of flow-weighted average TN concentrations was similar to that of retention, with outflow TN concentrations ranging from 68% to 97% of inflow concentrations across the various summary periods. For the entire study (May 2005-December 2007) outflow concentration was 85% of inflow concentration, with larger decreases in TN concentration occurring across the three May-September (outflow averaged 69% of inflow) and May-December (outflow averaged 77% of inflow) periods.

For both TN and TP, although variation in relative retention occurred among years for the various summary periods, these inter-annual differences were less than ~10% of inflow, and uncertainty analysis indicates that among-year values were not significantly different.

Overall net retention accounted for a relatively low (11% for TP, and 12% for TN) percentage of inflow on an annual basis. However, these observed values were generally within the range predicted using models developed from a broad range of lakes and reservoirs that incorporate inflow loading and other hydraulic characteristics.

In summary, these results provide a robust assessment of nutrient loading and reservoir retention dynamics for the three year period from May 2005 through December 2007, and can be utilized to evaluate potential effects of current proposals to remove Copco and Iron Gate Reservoirs.

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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, which then drain into large, shallow Upper Klamath Lake, and after a short stretch of river known as the Link River (followed by Lake Ewauna), the Klamath River proper begins. From this point the River continues through a series of impoundments, including Keno, J.C. Boyle, Copco, and Iron Gate Reservoirs, below which the river flows freely 190 miles to the Pacific Ocean.

This study focuses specifically on Iron Gate and Copco Reservoirs (Figure 1), located near the town of Yreka in northern California's Siskiyou County. PacifiCorp Energy (PacifiCorp) operates these reservoirs as part of the Klamath Hydroelectric Project (KHP) to regulate flows and generate electricity.

1.2 BACKGROUND

The Klamath River in California is listed as an impaired water body on the Clean Water Act (CWA) section 303(d) list for temperature, nutrients, microcystin, sediment, and dissolved oxygen. The North Coast Regional Water Quality Control Board (NCRWQCB) is in the process of developing a Total Maximum Daily Load (TMDL) for the Klamath River. In addition, PacifiCorp is in the process of relicensing the KHP with the Federal Energy Regulatory Commission, and the State Water Board has authority under section 401 of the Clean Water Act to issue water quality certification for the Project. The study was initially designed to provide critical information for the development of the technical TMDL, TMDL implementation plan, and for the water quality certification process.

The study was completed using funds provided to the Karuk Tribe of California via a State Water Resources Control Board and U.S. Environmental Protection Agency (U.S. EPA) water quality cooperative agreement (CP 96941301-1), with additional funding provided by the NCRWQCB, U.S EPA, and the Hydropower Reform Coalition. The study was conducted by the Karuk Tribe, Riverbend Sciences, Kier Associates, Aquatic Ecosystem Sciences LLC, and William W. Walker. All samples were collected by the Karuk Tribe Department of Natural Resources.

1.3 PREVIOUS AND CURRENT NUTRIENT STUDIES

A report covering the first year of the study (May 2005 – May 2006) was issued in June 2007 (Kann and Asarian 2007). This report provides results for the full May 2005 – December 2007 dataset, including inter-annual nutrient budget dynamics for 3 seasons, as well as refinements to analytical methodologies used to construct the budgets.

1.4 STUDY GOALS

The overall goals of this study were to 1) collect and analyze detailed nutrient and hydrologic data for Copco and Iron Gate Reservoirs, and 2) construct mass-balance nutrient budgets to evaluate potential effects of the reservoirs on nutrient dynamics in the Klamath River.

It is important to note that the goal of this report is not to comprehensively analyze and interpret all data collected as part of this study, but to focus on the calculation and interpretation of nutrient budgets. The detailed dataset collected as part of this study is also intended to provide baseline data for future analyses and efforts to understand Klamath River water quality dynamics.

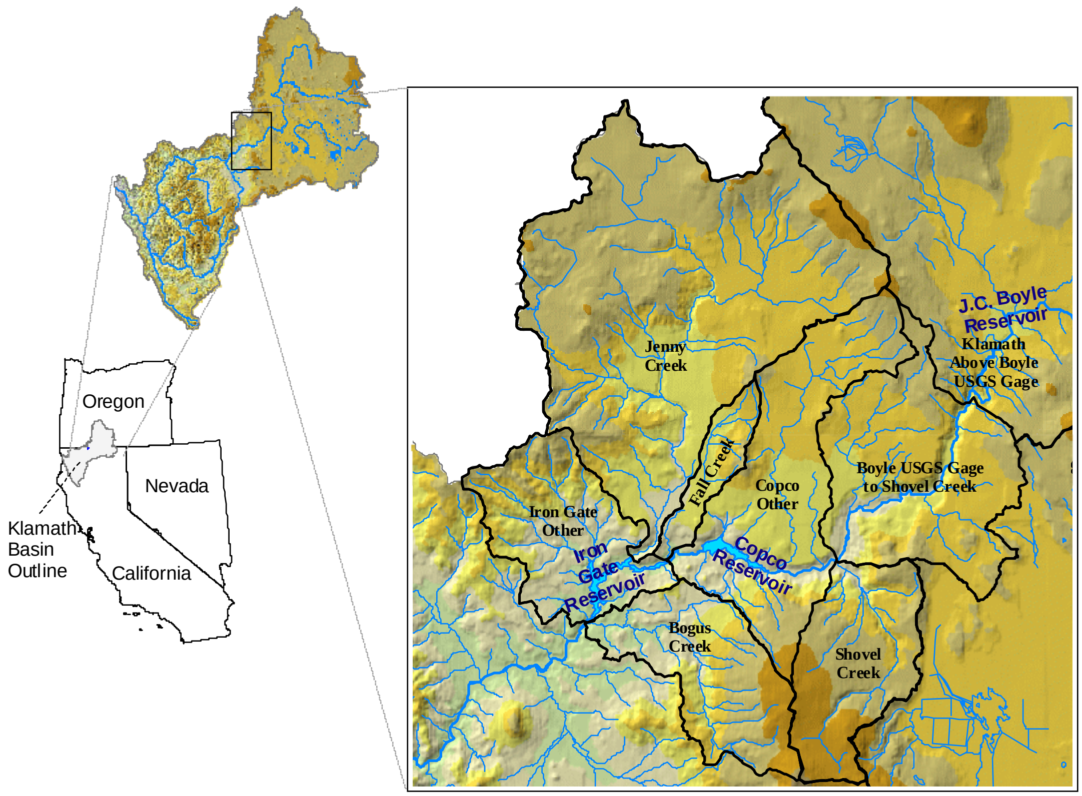

Figure 1. Regional location of Iron Gate and Copco Reservoirs, and watersheds (labeled in black) adjacent to the reservoirs.

2. METHODS

Methods for the first year of the study are described in Kann and Asarian (2007). *Rather than duplicate that information, we provide a relatively brief methodological summary and refer readers to that document for full details.* However, methodological improvements that were implemented subsequent to Kann and Asarian (2007) are outlined in detail below.

2.1 DEVELOPMENT OF MASS-BALANCE ANALYSIS FOR WATER AND NUTRIENTS

As summarized in Kann and Asarian (2005), crucial steps in determining the effect of reservoirs on water quality are the development of hydrologic and nutrient budgets on annual and sub-annual time scales. Thus, as outlined below, hydrologic (riverine discharge and reservoir volume data) and nutrient (riverine and in-reservoir concentrations of total nitrogen and total phosphorus) data were collected and/or assembled for inflow, outflow, and in-reservoir stations for both Copco and Iron Gate Reservoirs. These nutrient concentration and hydrologic data were used to compute nutrient loading for reservoir inflow/outflow and in-reservoir change in mass on a daily basis. Nutrient budgets were constructed from these daily time series and summarized on annual and seasonal time scales to assess temporal nutrient dynamics and the relative fate of nutrients in Project reservoirs.

2.1.1 Nutrient Concentration

2.1.1.1 Sampling locations and parameters

Samples were collected above, within, and below Copco and Iron Gate Reservoirs. Sampling stations and station codes used for this study are shown in Table 1 and Figure 2. The station codes will be used throughout this report.

Nutrient samples were collected approximately bi-weekly during the primary May-November sampling period, but were sampled less frequently during the winter period (Figure 3). The primary sampling station in each reservoir (CR01 and IR01; Figure 2 and Table 1) was located near the deepest portion of the reservoir at the same location established by PacifiCorp in previous monitoring efforts (e.g., PacifiCorp 2004). Secondary stations (CR02 and IR03) were sampled during the June through November period when the reservoirs tended to be less mixed both horizontally and vertically, but were not consistently sampled during all years (see below for details).

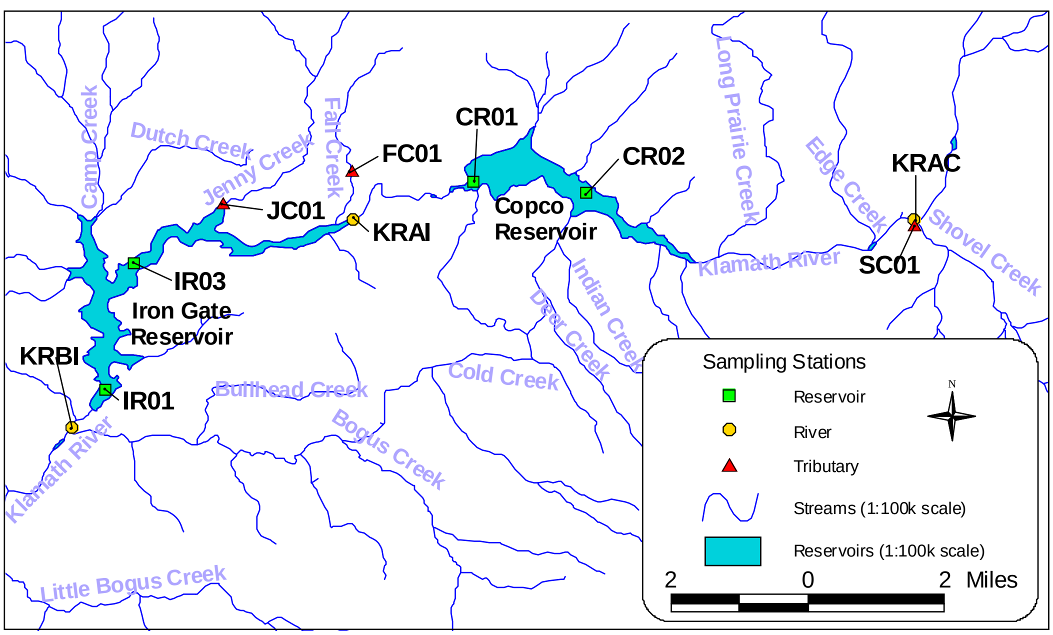

Figure 2. Location of discharge measurements and nutrient sample sites.

Table 1. Key and description for sampling locations shown in Figure 2.

Station Code	Station Description	Station Type	Latitude (decimal degrees)	Longitude (decimal degrees)	Watershed Area (km^2)
KRAC	Klamath River Above Copco Res.	River	41.97242	-122.20168	18708.0
CR02	Copco Res. Upper Half (east)	Reservoir	41.97993	-122.29660	
CR01	Copco Res. Near Dam (west)	Reservoir	41.98220	-122.32823	
KRAI	Klamath River Above Iron Gate Res.	River	41.97289	-122.98106	19061.5
IR03	Iron Gate Res. Upper Half (east)	Reservoir	41.96460	-122.42315	
IR01	Iron Gate Res. Near Dam (west)	Reservoir	41.93883	-122.43217	
KRBI	Klamath River Below Iron Gate Res.	River	41.93108	-122.44220	19786.7
SC01	Shovel Creek	Tributary	41.97150	-122.20180	132.1
JC01	Jenny Creek	Tributary	41.97710	-122.39760	544.3
FC01	Fall Creek	Tributary	41.98400	-122.36100	38.7

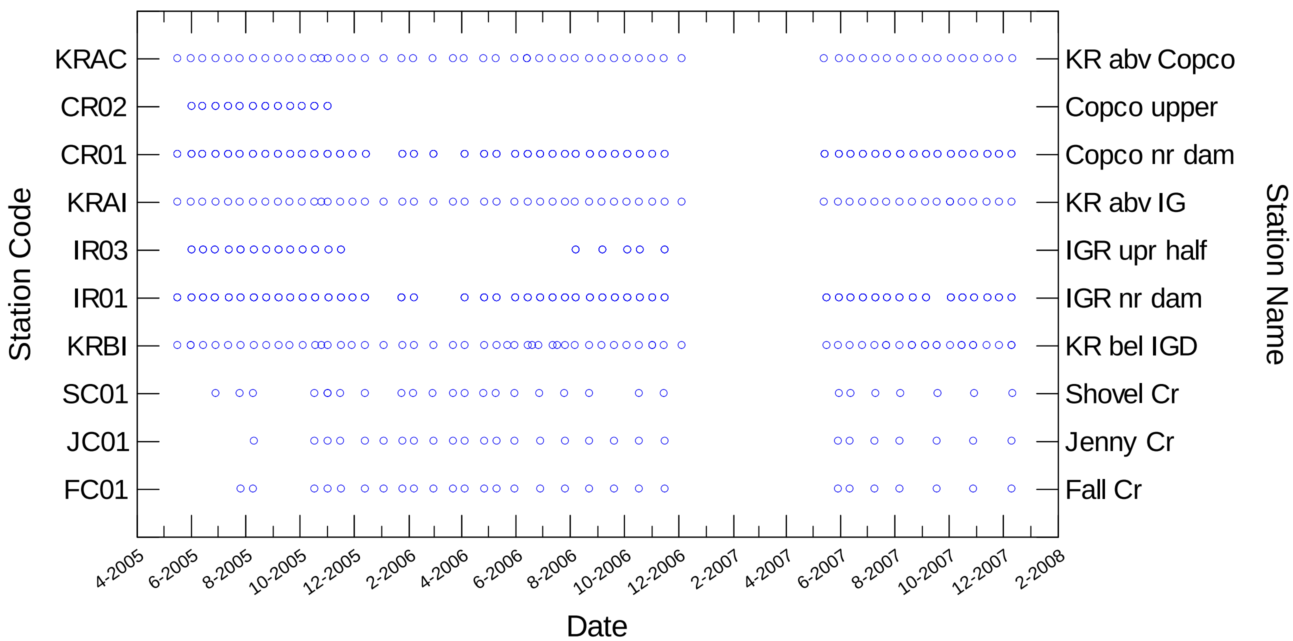

Figure 3. Timing of May 2005 – December 2007 nutrient samples collected in Copco and Iron Gate Reservoirs, the Klamath River, and tributaries.

Nutrient samples were collected in the Klamath River and tributaries to Iron Gate and Copco on the same (or adjacent) days that in-reservoir samples were collected (Figure 3). Samples were collected approximately bi-weekly from May 17, 2005 to December 5, 2006, and May 14, 2006 to December 12, 2007.

Parameters analyzed included ammonia (NH3), nitrate-plus-nitrite (NO_3-NO_2), 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, organic nitrogen (ORGN) was computed as TN minus NH3 minus NO_3-NO_2, particulate phosphorus (PP) was calculated as TP minus SRP.

2.1.1.2 In-Reservoir nutrient data

To encompass vertical variability due to consistent thermal stratification, samples were taken at multiple depths intended to correspond with the epilimnetic (surface), metalimnetic (middle), and hypolimnetic (bottom) layers. Aside from the initial Copco sample dates in 2005 when two vertical samples were taken, the number of depths sampled varied from three to five, depending on the water depth and degree of thermal stratification. Depth profiles of physical parameters were measured using a Quanta® multi-parameter probe, with measurements generally taken every five meters. Parameters included temperature, pH, dissolved oxygen, and conductivity. The depth profiles of the physical parameters were used to delineate stratification layers so that nutrient samples could be collected at representative depths for each layer.

Volume-weighted reservoir-wide mean nutrient concentrations were then computed for each sample date (see Kann and Asarian 2007 for details). To encompass an anoxic zone of elevated nutrient concentration that exists at the sediment-water interface along the bottom contour of much of the reservoir, and not only at the deepest area near the dam (based on analysis of the profiles at the secondary stations), the original method was adjusted to expand the concentration representing the deepest sample to a two-meter vertical zone covering areas of the reservoir bottom where maximum depth was at least 12 meters (the top 10 meters of the water column is generally oxic due to the photic zone and wind-driven mixing).

As noted above, secondary stations were established to evaluate and incorporate potential spatial variability in nutrient concentration that may influence the computation of respective volume-weighted means for the reservoirs. In 2005 secondary stations (CR02 and IR03) were sampled during the June through November period when the reservoirs tended to be less mixed both horizontally and vertically (Figure 2), and these data were used in the Kann and Asarian (2007) analysis. In 2006, IR03 was sampled once per month during the June-November stratified period, and neither secondary station was sampled in 2007. Computation of reservoir TP and TN mass using primary stations alone vs. both primary and secondary stations (Table 2) indicated that for Iron Gate reservoir-wide TP mass, adjustment of TP concentration (+12% during July-September, +5% in October, and -8% in November) for dates when only the primary station was sampled would account for the relatively consistent pattern observed. Due to the lack of consistent patterns and relative insensitivity to using primary alone vs. primary and secondary stations together, no adjustments were made to TP in Copco, or TN in either reservoir.

Table 2. Percent difference in reservoir-wide nutrient concentration calculated using two stations vs. one station in each reservoir. Positive numbers indicate that the two-station mean was higher than the one-station mean.

			% Difference in Concentration Between 1 and 2 Station Methods					
			TP			TN		
Reservoir	Month	Number of Sample Days	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Copco	June	3	6	4	7	2	0	3
	July-Sept	6	1	-5	4	4	-2	15
	Oct	2	-1	-1	0	1	-1	3
	Nov	1	1	1	1	-1	-1	-1
Iron Gate	June	3	1	0	1	1	0	1
	July-Sept	8	12	4	18	2	-12	12
	Oct	4	5	-7	12	2	-2	5
	Nov	3	-8	-11	-6	1	-1	3

2.1.1.3 Accounting for effects of hydropower peaking on nutrient concentration at KRAC

Adjusting for effects of hydropower peaking

Hydropower peaking operations upstream at J.C. Boyle Dam that can cause substantial diel fluctuations in nutrient concentrations at KRAC necessitated an evaluation of the relationship between the concentration at the time a given sample was collected and the flow-weighted average concentration for the sampling day. For the initial May 2005 – May 2006 analysis (Kann and Asarian 2007) the majority of KRAC samples were considered to be representative of flow-weighted daily averages and hence were not adjusted. However, in examining the entire 2005-2007 KRAC dataset, it became clear (due to both abnormally low TN and TP concentrations and a comparison of sampling time and upstream flow releases) that many KRAC samples (including some in 2005) did not represent flow-weighted daily average concentrations. Thus, in order to adjust these data prior to inclusion in the nutrient budgets, we initiated high-frequency diel collection of nutrient and discharge data at KRAC to determine the timing, magnitude, and causes of the diel fluctuations in TN and TP concentrations at KRAC. These data provided the basis for adjusting KRAC samples to represent daily flow-weighted average concentrations. Adjustments ranged from -10% to +45% for TN and -5% to +25% for TP. Details of the diel data analysis and adjustment methods are described in Appendix A2.

Recommendations for future sampling

Timing sampling to occur when daily flow-weighted mean nutrient concentration is achieved would be difficult because the sub-daily transitions between high concentration and low concentration occur relatively rapidly (particularly on days with a short baseline period between hydropower peaks). However, because the high concentration period occurs over a relatively long period of time (see Appendix A2 for details), the recommended approach is to collect samples during the high-concentration period, with an adjustment downward to estimate the daily flow-weighted average concentration. There are typically two windows within each day to do this: one in the morning and one in the evening (length varies from day to day). The following is a list of rules for when to collect samples during the windows of maximum concentration:

1. EARLY PART OF DAY:
Collect samples prior to (inclusive) 12 hrs since return to baseline at USGS Boyle gage, or prior to (inclusive) 5 hrs since ramp up begins at Boyle Gage, whichever is earlier.

2. LATE PART OF DAY:
Collect samples after (inclusive) 11 hrs since ramp up begins at Boyle Gage.

The hydrographs change from day to day, month to month, and season to season, so ideally flows should be checked prior to sample trips to ensure samples will be collected within the above described windows. PacifiCorp posts their flow schedule online three days in advance for rafters[1] and the past 60 days of sub-hourly USGS flow data are also available online[2].

2.1.1.4 Nutrient concentration for ungaged inflow

To account for the addition of ungaged inflow as a component of the hydrologic and nutrient budgets, nutrient concentrations ascribed to ungaged accretions to Iron Gate and Copco were based on samples from Jenny Creek and Shovel Creek, respectively.

2.1.1.5 Estimation of daily nutrient concentrations

For the initial analysis of May 2005 – May 2006 data, mainstem and tributary concentration data were linearly interpolated between adjacent sample dates to generate a daily record of concentration to combine with daily hydrologic data for input to the mass-balance model (Kann and Asarian 2007). In order to refine the estimation of daily concentration and subsequent load estimates and to address comments regarding this technique (e.g., Butcher 2008; PacifiCorp 2006), we employed a multiple regression based-algorithm that represented concentration variations associated with flow (i.e. magnitude as well as ascending/descending limb of hydrograph), season (i.e. Julian day), and year (Walker and Havens 2003). For each site and nutrient (TN and TP), these models were used to generate a daily series of predicted concentrations for the entire period of record. In addition, as described in Walker and Havens (2003), residuals (observed - predicted values) between adjacent sampling dates were interpolated to generate a daily series of deviations from the regression. Thus, by combining (summing) the regression-based best-fit time series with the residual time series, information from relationships between concentration, flow and season, as well as the adjacent sample points was incorporated to generate daily concentration and load series for use in the nutrient budgets.

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[1] http://www.pacificorp.com/hydro_hiws/JCBoyleEstFlow.html
http://www.pacificorp.com/Article/Article45605.html

[2] http://waterdata.usgs.gov/usa/nwis/uv?site_no=11510700

Uncertainty (variance) of load estimates for each station and parameter was computed as:

$$\text{Uncertainty (T)} = SE^2(T) = \Sigma\, Si^2 / Ni$$

where:
T = Total Load = Σ Li
SE = Standard Error of Total Load Estimate
N = Fixed Total Samples for station i
Si = Standard Deviation of difference between observed and regression predicted loads over all sampling dates for station i

The uncertainty analyses for inflow and outflow load presented in this report address only the uncertainty associated with the prediction of daily nutrient concentrations from the continuously measured flows and nutrient samples that were collected approximately biweekly. They do not incorporate additional sources of uncertainty such as potential errors in USGS flow measurements or laboratory processing of nutrient samples.

2.1.2 Hydrologic Data

Data sources and methods for hydrologic data were similar to those used in the Kann and Asarian (2007) report and will not be repeated in detail here. However, several methodological improvements were made from the Kann and Asarian (2007) report including accounting for ungaged inflows (including those contributing to KRAC) and more accurately representing discharge for other tributaries.

2.1.2.1 In-Reservoir hydrologic data

Daily 8 a.m. reservoir elevation data for the years 2005-2006 were obtained from PacifiCorp[3]. Daily lake volume was then computed from the reported 8 a.m. elevation by applying the elevation-volume relationship developed from bathymetric surveys by Eilers and Gubala (2003).

Daily precipitation records were obtained for the Montague Airport[4], and daily precipitation volume was computed as a product of precipitation and lake surface area as derived from elevation–surface area curves (Eilers and Gubala 2003).

Because daily pan evaporation measurements utilized for construction of the hydrologic budget for 2002 (Kann and Asarian 2005) were discontinued, long-term mean monthly pan evaporation values

[3] PacifiCorp provided the following disclaimer with the data: "The source of this information is from an operations database and not necessarily a database specifically designed and QA/QC'd for water management purposes. That is, the database was not designed nor is it routinely used to create a meaningful hydrologic record, instead its purpose is to predict operational relationships between the measured parameters such as river flows, reservoir elevations, and penstock flows."
[4] Available online at:
http://www.wunderground.com/history/airport/KSIY/2006/1/11/DailyHistory.html?req_city=NA&req_state=NA&r eq_statename=NA

(WRCC 2005)[5] were used. Data were corrected to approximate open-water evaporation by multiplying by 0.7 (Farnsworth et al. 1982), and daily estimated evaporative loss from the lake surface was computed as the product of open-water evaporation and lake surface area.

2.1.2.2 Inflow/outflow data

<u>Mainstem stations</u>
Streamflow data for the Klamath River below J.C. Boyle Powerhouse (USGS gage 11510700; 16 miles upstream from Copco Reservoir) were obtained from U.S. Geological Survey[6]. These data were combined with estimated accretion between the gage and KRAC (see details below) to represent mainstem hydrologic inflow to Copco Reservoir.

Daily outflow from Iron Gate Reservoir was computed by subtracting estimated flow for Bogus Creek (which is located below Iron Gate Dam but upstream of the USGS gage) from the USGS Iron Gate gage (11516530)[7]. Bogus Creek flow data were estimated based on a watershed area accretion method similar to that used by PacifiCorp (2005b). These estimated values compared well to several instantaneous flow measurements that were collected by the Karuk Tribe during the summer. The exception to this was in 2006 when accretion-based flows dropped to zero while measured minimum flows were approximately 10 cfs. Therefore, when accretion-based flow estimates were less than 10 cfs in 2006, they were adjusted upwards to be equal to 10 cfs.

Daily lake outflow volume for Copco Reservoir (station KRAI Table 1; also the inflow to Iron Gate) was obtained from PacifiCorp (see footnote above for details); however, data appear to be inaccurate at times, particularly during high flows when the Copco spillway is operating. Thus, a record of daily average flow was derived by treating the KRAI flow as an unknown and solving the hydrologic budget for it. We did this using both the Iron Gate and Copco hydrologic budgets, and both methods resulted in an estimate of KRAI flows lower than reported by PacifiCorp (Figure 4). For the purposes of the hydrologic and nutrient budgets, we used the average of the two hydrologic budget-based estimates for KRAI flows.

<u>Tributary stations and ungaged accretions</u>
The total watershed area contributing to the ungaged accretions between the J.C. Boyle and Iron Gate USGS gages was determined using GIS, and the ratios of individual areas to the total accretion area were calculated (Table 3, Figure 1). The watershed areas of Jenny and Fall Creeks were excluded from this calculation as independent flow estimates were available for those tributaries (see below).

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[5] http://www.wrcc.dri.edu/htmlfiles/westevap.final.html
[6] http://waterdata.usgs.gov/usa/nwis/uv?site_no=11510700
[7] http://waterdata.usgs.gov/usa/nwis/uv?site_no=11516530

Table 3. Watershed areas for the ungaged accretion between USGS gages below J.C. Boyle Powerhouse and Iron Gate Dam. Areas for Fall Creek and Jenny Creek are shown in Table 1.

	Area	
Watershed	(km^2)	(%)
Boyle USGS gage to Shovel Creek	227.6	26.5%
Shovel Creek	132.1	15.4%
Copco Other	221.4	25.8%
Bogus Creek	134.1	15.6%
Iron Gate Other (excluding Fall and Jenny Creeks)	142.2	16.6%
Total	857.5	100.0%

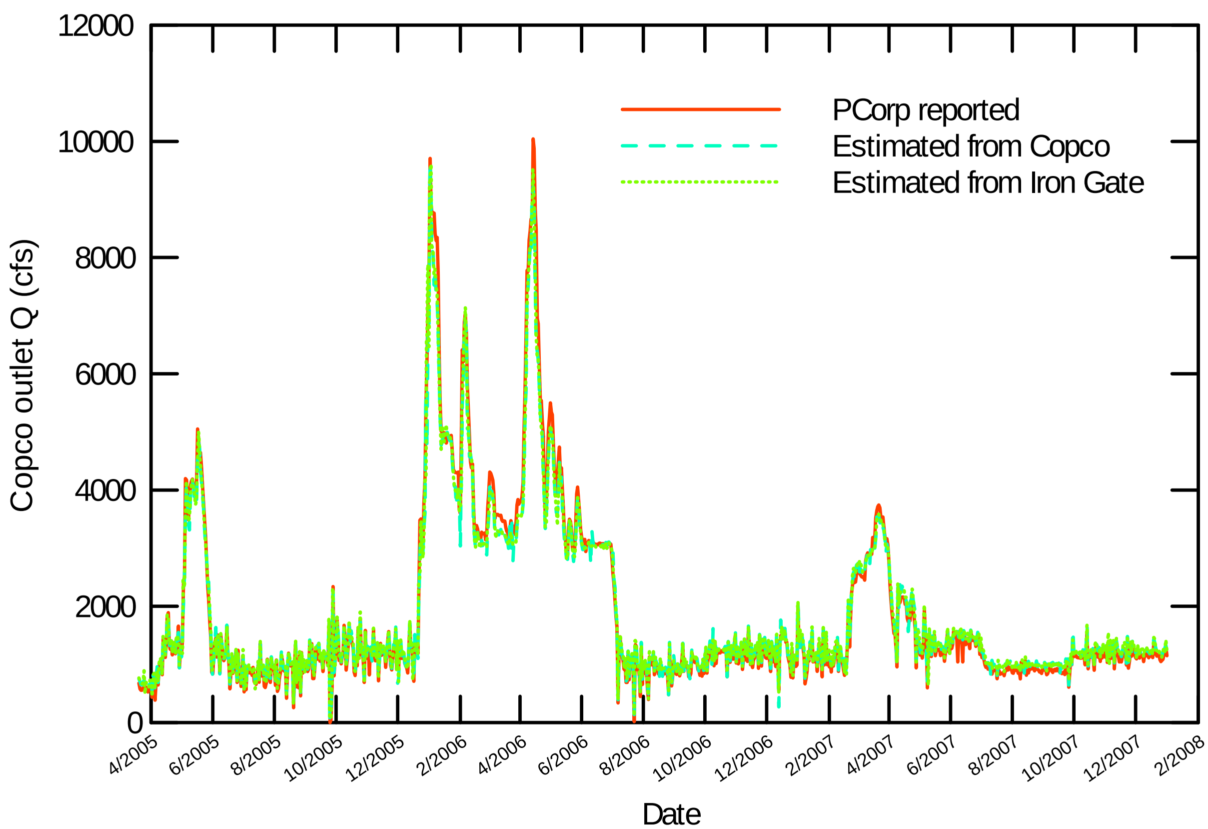

Figure 4. A comparison of three methods for determining daily average flows for the outlet of Copco Reservoir (KRAI). PacifiCorp data are from lookup tables based on performance testing, engineering specifications and/or engineering equations. Estimated data were derived using water balances for Copco and Iron Gate Reservoirs (see above for details).

The daily flow difference between the Boyle and Iron Gate USGS gages was then calculated and adjusted to take into account precipitation, evaporation, changes in reservoir storage, as well as flows from Jenny and Fall Creeks. Because the resulting estimates of the ungaged accretions showed high day to day variation (apparently caused by errors in daily changes in reservoir storage), data were smoothed with a series of moving averages chosen to reduce periods of negative flow. When necessary, smoothed flows were further adjusted upwards to 1 cfs to eliminate periods of negative flow (Figure 5). This final ungaged accretion was then apportioned to the various watersheds according to their relative areas (Table 3).

For most of 2005, Shovel Creek discharge was estimated based on periodic flow measurements as described in Kann and Asarian (2007); however, for dates prior to the first staff gage measurement on 6/29/2005 and after 11/5/2005, Shovel Creek flows were estimated using the watershed area accretion method described above.

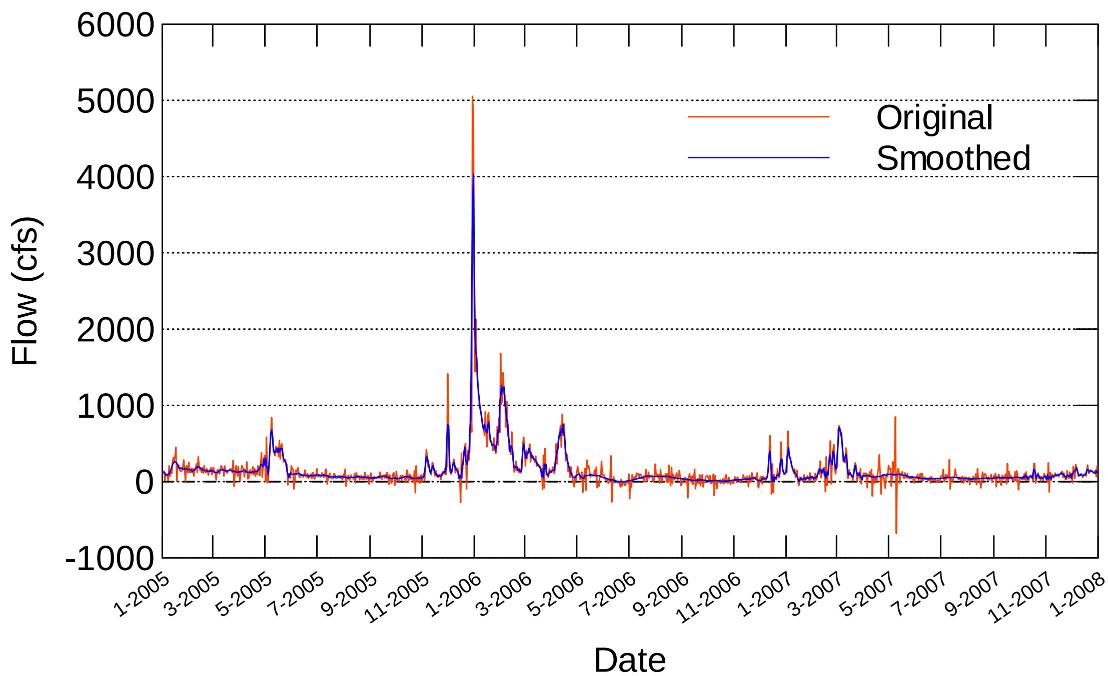

Figure 5. Estimated ungaged accretion between USGS gages below J.C. Boyle and Iron Gate Dam.

Flow data for Jenny Creek were obtained from the BLM (2008) station located approximately one mile below the confluence of Spring Creek and Jenny Creek. The stage-discharge curve provided by BLM extrapolated flows over ~ 80 cfs because no measurements were taken during high flow events that prevented wading (Montfort, pers. comm.). Such flows occurred frequently in the winter and spring and it became apparent during construction of the hydrologic budgets (due to negative estimated flows for ungaged accretions during May of 2006) that the highest Jenny Creek flows were over-estimates. Evaluating ungaged accretion indicated that flows of 1000 cfs and greater would need to be reduced by 25% to avoid sustained negative accretion. Likewise, flows of 80-1000 cfs were reduced by a lesser degree by linearly scaling from 0% at 80 cfs to 25% at 1000cfs.

Discharge estimates for Fall Creek are based primarily on historical monthly averages from a discontinued USGS gage; detailed methods are contained in Kann and Asarian (2007).

Although greater uncertainly exists in estimates of tributary inflow relative to main-stem inflow, with the exception of sporadic high flow events in the winter and spring, tributary inputs are generally only a very small percentage of mainstem inflows (generally <3%; see below).

2.1.2.3 Hydrologic Residual

As a check on error in measured discharge and lake hydrologic characteristics, the residual of the reservoir water balance (hydrologic residual) was computed as:

Hydrologic Residual = outflow + evaporation + Δ lake storage – inflow [tributary + mainstem] – precipitation

where Δ lake storage is the change in lake storage for the time step analyzed

2.1.3 Nutrient budget construction

The above estimates of nutrient concentration and water volume were used in all subsequent determinations of nutrient mass. The nutrient mass from each surface inflow and outflow was computed as the product of daily estimated nutrient concentration and daily mean discharge. The nutrient mass contained in each reservoir was computed as the product of daily reservoir volume and daily estimated reservoir-wide volume-weighted mean nutrient concentration (described above).

Atmospheric nutrient inputs (the sum of wetfall and dryfall, but excluding N input via nitrogen fixation by phytoplankton) were estimated at fixed areal rates of 18 $kg/km^2\ yr^{-1}$ for phosphorus, and 1080 $kg/km^2\ yr^{-1}$ for nitrogen (U.S. EPA, 1975).

2.1.3.1 Nutrient retention

For TN and TP (separately), net nutrient retention was calculated as the residual of the nutrient mass-balance equation as follows:

Net Retention = inflow mass [mainstem + tributary + atmospheric] – outflow mass - Δ reservoir storage

Net retention reflects 1) net losses from the water column resulting from sedimentation, 2) atmospheric fixation and denitrification (for nitrogen only), 3) nutrient releases from bottom sediments, and 4) the cumulative effects of errors in the other mass-balance terms. Negative retention values denote a source from within a reservoir.

As noted above, although daily nutrient mass terms were generated for input to the mass-balance model, it is not the intent to imply that daily values represent specific daily fluctuations. Rather, these daily values were summarized to represent both sample period and whole season or annual dynamics and to account for travel time through the reservoir complex, which ranges between 10-30 days. Thus, budgets were summarized for Copco and Iron Gate both separately and combined (to evaluate the net effect of both reservoirs in tandem) for 1) sample periods (~biweekly), 2) the approximate reservoir algal growing season (mid-May to end of September), 3) the study start through turnover (mid-May to mid-December), 4) annually (mid-May to mid-May), and 5) the winter/early spring period (mid-December to mid-May). Percent retention was calculated as a percent of the inflow mass.

Uncertainty for nutrient retention (retention standard error) was calculated as the square root of the sum the load variance (square of load standard error) for each of the major terms in the retention equation (mainstem inflow, tributaries, mainstem outflow).

Change in reservoir storage was not incorporated into calculations of retention uncertainty because it is difficult to quantitatively assess, and is a very minor component of the retention equation at seasonal time scales, typically equivalent to less than a few percent of inflow, especially for phosphorus (see Figures A5-1 to A5-12 in Appendix A5). For example, the entire May 2005-December 2007 study period, the change in storage for both reservoirs combined is equivalent to 0.1% of TP inflow and 1.3% of TN inflow.

3. RESULTS AND DISCUSSION

3.1 VERTICAL DISTRIBUTION OF TEMPERATURE, DISSOLVED OXYGEN, PH, NUTRIENTS, AND CHLOROPHYLL

Depth distribution of temperature, dissolved oxygen (DO), and pH is an important aspect of water quality dynamics and fish habitat, and depth-time plots of isotherms and isopleths for these parameters allows both seasonal and depth distribution to be evaluated simultaneously (Figure 6, Figure 7). For the purposes of this report they were mainly utilized to determine (along with the profile plots in Appendix A1) stratification and mixing patterns with respect to understanding nutrient dynamics. As noted above, because secondary stations were sampled only in 2005 (CR02 and IR03) and 2006 (IR03), only the primary stations (CR01 and IR01) are shown here (refer to Kann and Asarian [2007] for CR02 and IR03 trends).

Temperature isotherms show that stratification begins around April in Iron Gate Reservoir and during late May to early June in Copco Reservoir (Figure 6, Figure 7). Copco also showed earlier fall mixing than did Iron Gate, with complete mixing occurring nearly a month later in Iron Gate (early December) than it did in Copco (early November). Likewise, low dissolved oxygen (< 3mg/L) extended further up in the water column and longer in the season in Iron Gate. Coinciding with the period of elevated upper water column temperatures during summer months, pH and dissolved oxygen also showed elevated levels during this same period. Supersaturated dissolved oxygen and high pH near the surface during the stratified period are the likely reflection of higher algal biomass and productivity from buoyant cyanobacteria concentrating near the reservoir surface (see below for description of chlorophyll dynamics)

Figure 8 through Figure 11 illustrate differences in nitrogen and phosphorus concentrations at various depths over time in Copco and Iron Gate Reservoirs. In Iron Gate, the deepest depths generally had the highest TN concentrations, except during periods when organic N was very high in surface samples such as August-September 2005 and August 2007. This trend was also present in Copco Reservoir, but there were more occasions (relative to Iron Gate) in the July - September period when TN concentrations at the 1 and 10m depths exceeded those in the deepest samples.

During the period of deeper reservoir anoxia, NH_3 increased in the bottom layer, reaching a seasonal maximum in late September/early October in Copco (Figure 8) and October/November in Iron Gate (Figure 10). Coincident with the period of maximum stratification and low dissolved oxygen, NO_3-NO_2 at the deepest depths followed a generally decreasing pattern from May through August/September at Copco and September/October in Iron Gate prior to reservoir mixing. Minimum late summer/early fall NO_3-NO_2 concentrations at the deepest depths were lower in

Copco than in Iron Gate, with Copco nearing zero (e.g. <0.05 mg/L) in all three years compared to Iron Gate which only approached zero in 2006.

Although the exact timing and magnitude varied somewhat, NO_3-NO_2 and TIN in the upper layers (1m, and to a lesser extent 5-10m) in Copco Reservoir exhibited similar seasonal patterns within each year (Figure 8). Concentrations decreased from May to near zero in mid-June, increased to a peak in July or August, declined again to another near-zero low in late August or early September (except in 2005 when the September low in TIN was ~0.4 mg/L), before finally increasing again to an annual maximum in December. NO_3-NO_2 and TIN concentrations at the 1m depth in Iron Gate (Figure 10) were much lower than in Copco, with 13 of 15 Iron Gate samples in the July to September 15 period having TIN less than 0.04 mg/L compared to only 3 of 15 at Copco. The seasonal patterns of NO_3-NO_2 and TIN are likely the result of phytoplankton growth in the upper reservoir layers, as organic N and chlorophyll (Figure 12) were often high during this period. The concentration of all forms of nitrogen at specific depths then tended to converge during water column mixing in the fall months.

During the stratified period, TP and SRP increased in the bottom layer through early October in Copco (Figure 9) and through October or early November in Iron Gate (Figure 11). Similar to ammonia increases, SRP increases generally coincided with the development of an anoxic hypolimnion, and are possibly reflective of internal P loading due to release of iron-bound P. As noted by Moisander (2008, 2009) the observed anoxic layer and associated increased concentrations of NH_3 and SRP appears to provide a nutrient source for vertically migrating *Microcystis aeruginosa* colonies. SRP in the surface layer of Copco followed an overall increasing pattern from May through August or September each year, before declining into December. SRP in the surface layer of Iron Gate followed a similar overall pattern, but also declined in July of each year and did not peak until later (October).

There was also a seasonal increase in particulate P (PP) in the surface (1 m) of both reservoirs that likely stems from phytoplankton concentrating near the surface during the stratified period. This trend was consistent with the trend in organic nitrogen. Particulate P was also often elevated in the deepest samples at both reservoirs during the stratified period. As with nitrogen, the concentration of all forms of phosphorus at specific depths then tended to converge during water column mixing in the fall months.

During the stratified period TIN:SRP mass ratios tended to be lower in the upper water column layers and showed an increasing trend with depth in Iron Gate (Figure 11), but were quite variable in Copco (Figure 9). In the upper layers during the stratified period, for both reservoirs the TIN:SRP mass ratios were relatively low (<5 in Iron Gate and <7 in Copco) and TN:TP ratios were variable (range ~4-12 in Iron Gate and ~5-10 in Copco).

Although the observed trends in the depth distribution of nutrients are consistent with the observed stratification and algal production; as mentioned above, it is not the intent of this report to provide a detailed analysis of the nutrient dynamics relative to physical and biological processes occurring in the reservoirs. However, these data will provide the base for future analyses of nutrient, physical, and biological dynamics in the reservoirs.

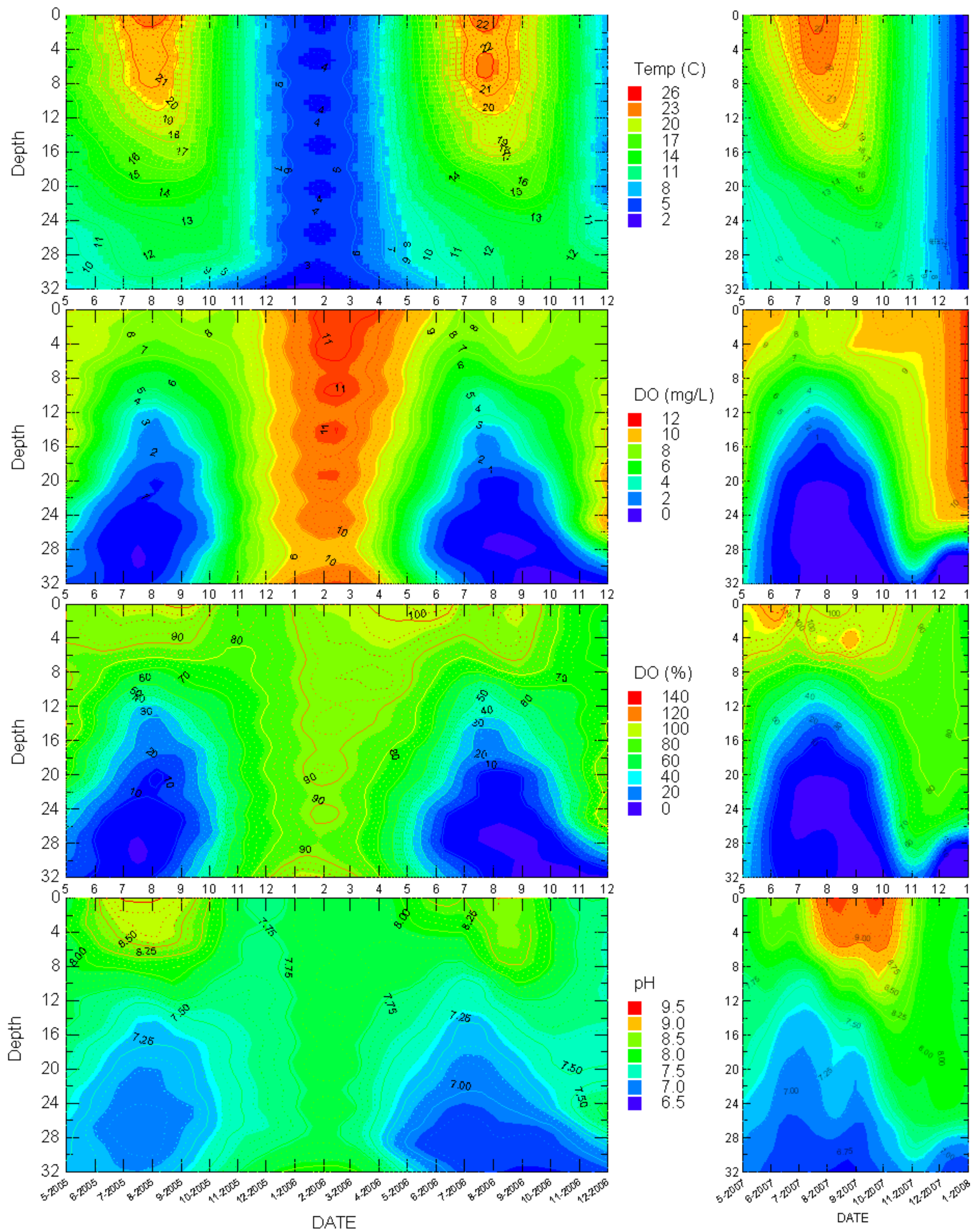

Figure 6. Depth-time distributions of isopleths of temperature, dissolved oxygen, and pH at station CR01 in Copco Reservoir, May 2005-December 2007.

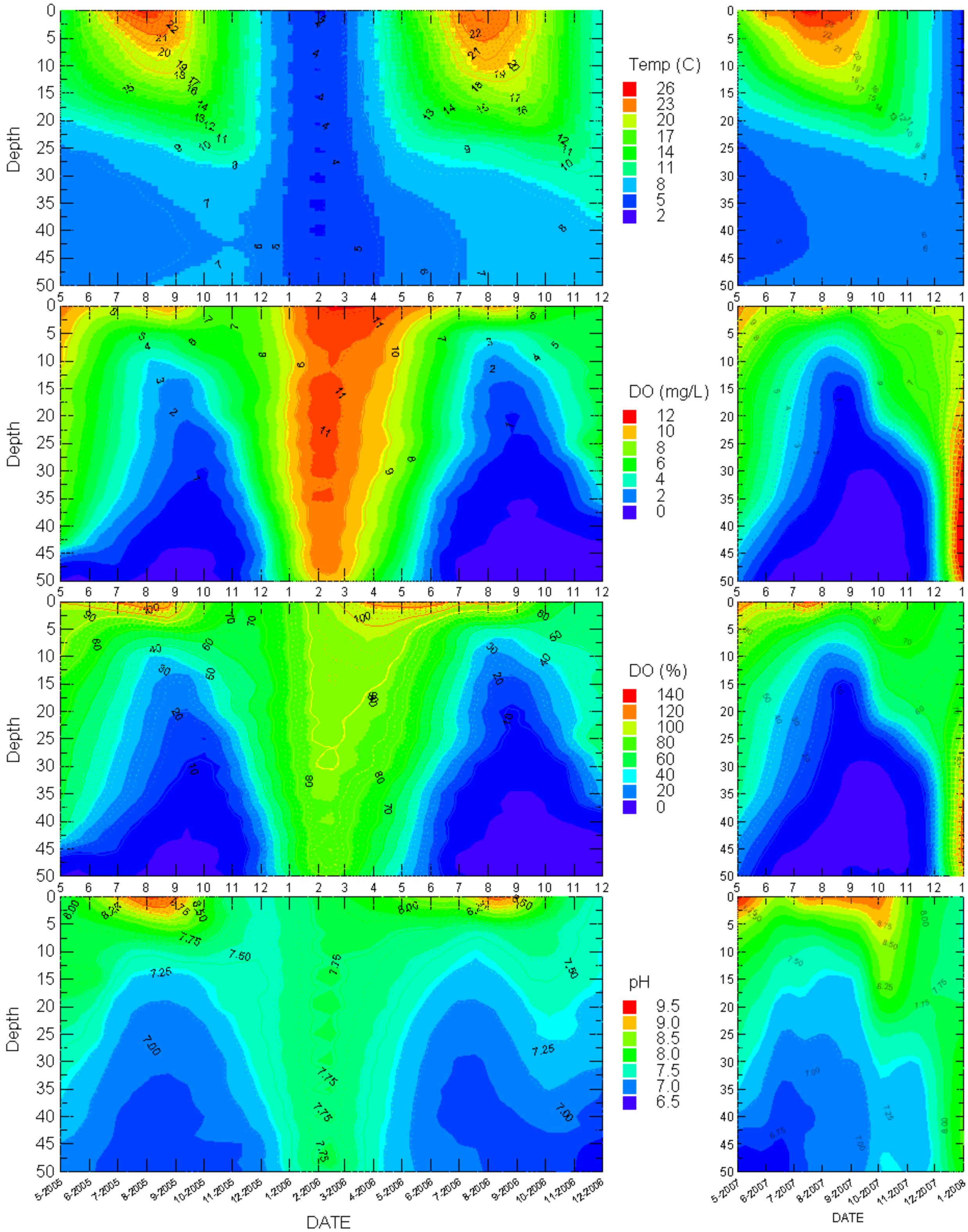

Figure 7. Depth-time distributions of isopleths of temperature, dissolved oxygen, and pH at station IR01 in Iron Gate Reservoir, May 2005-December 2007.

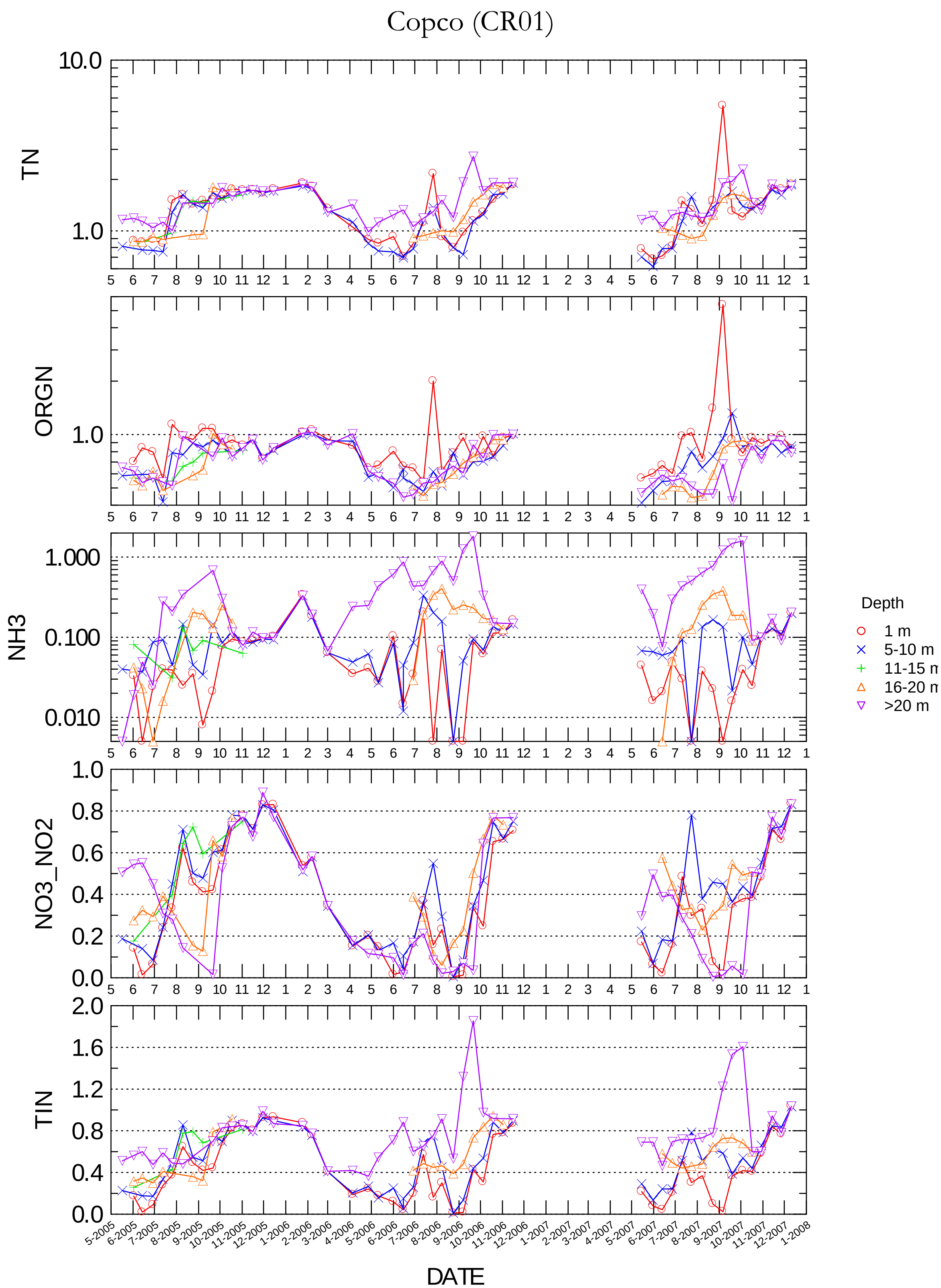

Figure 8. Depth-profiles of nitrogen concentrations at Copco Reservoir sampling station CR01, May 2005 – December 2007.

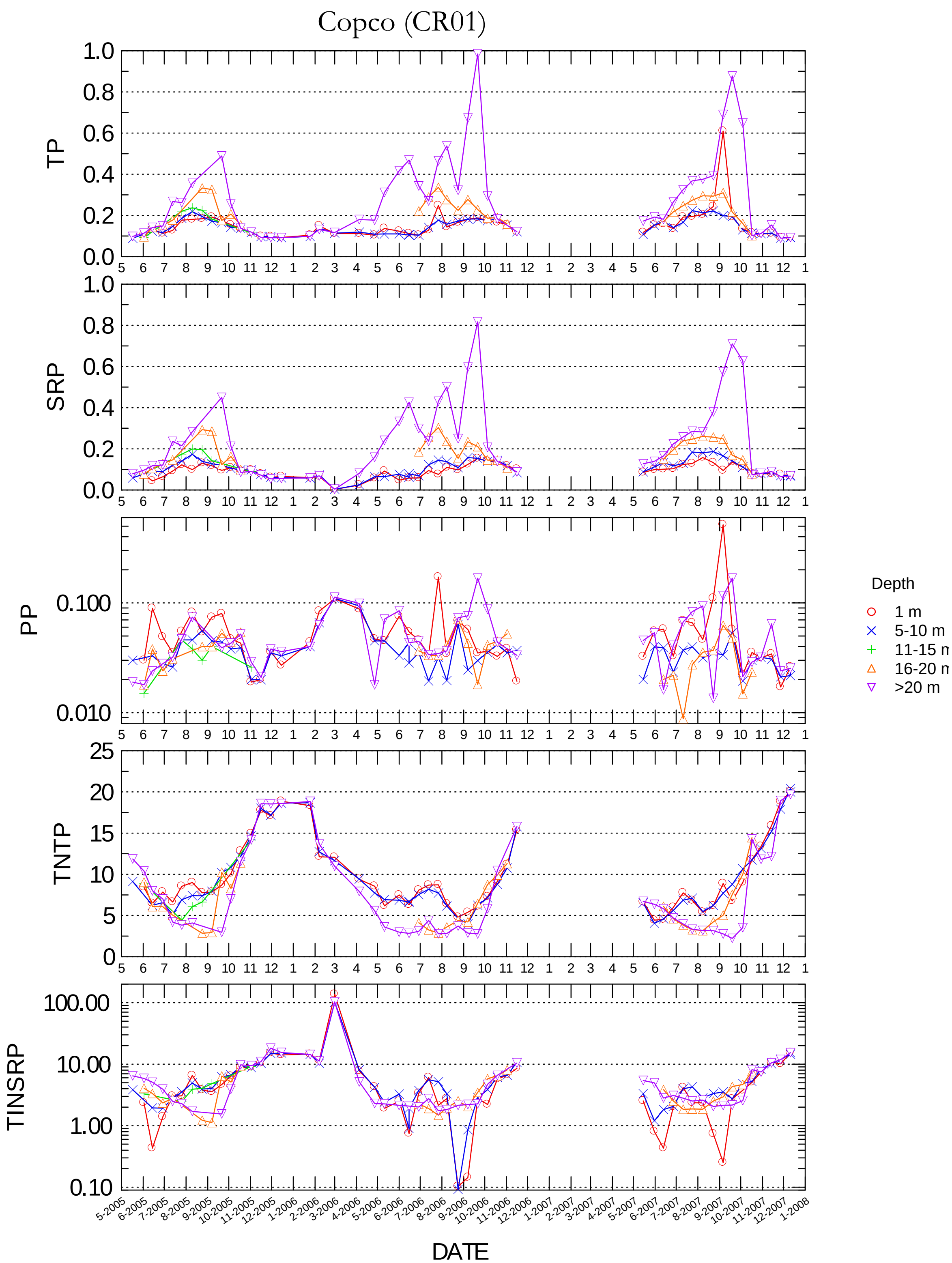

Figure 9. Depth-profiles of phosphorus concentrations and nitrogen:phosphorus mass ratios at Copco Reservoir sampling station CR01, May 2005 – December 2007. TNTP is mass ratio of TN to TP, and TINSRP is mass ratio of TIN to SRP.

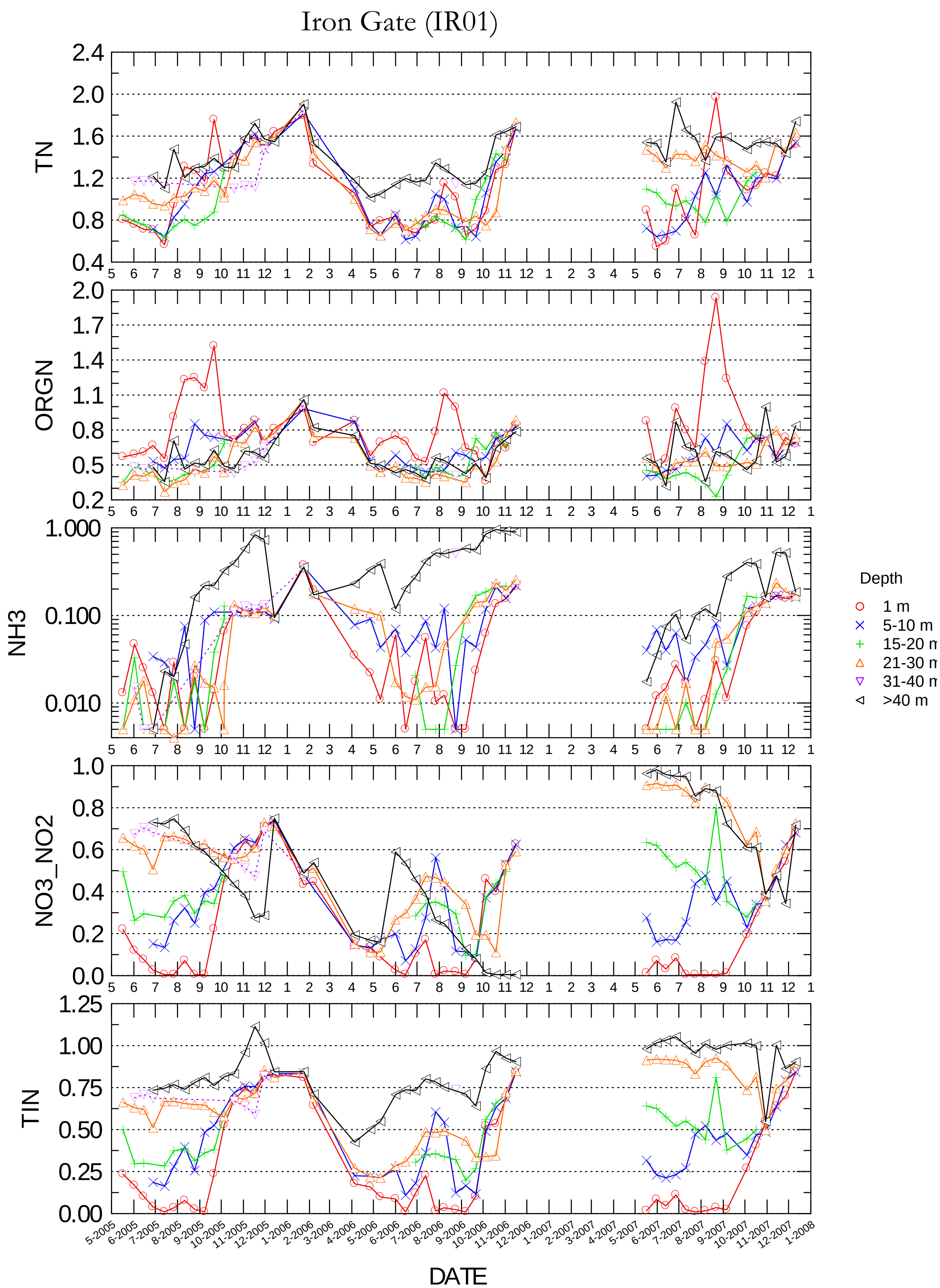

Figure 10. Depth-profiles of nitrogen concentrations at Iron Gate Reservoir sampling station IR01, May 2005 – December 2007.

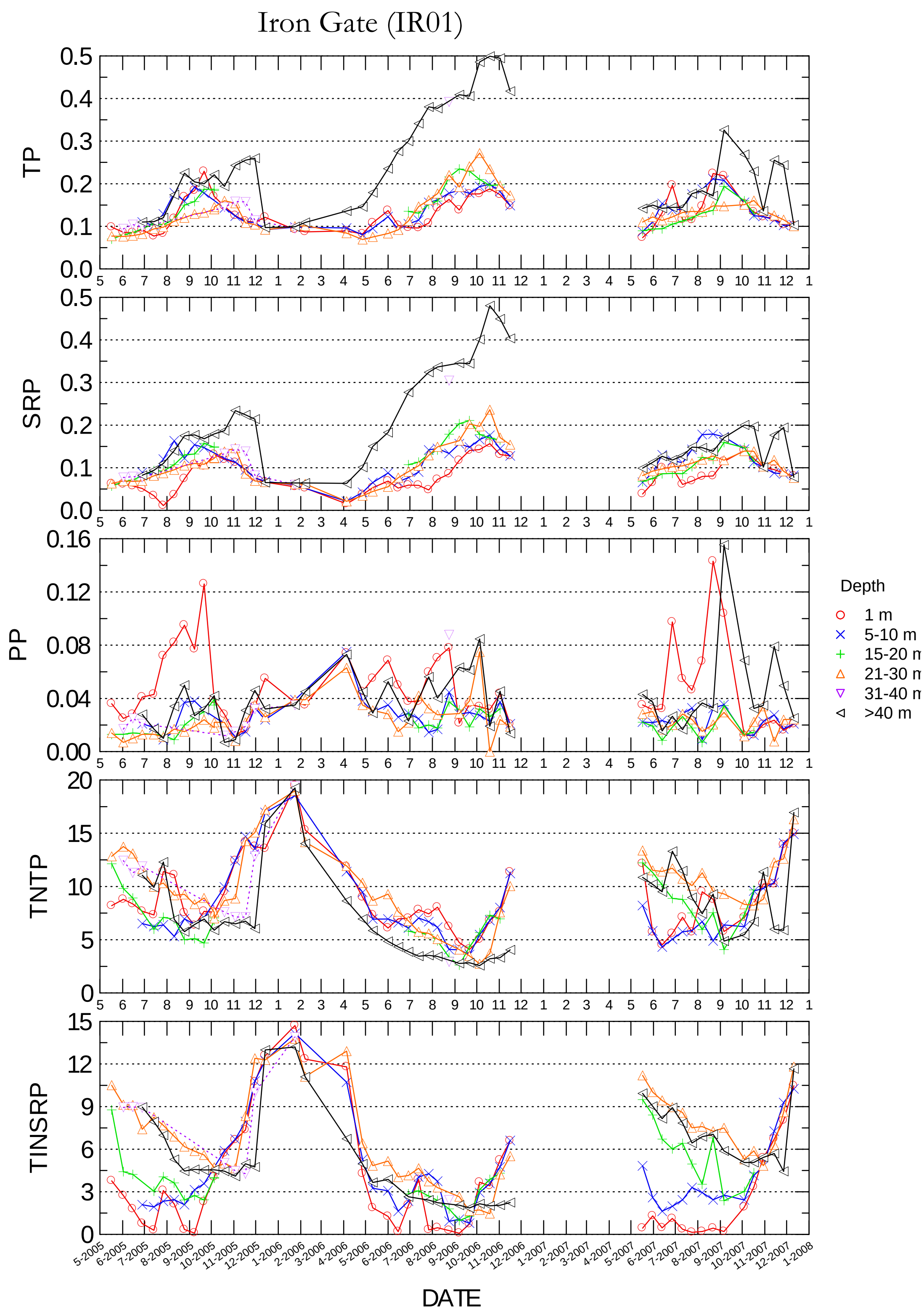

Figure 11. Depth-profiles of phosphorus concentrations and nitrogen:phosphorus mass ratios at Iron Gate Reservoir sampling station IR01, May 2005 – December 2007. TNTP is mass ratio of TN to TP, and TINSRP is mass ratio of TIN to SRP.

Chlorophyll-*a* concentrations, an indicator of algal biomass, were highest in both reservoirs during the summer stratified period in the surface (1m) samples, but still exceeded 10 ug/L at times in both reservoirs even at 10 meters depth (Figure 12). During unstratified periods, chlorophyll levels were similar among all sampled depths (<=10m), and a smaller peak in chlorophyll concentrations occurred in March 2005, likely the result of a diatom bloom. High chlorophyll levels in these reservoirs have been demonstrated to be associated with large blooms of *Microcystis* and or *Aphanizomenon* (Kann and Asarian 2007, Kann and Corum 2009).

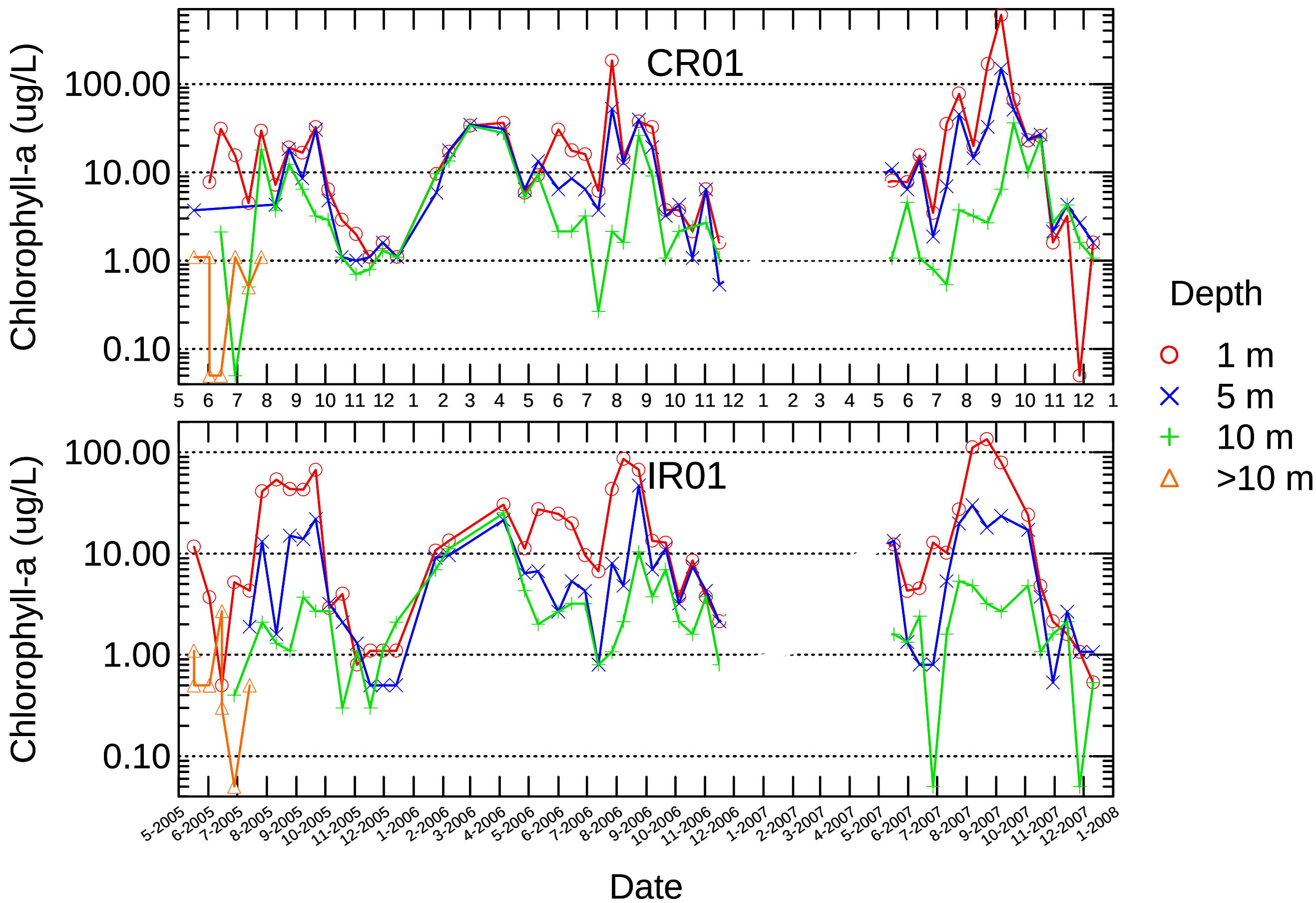

Figure 12. Chlorophyll-*a* at measured depths for reservoir stations CR01 and IR01, May 2005 – December 2007.

3.2 LONGITUDINAL NUTRIENT CONCENTRATIONS

Time series of all mainstem inflows[8], outflows, and in-reservoir volume-weighted means for nutrient parameters in Iron Gate and Copco Reservoirs are shown in Figure 13 through Figure 15, and figures are also provided for total organic carbon (Figure 16) and chlorophyll-*a* (Figure 18).

[8] Inflow values shown in these figures are not flow-weighted averages that take into account dilution by small tributaries; they are the directly measured concentrations (with the exception of KRAC, some data at that station are adjusted to

3.2.1 Nitrogen

From May-September, NH_3 concentrations were often lowest at KRAC or KRBI, with the highest concentrations in Copco Reservoir (Figure 8). The likely cause of these low NH_3 concentrations at KRAC is that during warm months, high concentrations of ammonia released from Keno Reservoir are rapidly nitrified[9] in the turbulent oxygen-rich river reach between Keno Dam and Copco Reservoir (Deas 2008). Compared with the May-September period, the October-December period exhibited reductions in Copco Reservoir NH_3 coincident with the return of oxygen to the reservoir's depths (Figure 6), increasing NH_3 in the still-stratified Iron Gate Reservoir and its outlet KRBI, and NH_3 concentrations at KRAC increasing but still remaining lower than any other station. At all locations except Copco Reservoir, the highest ammonia concentrations of the study were observed during the peak flows in early and late January 2006, subsiding to more commonly observed levels by the end of February 2006. Incomplete nitrification (caused by low water temperatures slowing down nitrification rates), potentially exacerbated by non-point sources of NH_3 from upstream, are likely causes of high winter ammonia levels.

During the thermally stratified period from June through October, NO_3-NO_2 concentrations at KRAC were substantially higher than in the two reservoirs and at reservoir outlets KRAI and KRBI (Figure 8). This difference was generally not present during isothermal periods. NO_3-NO_2 concentrations at KRBI were consistently lower than or equal to the other locations. Even during the stratified period, NO_3-NO_2 concentrations at Copco Reservoir were similar to its outlet KRAI. Iron Gate Reservoir NO_3-NO_2 concentrations showed somewhat less variation than the other locations, being generally higher than other stations in May-June and lower in October-December. With the exception of January and February 2006, NO_3-NO_2 comprised the greatest portion of the TIN.

In the May-October periods of 2005, concentrations of organic N were typically higher at KRAC than downstream at KRAI and KRBI, but in 2007 from mid-August to mid-September during peak phytoplankton blooms there were three consecutive samples when organic N was substantially higher at KRBI and KRAI (2006 was too difficult to judge due to timing of sample collection at KRAC). Organic N generally comprised ≥50% (up to 90%) of the TN at all locations, with the percentage following a seasonal pattern of being highest in May-September and lowest in November-December (Figure 15). High May-September organic N composition corresponds with algal blooms in the study area (see chlorophyll-*a* data in Figure 12 and Figure 17) and upstream. KRAC had the lowest percent composition of organic N, due to high concentrations of NO_3-NO_2 resulting from the decomposition of organic matter from upstream sources.

Overall TN concentrations showed a longitudinal decrease, with concentrations being most often highest at KRAC and lowest at KRBI. This is likely due to 1) nutrient storage in the water column and sediments of the reservoirs, 2) penstock intakes that draw water from intermediate depths where concentrations are lower, and 3) possible atmospheric losses through denitrification. TN

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estimated flow-weighted daily mean to account for hydropower peaking effects). Flow-weighted biweekly summaries for total inflow are shown in Table A3-1 of Appendix A3, Figure 27, and Figure 28.

[9] Nitrification is the conversion of NH_3 to NO_3-NO_2

concentrations were typically very similar in Copco Reservoir and its outlet KRAI, and generally lower than at inflow KRAC, except during/after turnover in mid-October through mid-December and in May through mid-June, when patterns were variable (Figure 8).

There is some evidence of a longitudinal time lag in TN concentrations. For example, TN concentrations at KRAC begin to rise rapidly each year in late June or early July, but this rise does not appear at KRBI for approximately one month.

3.2.2 Phosphorus

Temporally, TP concentrations were typically lowest at all locations in December (after turnover in both reservoirs, but prior to onset of high winter flows), fluctuate with flow until May when they begin climbing to reach a peak in July-September (depending upon the location), before falling again to back to annual lows in December (Figure 14).

Longitudinally, TP concentrations generally showed a decreasing pattern at river stations (highest at KRAC, intermediate at KRAI, lowest at KRBI) from June through August or September, but then exhibit an opposite pattern until perhaps late December (with only one season of data from mid-December through mid-May, it is difficult to determine the timing). This reversal is likely the result of the combination of internally-driven reservoir nutrient dynamics and a temporal lag as nutrients move through the reservoirs resulting from hydraulic residence time. This apparent temporal lag varies from approximately one to two months. The longitudinal attenuation of annual maximum concentrations was not nearly as large for TP as it was for TN.

During the period of reservoir stratification, reservoir-wide average TP concentrations were frequently higher than at reservoir outlets (most substantially at Copco in July-October, but with a lower magnitude and consistency at Iron Gate except for July-September 2006)(Figure 14). This was in contrast to the pattern observed for TN where in-reservoir concentrations were only occasionally substantially higher than outlet concentrations.

In May-December, SRP accounted for a substantial majority (~50-90%, Figure 15) of the TP, and exhibited similar temporal and longitudinal dynamics as TP (Figure 14). Inversely, PP generally was only a small portion of the TP during the May-December period, but comprised a majority of TP during the January-April period and was particularly high during peak flow events.

The mass ratios of total nitrogen to total phosphorus (TN:TP) and total inorganic nitrogen to SRP (TIN:SRP) were generally higher in Copco inflow than in Copco Reservoir and its outflow, indicating that conditions are potentially more nitrogen-limiting below Copco than above (Figure 14), but in mid-January through May TN:TP and TIN:SRP ratios sometimes showed an opposite pattern. The ratios of TN:TP and TIN:SRP were further reduced at KRBI, especially during the August through mid fall period (Figure 14). Reduction in these ratios increases potential for N limitation and has the potential to promote the growth of nitrogen fixing blue-green algae.

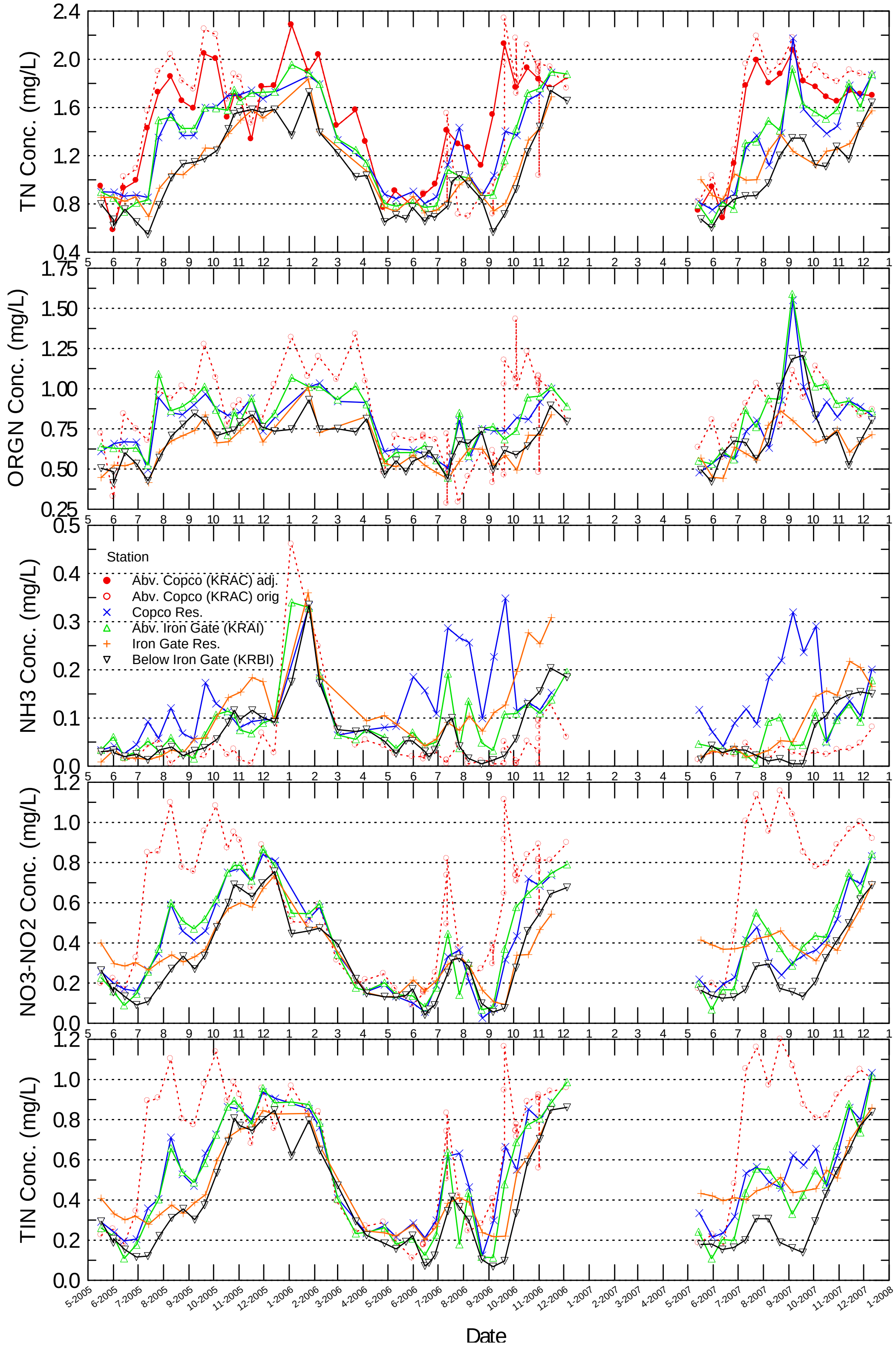

Figure 13. Biweekly time series of nitrogen concentrations above, within, and below Copco and Iron Gate Reservoirs, May 2005 – December 2007. KRAC data are affected by hydropower peaking (see section 2.1.1.3) but sufficient data were only available to adjust TN and TP. Comparison of adjusted and unadjusted TN (or TP) for a sample can be used to approximate the effect of adjustment on other parameters.

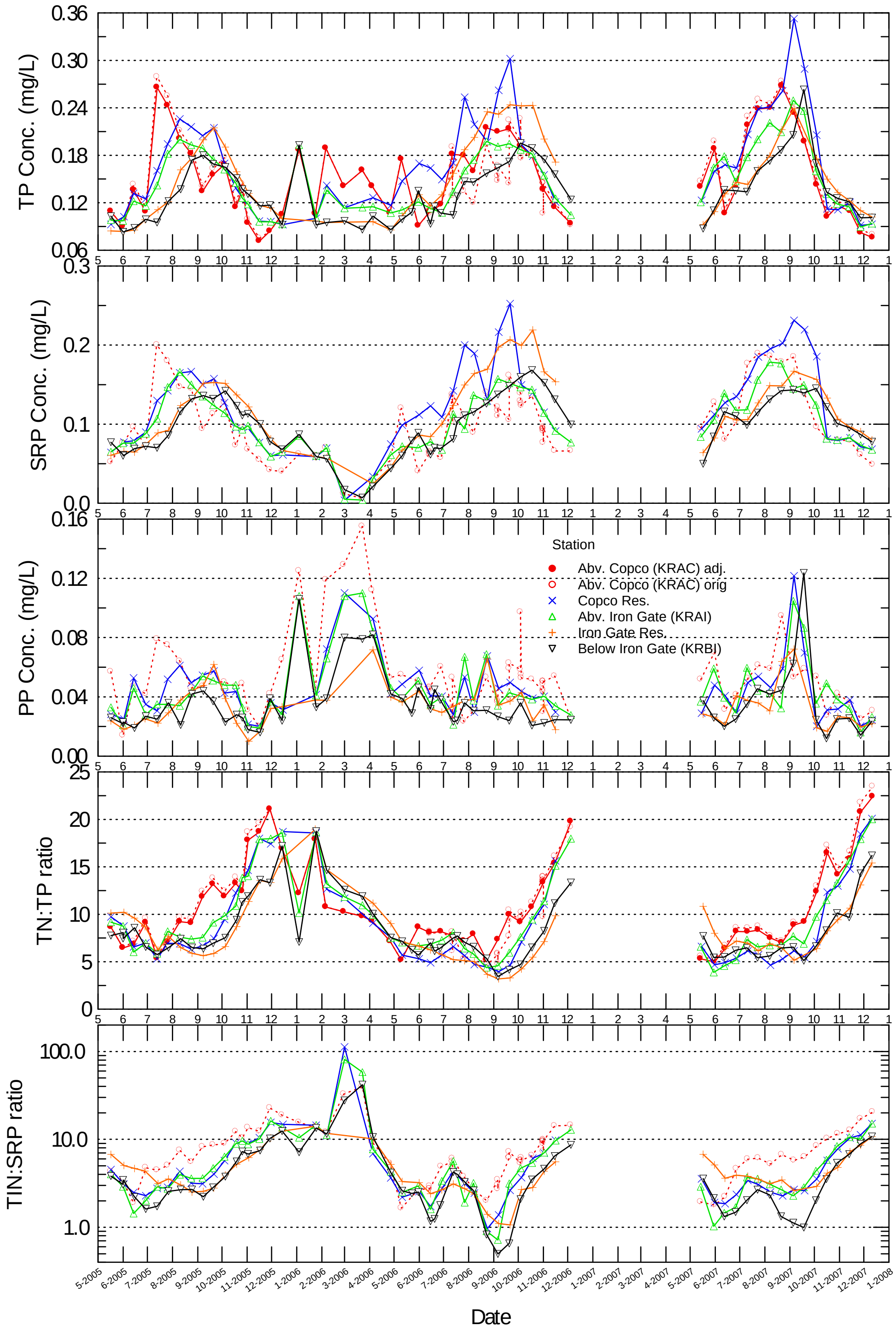

Figure 14. Biweekly time series of phosphorus concentrations and nitrogen:phosphorus ratios above, within, and below Copco and Iron Gate Reservoirs, May 2005 – December 2007. KRAC data are affected by hydropower peaking (see section 2.1.1.3) but sufficient data were only available to adjust TN and TP. Comparison of adjusted and unadjusted TN (or TP) for a sample can be used to approximate the effect of adjustment on other parameters.

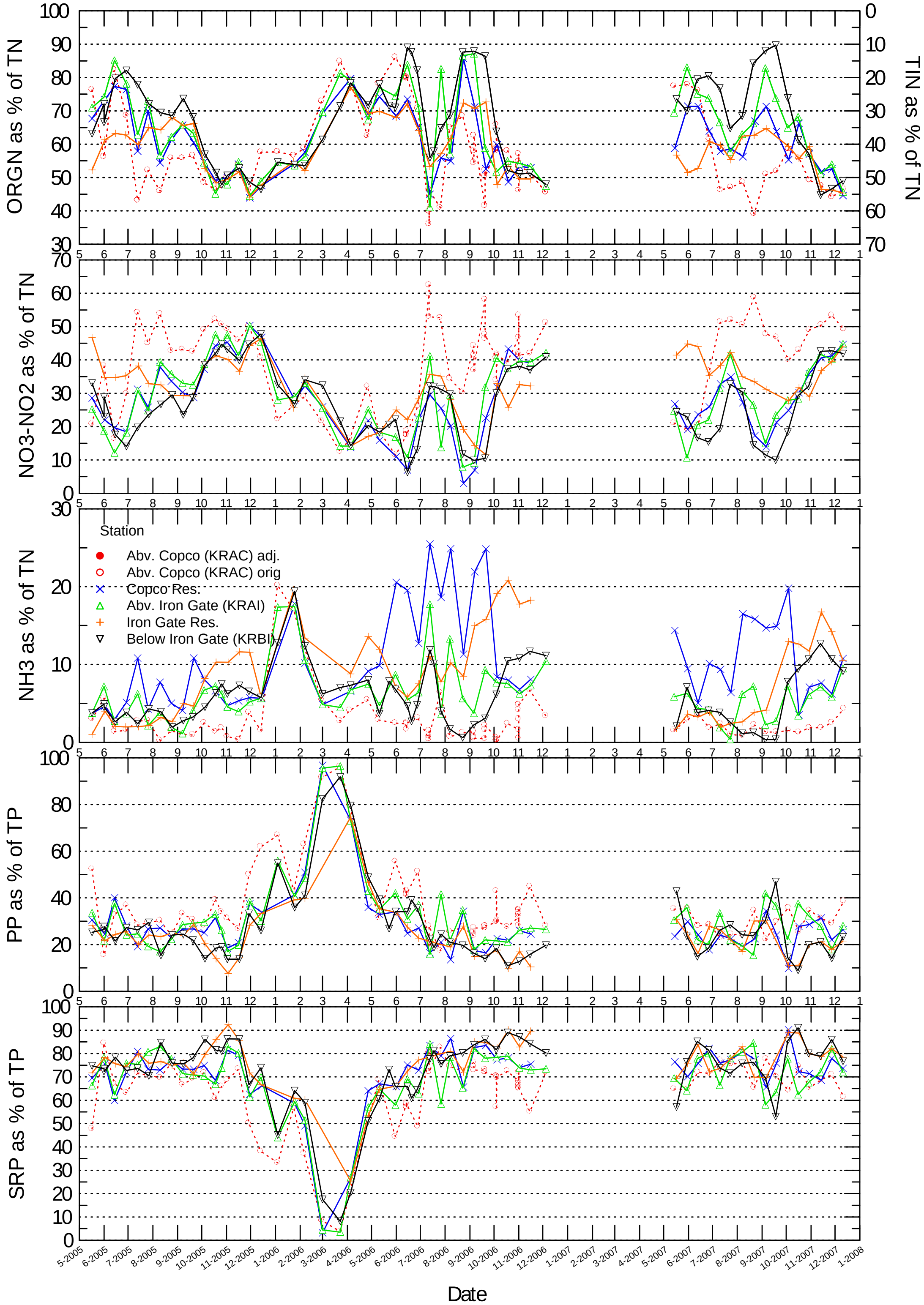

Figure 15. Biweekly time series of percent composition of nitrogen and phosphorus species above, within, and below Copco and Iron Gate Reservoirs, May 2005 – December 2007. KRAC data are affected by hydropower peaking (see section 2.1.1.3) but sufficient data were only available to adjust TN and TP. Comparison of adjusted and unadjusted TN (or TP) for a sample can be used to approximate the effect of adjustment on other parameters.

3.2.3 Carbon and Chlorophyll-*a*

From mid-May through October, TOC concentrations are generally higher at KRAC than KRAI or KRBI, although on other dates the pattern is reversed (Figure 16; some of the low TOC concentrations at KRAI, particularly in summer 2006, are unrepresentatively low due to the timing of sample collection and hydropower peaking effects). TOC concentrations were substantially lower in 2007 than in 2005-2006; the reason is unclear.

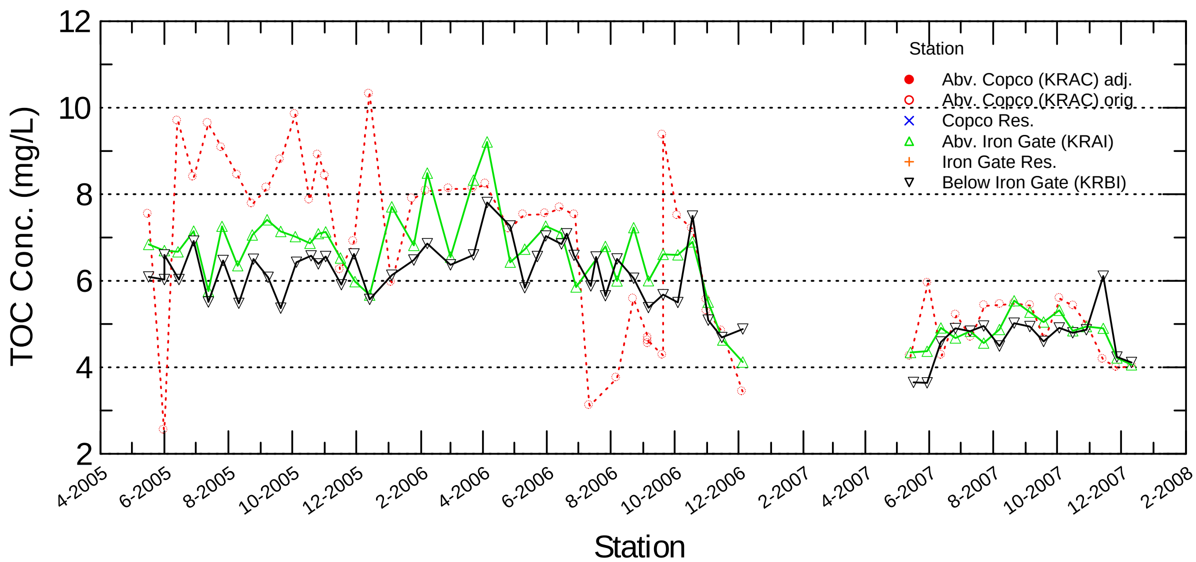

Figure 16. Biweekly time series of total organic carbon (TOC) concentrations at Klamath River above Copco (KRAC), Klamath River above Iron Gate (KRAI), and Klamath River below Iron Gate (KRBI), the only stations where TOC was measured, May 2005 - December 2007. Due to insufficient data, KRAC samples were not adjusted to account for hydropower peaking effects.

Of the three river stations, chlorophyll-*a* concentrations were typically substantially higher in July-September at KRAI and KRBI than at KRAC, indicating an increase through the reservoir complex (Figure 17). Peak chlorophyll in March 2006 was similar to or higher than peaks in summer 2005 and 2006 (but lower than summer 2007), perhaps caused by outwash from Upper Klamath Lake during typical spring diatom blooms. The June-September distribution compared among stations also confirms a substantial increase in chlorophyll from above to below the reservoir complex (Figure 18). The pattern was consistent in all years, although overall values were higher in 2007, particularly at KRBI.

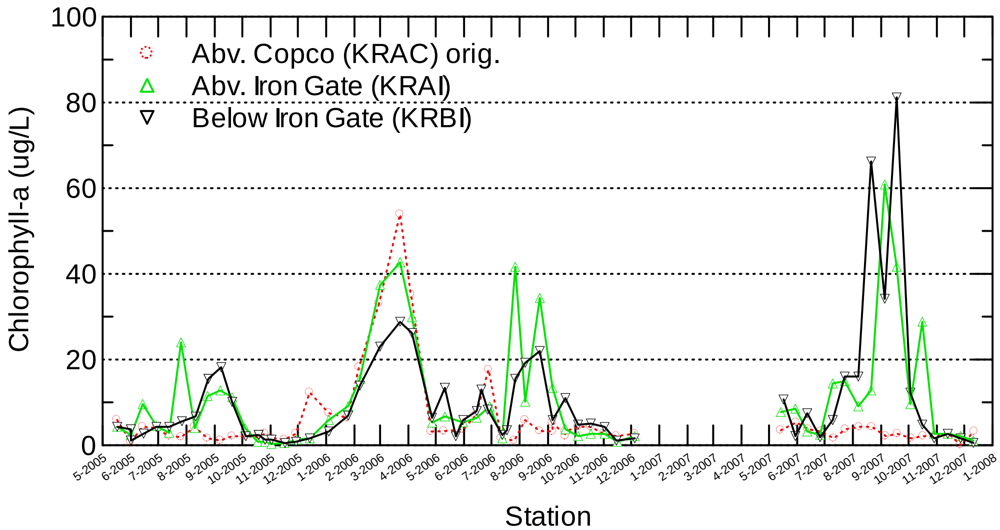

Figure 17. Biweekly time series of chlorophyll-*a* concentrations at Klamath River above Copco (KRAC), Klamath River above Iron Gate (KRAI), and Klamath River below Iron Gate (KRBI), May 2005 - December 2007. KRAC samples were not adjusted to account for hydropower peaking effects; however, based on time of day that samples were collected, the above chlorophyll values for summer 2005 and summer 2007 are likely somewhat higher than daily flow-weighted averages, and summer 2006 samples are likely somewhat lower than daily flow-weighted averages.

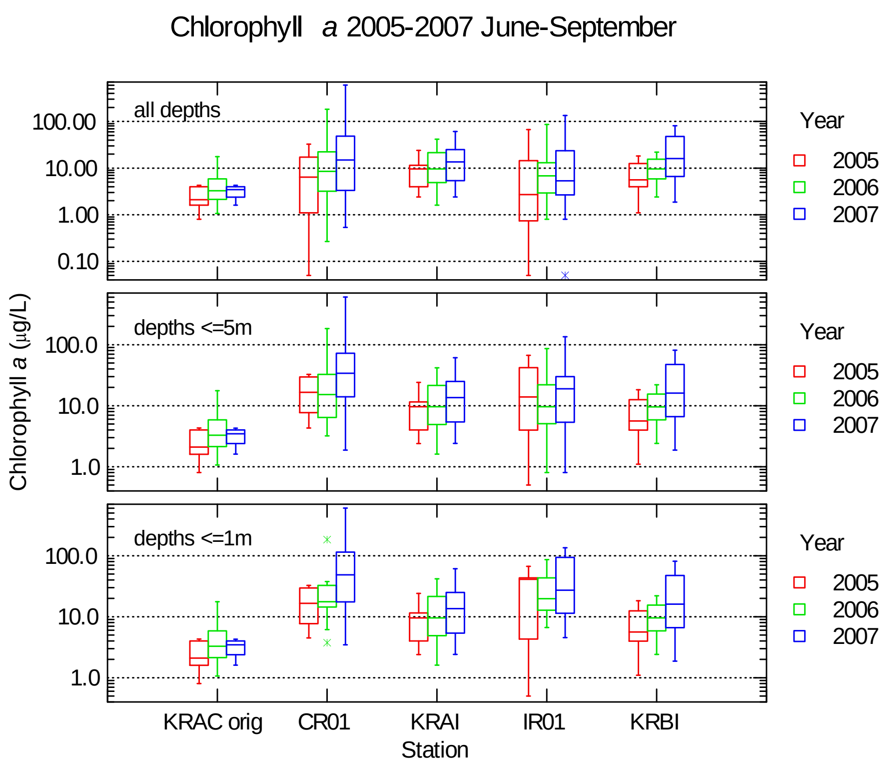

Figure 18. Longitudinal chlorophyll *a* concentrations for all measured reservoir depths (top panel), depths ≤ 5m (middle panel), and depths ≤ 1m (bottom panel), June-September, 2005-2007. Note that values for river stations KRAC, KRAI, and KRBI are only for the 0-1 m layer which represents the entire mixed water column. As noted in Figure 17, KRAC samples were not adjusted to account for hydropower peaking effects.

3.3 HYDROLOGIC BUDGETS

Hydrologic data were assembled for dates corresponding to timing of nutrient data: May 17, 2005 though December 11, 2007. While the budgets were constructed using metric units, river and tributary flows are graphically shown in cubic feet per second (cfs) because these are the units most commonly discussed in the Klamath Basin.

3.3.1 Copco Reservoir

Daily time series for major water balance terms for Copco Reservoir are presented in Figure 19, Figure 20, Appendix E3 (electronic), and a bi-weekly summary table is included in Appendix A3. As expected for a mainstem reservoir, inflow to Copco was dominated by the Klamath River (Figure 19b). Mainstem inflows vary seasonally and are low in the summer and higher in late fall, winter, and spring due to rain events and snowmelt, although the timing and magnitude of these flows varied substantially among years. Mainstem inflows increased substantially starting in mid-December 2005, reaching a peak of 8677 cfs on 1/2/2006, and generally remained above 3000 cfs through the end of June 2006, including several relatively high peaks (Figure 19b). Flows from December 2006 to June 2007 were much lower than in the previous year, reaching 3000 cfs for only a few weeks in March.

Aside from the high flow periods in May 2005 and early January 2006 when Shovel Creek and other ungaged accretions were >10% of inflow, in general for the entire May 2005-December 2007 study period they represented only a small portion (3.2%) of the total inflow (see Table A3-1 in Appendix A3).

Water load (total inflow/surface area) and residence time (outflow/volume) were computed as a check on other water balance terms (Figure 19d). Water load and residence time are inversely proportional, and residence time is on the order of ~5 days during high winter and spring flows, increasing to 15-25 days during the summer (Figure 19d).

Due to a small surface area relative to total reservoir volume, evaporation represented only 0.3% of the outflow volume over the entire study period, peaking in July at a cfs equivalent of 10 (Figure 19a; Table A3-1 in Appendix A3). The general trend of total outflow mirrors that of total inflow, and reservoir storage and change in storage fluctuate on a seasonal and daily basis according to PacifiCorp hydroelectric operations and minimum in-stream flows for fish (Figure 20a).

As noted earlier, the hydrologic residual is a term that includes measurement error in all budget terms. During the low-flow June through October period of 2005, the residual term was generally within ±50 cfs, or about 5% of inflow (Figure 20c,d). During the higher-flow periods, residuals were larger on an absolute (cfs) basis, but smaller on a relative (percent) basis compared to lower-flow periods. Various spikes exceeding the ±5 % or 50 cfs level for the residual could be due to measurement error in any of the terms, including daily stage or inflow/outflow measurements. However, such daily spikes are expected to have little influence on the hydrologic budget as a whole. Spikes most often occurred surrounding precipitation events or large daily changes in reservoir storage. Low hydrologic residuals were expected, given that ungaged inflows were set according to the accretion between upstream and downstream gages, and the method used for estimating Copco ouflow had the effect of equally distributing the residual between the two reservoirs.

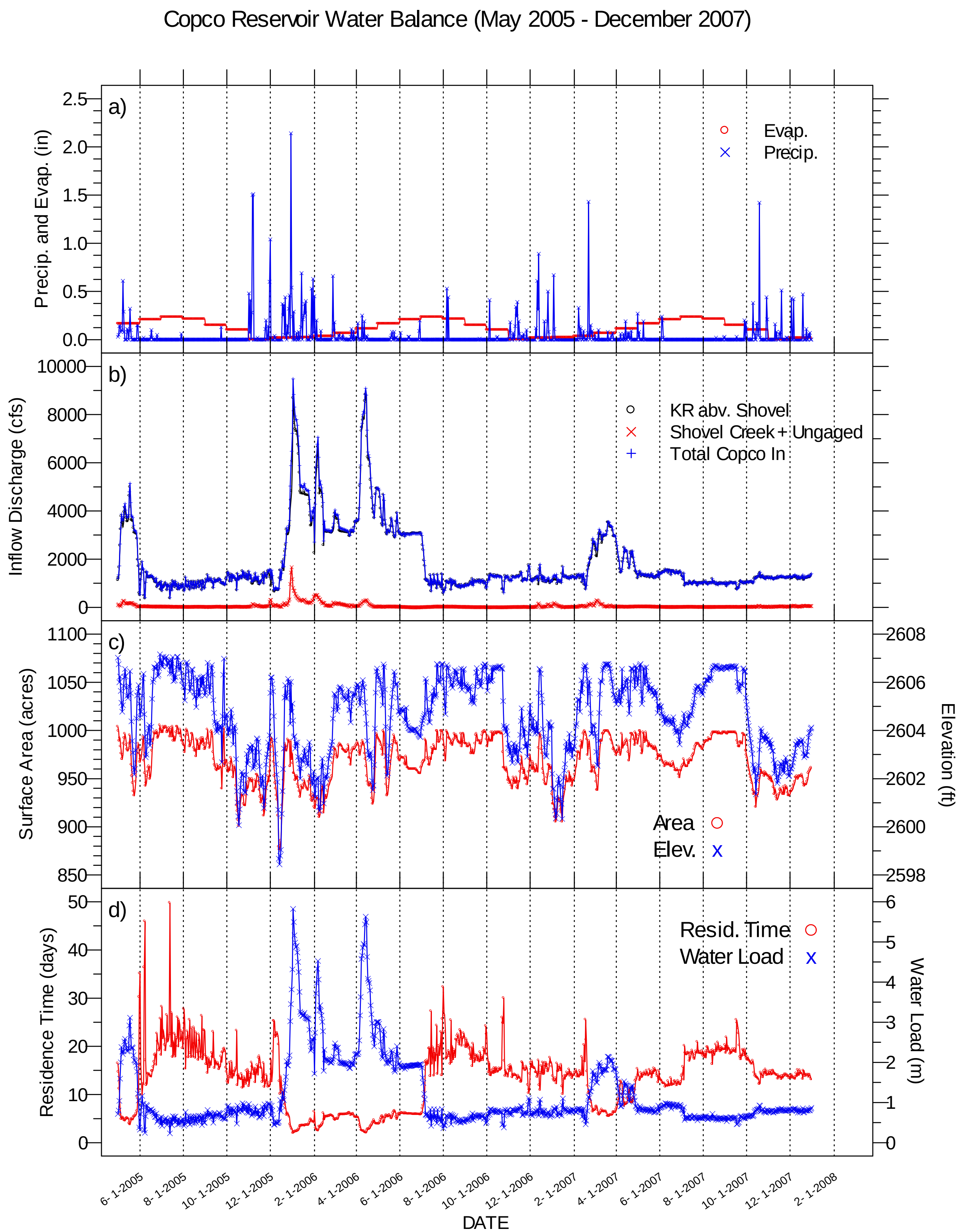

Figure 19. Daily time series of Copco Reservoir water balance input terms, May 2005 - Dec 2007.

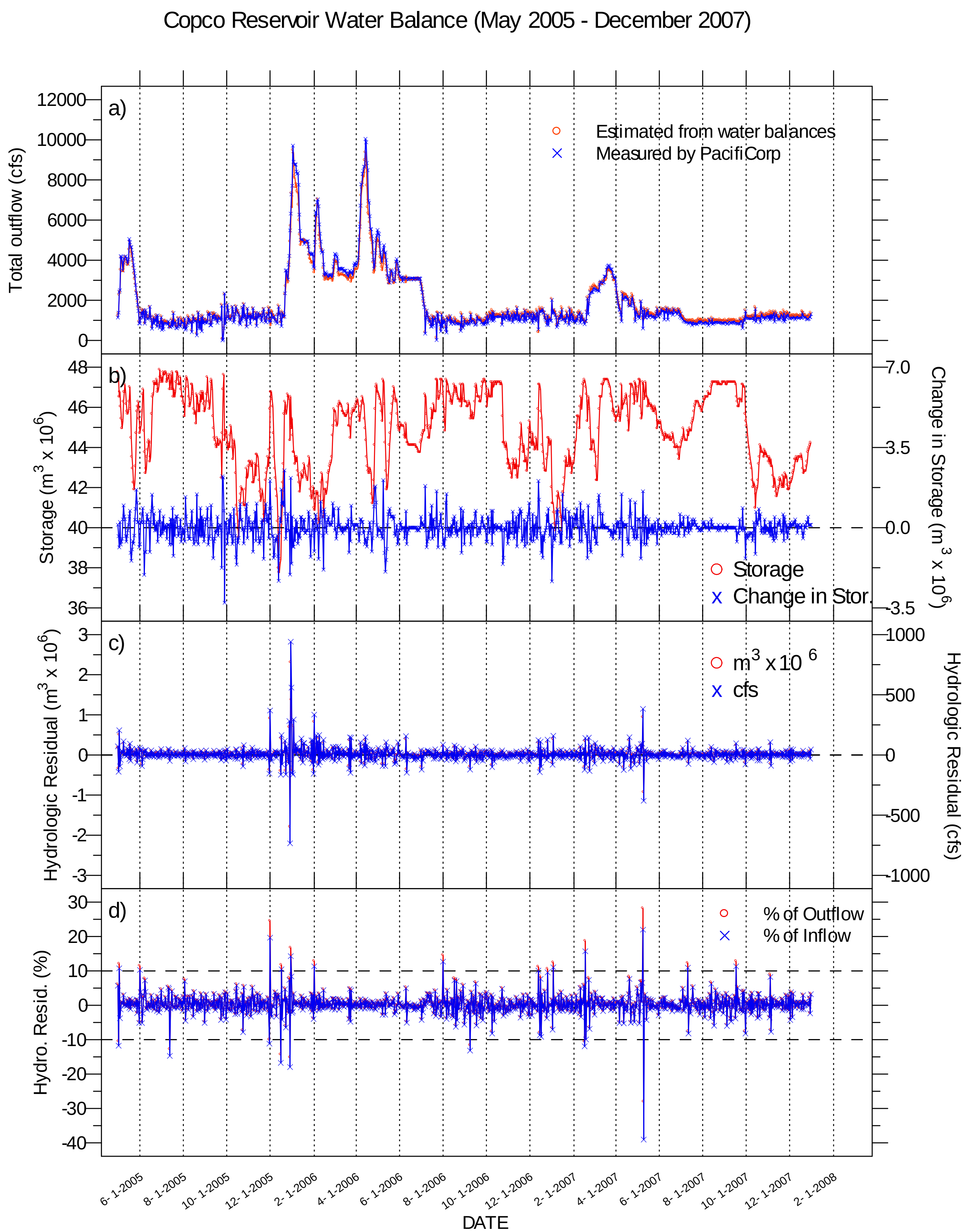

Figure 20. Daily time series of Copco Reservoir water balance reservoir terms, May 2005 – Dec 2007.

3.3.2 Iron Gate Reservoir

Daily time series for major water balance terms for Iron Gate Reservoir are presented in Figure 21, Figure 22, Appendix E3 (electronic), and a bi-weekly summary table is included in Appendix A3. Again, as expected for a mainstem reservoir, inflow to Iron Gate was dominated by the Klamath River, in this case the outflow from Copco. Mainstem inflow showed a May 2005 spring runoff peak, then declined to summer low flows (Figure 21b), increased again in mid-December and remained high through June 2006 before declining to summer lows until rising to higher flow again from late February 2007 through late June 2007, then falling and remaining low through the end of the study period. Tributaries (Figure 21a) were more important than they were for Copco Reservoir, contributing 8.3% for the entire May 2005 – December 2007 period, and as much as 18.1% during the mid-December to early January sampling period (see Table A3-2 in Appendix A3). Copco outflow contributed ~95% of the inflow during the low-flow months.

There were occasional spikes in residence time, as high as 212 days, driven by sharply reduced outflows from Copco Reservoir (Figure 21d). Aside from these spikes, residence time is on the order of about 3-10 days during the winter and spring, increasing to 25-30 days during the summer (Figure 21d).

As with Copco, evaporation represented only a small portion of the total outflow volume (0.2% over the entire study period), peaking in July at a cfs equivalent of 10 (Figure 19a; Table A3-1 in Appendix A3). However, unlike Copco Reservoir, Iron Gate outflow fluctuation is muted relative to inflow (Figure 22a). Reservoir storage and change in storage fluctuates on a seasonal and daily basis according to PacifiCorp hydroelectric operations and minimum in-stream flows for fish (Figure 22b).

Similar to Copco, low-flow period residuals were generally less than ±50 cfs, or about 5% of inflow (Figure 22c). Also similar to Copco, during the higher-flow periods residuals were larger on an absolute (cfs) basis, but smaller on a relative (percent) basis compared to lower-flow periods.

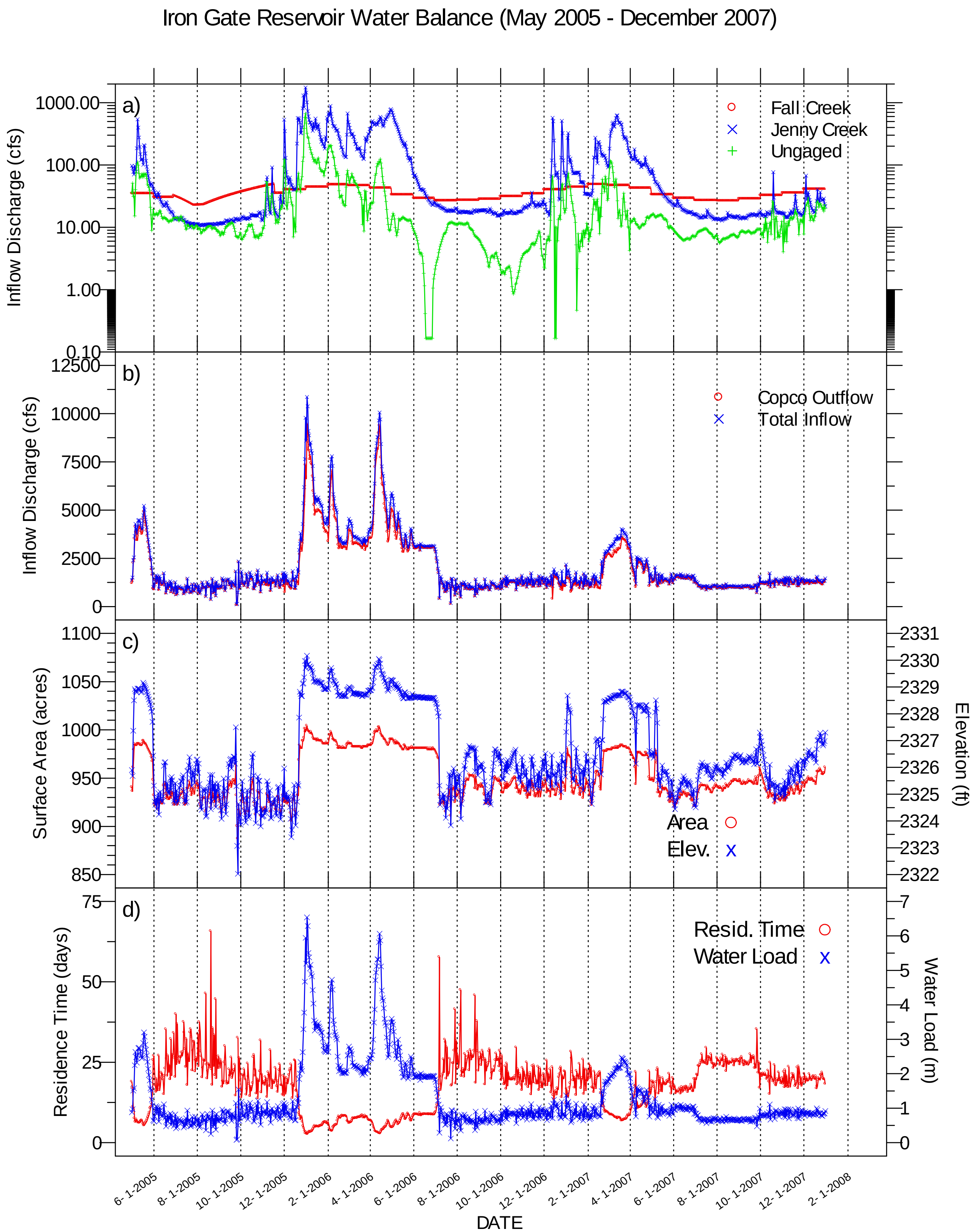

Figure 21. Daily time series of Iron Gate Reservoir water balance reservoir terms, May 2005 - Dec 2007.

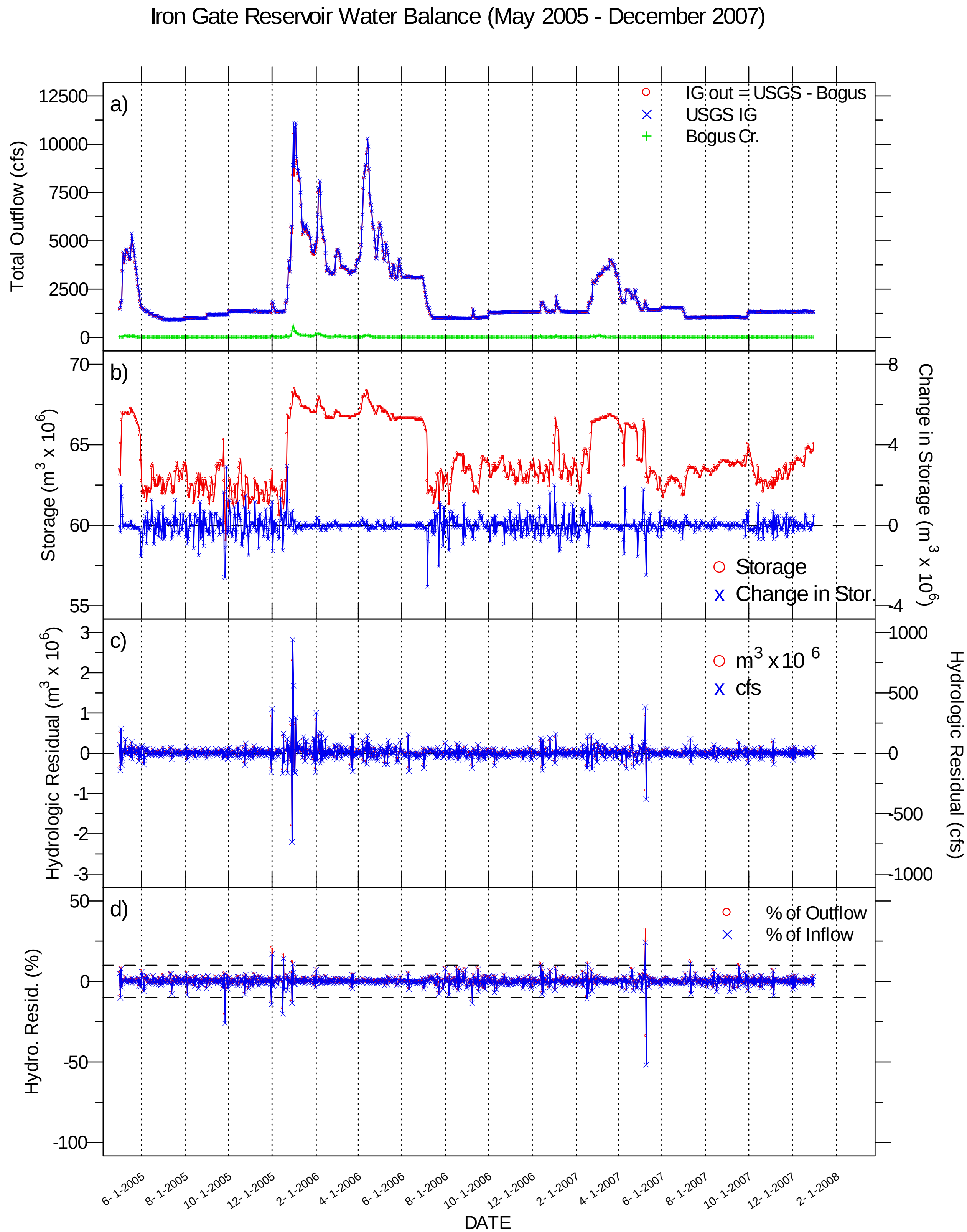

Figure 22. Daily time series of Iron Gate Reservoir water balance reservoir terms, May 2005 - Dec 2007.

3.4 ESTIMATION OF DAILY NUTRIENT CONCENTRATIONS AND LOADS

Daily concentration and subsequent daily load estimates based on the multiple regression modeling method (Walker and Havens 2003) are shown in Appendix A6.

The predictive equation utilized is:

$$\text{Ln (Conc)} = B0 + B1\ \text{LnQ} + B2\ \text{LnQ}^2 + B3\ \text{LnQ}^3 + B4\ \text{Sin}(t) + B5\ \text{Cos}(t) + B6\ \text{Sin}(2t) + B7\ \text{Cos}(2t) + B8\ \text{Year} + B9\ (\text{Year})^2 + B10\ \text{QDeriv}$$

Where:

LnQ = Natural Log of Daily Flow
QDeriv = Natural Log (Q (day) / Q (Day-1)), = 0 if either flow = 0
year = year + fraction of year = Year + julian Day / 365.25
t = 2 x Pi x Julian / 365.25
B0 = Regression Intercept, Predict Natural Log of Daily Concentration
Q = flow in units of $m^3 \times 10^6$
Conc = Concentration in mg/L
B0 through B10 are empirically-derived coefficients

Regression coefficients, coefficient of determination (R^2), and standard errors for the various stations and parameters are shown in Table 4 and Table 5. For both TN and TP, relative standard errors are less than 3% for all mainstem stations, and less than 10% for most tributary stations.

Alternative load calculation algorithms are also applied for comparison (Table 6 and Appendix A6). Results for the entire monitoring period appear to be reasonably insensitive to load calculation method. A comparison of Method 3 (Simple Linear Interpolation of concentrations between sampling dates) used in Kann and Asarian (2007) and Method 5 (Regression with residual interpolation) used in this study shows that total load did not differ by more than 4% at any mainstem station and 10% at any tributary station (Table 6).

3.5 NUTRIENT BUDGETS

As described in the methods, hydrologic budget terms were multiplied by nutrient concentration to obtain estimates of nutrient mass in kilograms. These terms, as well as the retention term, were computed for TP and TN. Negative retention values denote a source from within the system (i.e., from internal loading or nitrogen fixation), and positive values denote a sink.

As noted above, daily data were summarized by 1) sample periods (~biweekly), 2) the approximate reservoir algal growing season (mid-May to end of September), 3) the study start through turnover (mid-May to mid-December), 4) annually (mid-May to mid-May), and 5) the winter/early spring period (mid-December to mid-May).

Table 4. Total load, standard error, and regression coefficients for each station for total phosphorus. See above for predictive equation.

Location	Total Load	Load Std Error	Relative Standard Error	Regression R2	B10	B9	B8	B7	B6	B5	B4	B3	B2	B1	B0
KRAC	637.4	14.84	2.3%	0.76	-0.3462	-0.1206	483.9014	-0.1554	0.2089	-0.1937	-0.0047	0.1759	-0.5292	0.1654	-485593
KRAI	613.7	10.63	1.7%	0.86	-0.1036	-0.0652	261.7836	-0.1321	0.1447	-0.2374	-0.1212	0.3495	-1.5719	2.0582	-262724
KRBI	597.8	16.14	2.7%	0.80	0.0563	-0.0728	292.1034	-0.0987	0.0342	-0.1656	-0.3795	0.2128	-1.0151	1.6045	-293151
SC01	3.1	0.22	7.0%	0.74	0.0514	0.0001	-0.3174	-0.0421	0.1669	0.1201	-0.0303	-0.0119	-0.1212	-0.3446	309
FC01	2.7	0.14	5.3%	0.24	1.2114	0.0794	-318.7173	0.0563	0.0735	0.0490	0.0215	8.8664	64.8124	156.8617	320058
JC01	7.3	0.35	4.8%	0.76	-0.2802	-0.0611	245.2263	0.1646	-0.0477	-0.0756	-0.0767	0.0598	0.3935	0.6623	-245965
Copco other	5.2	0.36	6.9%	0.75	0.0713	-0.0178	71.4011	-0.0463	0.1684	0.1346	-0.0313	-0.0104	-0.0919	-0.2124	-71654
Iron Gate other	1.8	0.10	5.7%	0.42	0.0679	-0.0941	377.4710	0.1007	-0.0927	-0.1232	-0.1041	0.0037	0.0472	0.2696	-378668

Table 5. Total load, standard error, and regression coefficients for each station for total nitrogen. See above for predictive equation.

Location	Total Load	Load Std Error	Relative Standard Error	Regression R2	B10	B9	B8	B7	B6	B5	B4	B3	B2	B1	B0
KRAC	6503.4	111.26	1.7%	0.81	-0.1681	0.0504	-202.3644	-0.0062	0.2085	0.2748	-0.2048	0.0358	-0.1092	0.0659	203019
KRAI	6085.5	92.20	1.5%	0.83	-0.0420	0.1042	-418.1809	0.0174	0.1418	0.3627	-0.1773	0.0560	-0.3166	0.5823	419570
KRBI	5688.0	95.72	1.7%	0.79	0.6595	0.0425	-170.6167	0.0751	0.1411	0.3966	-0.1469	0.1093	-0.8067	1.7917	171190
SC01	9.8	0.58	5.9%	0.65	0.0990	0.3627	-1455.5470	0.0021	-0.0315	0.3762	0.2047	-0.0025	-0.0527	-0.2909	1460486
FC01	14.0	0.76	5.4%	0.58	3.8984	-0.1513	607.0586	0.0771	-0.0381	0.1655	0.0738	-11.3362	-83.6516	-204.6736	-609189
JC01	49.1	3.94	8.0%	0.48	-0.3594	0.1257	-504.5477	0.1456	-0.1194	0.0460	0.0627	0.0263	0.1816	0.3348	506358
Copco other	16.7	0.87	5.2%	0.66	0.0793	0.3364	-1349.9656	0.0031	-0.0400	0.3590	0.1801	-0.0112	-0.1301	-0.4282	1354539
Iron Gate other	11.9	1.28	10.7%	0.46	0.0454	0.0112	-45.2228	0.1343	-0.1295	0.0647	0.0395	-0.0009	-0.0357	-0.1175	45478

Table 6. Comparison of results of five algorithms for calculating mean daily load for each station and parameter (TN and TP), for the period 5/1/2005 – 12/31/2007. SE = Standard Error. Units are metric tons per day. Key to methods: 1 = Constant flow-weighted-mean concentration (flow-weighted average of concentration from sampled days multiplied by the mean flow over the entire period), 2 = Constant flow-weighted-mean concentration within low and high-flow strata (above and below the mean flow for the entire period), 3 = Simple Linear Interpolation of concentrations between sampling dates (previously utilized method), 4 = Regression without residual interpolation (similar to method 5, but without the residual interpolation), 5 = Regression with residual interpolation (final method utilized herein).

Para-meter	Location	Method 1 Load	Method 1 SE	Method 2 Load	Method 2 SE	Method 3 Load	Method 3 SE	Method 4 Load	Method 4 SE	Method 5 Load	Method 5 SE	3 Load as % of 5 Load
TN	KRAC	6.919	0.452	6.999	0.458	6.746	0.441	6.710	0.115	6.670	0.114	101.1%
TN	KRAI	6.324	0.400	6.389	0.402	6.236	0.394	6.289	0.095	6.242	0.095	99.9%
TN	KRBI	5.519	0.303	5.567	0.306	5.601	0.307	5.895	0.099	5.834	0.098	96.0%
TN	SC01	0.0097	0.0006	0.0097	0.0006	0.0099	0.0006	0.0103	0.0006	0.0101	0.0006	98.4%
TN	FC01	0.0141	0.0008	0.0140	0.0008	0.0147	0.0008	0.0145	0.0008	0.0144	0.0008	102.8%
TN	JC01	0.0512	0.0043	0.0509	0.0043	0.0539	0.0045	0.0508	0.0041	0.0503	0.0040	107.1%
TN	Copco other	0.0163	0.0010	0.0163	0.0010	0.0168	0.0010	0.0175	0.0009	0.0172	0.0009	97.6%
TN	Iron Gate other	0.0118	0.0015	0.0118	0.0015	0.0122	0.0015	0.0120	0.0013	0.0122	0.0013	99.9%
TP	KRAC	0.6781	0.0309	0.6812	0.0316	0.6636	0.0302	0.6644	0.0155	0.6537	0.0152	101.5%
TP	KRAI	0.6664	0.0311	0.6714	0.0317	0.6390	0.0298	0.6305	0.0109	0.6294	0.0109	101.5%
TP	KRBI	0.6590	0.0371	0.6632	0.0378	0.6367	0.0359	0.6110	0.0165	0.6131	0.0165	103.9%
TP	SC01	0.00318	0.00022	0.00317	0.00021	0.00320	0.00022	0.00321	0.00023	0.00318	0.00022	100.8%
TP	FC01	0.00271	0.00013	0.00271	0.00014	0.00277	0.00014	0.00281	0.00015	0.00280	0.00015	98.9%
TP	JC01	0.00792	0.00070	0.00790	0.00071	0.00826	0.00073	0.00760	0.00037	0.00748	0.00036	110.4%
TP	Copco other	0.00536	0.00036	0.00536	0.00035	0.00541	0.00036	0.00544	0.00037	0.00538	0.00037	100.6%
TP	Iron Gate other	0.00181	0.00020	0.00180	0.00020	0.00187	0.00021	0.00182	0.00010	0.00183	0.00011	102.4%

3.5.1 Copco Reservoir

3.5.1.1 Phosphorus

Sampling period (generally bi-weekly) time series for major nutrient mass-balance terms for Copco Reservoir are presented in Figure 23, Figure 24, and Appendix A3. Over the entire study, the Klamath River above Shovel Creek contributed 98.7% of the TP load, with Shovel Creek and other tributaries contributing the remainder (Appendix A3). Although timing and magnitude varied by year, TP inflow loading to Copco followed a seasonal pattern that was generally similar among years (Figure 23). Loading was highest during peak winter and spring high flows (May 2005, December 2005-June 2006) then decreased as flows fell to relatively stable summer lows. Loading then increased through the summer in each year, rising along with concentrations to reach a peak in late September (2005 and 2007) or October (2006), then falling along with concentration to early December lows. Atmospheric input was very low for all time periods, generally less than 0.1% of total input load (Appendix A3).

In each year, in-reservoir TP storage was low in May, climbed to a peak in August or September, and then decreased consistently to a low in late November or early-December. In 2006, in-reservoir TP then generally climbed slowly through winter and spring, with the exception of a peak in early January coincident with the highest flows of the study period.

TP retention varied over the study period in Copco Reservoir. From May to August it was mostly negative (which denotes a source from within the system likely due to release from the sediments) in 2005 and 2007, but alternated between negative and positive in 2006 (this alternation may not be meaningful due to the short time intervals). Retention was positive in late September and early October of every year (perhaps due to settling of algal particulate matter during the seasonal decline of algal blooms). Retention in mid-October through December varied (sometimes negative, sometimes positive) within and among years. Retention was consistently positive from mid-January through early May 2006.

At seasonal time scales, Copco TP retention as a percent of inflow mass was generally low or negative, ranging from -11% to +13% across the summarized seasonal periods (Table 7). Over the entire May 2005 to December 2007 study period, 32.5 metric tons (MT) or 5% ± 3% of the total inflow load of 626.5 MT of TP was retained (Table 7). Overall (as calculated by summing retention and loading across both periods, which is similar to, although not identical to the mean of the two periods) Copco TP retention was positive (+7%) for both May-May calendar years, slightly negative in two of the three May-December periods (-2%), negative in all three May-September periods (-7%), and positive (+10%) for the December 2005-May 2006 period.

3.5.2.2 Nitrogen

On a whole season basis KRAC contributed 99.4% of the TN load (Appendix A3). High flow period TN loading at KRAC was similar to TP, but showed a different pattern during the low-flow season (Figure 24a). TN loading declined along with descending flows from May through the end of June in 2005 and end of July in 2006, and then rose steadily to a peak in early October before dropping slightly to lows in mid-December. Timing of TN loading differed in 2007 and was already at a seasonal low by the time sampling started in May, but then climbed rapidly to reach a plateau in mid-July where it remained for several months before increasing slightly prior to the cessation of sampling in December. In December 2005, TN loading rose sharply with the onset of higher flows (Figure 24a). Shovel Creek and other tributaries contributed 0.4% of the load on a whole season basis, with a maximum of 1.2% in any single sampling period (Appendix A3). Atmospheric input was very low, accounting for 0.2% of the total load for the entire study period.

Reservoir TN storage was typically low in May, rose rapidly through mid/late July, with a final peak in December (Figure 24c). However, the inter-annual trend for the July-December period was highly variable. For example, storage fluctuated with a generally upward trend during August-December in 2005, fell sharply to near-May levels in late July through mid-August before rising rapidly again though December in 2006, and showed the highest storage of the study period in early September of 2007. The high storage in September of 2007 was likely driven by exceptionally high TN concentrations in the surface samples at the height of the phytoplankton bloom.

For the December 2005 to May 2006 winter/spring period, TN storage generally declined except for a rise from mid-December to early January associated with a large winter storm event.

From mid-May though October of each year TN retention (although fluctuating) was mostly positive or near zero, with only a few periods of negative retention (Figure 24d). Retention was generally negative or near-zero in November and December (though there were some positive periods in 2007). In the January-May winter/spring period, retention was consistently positive.

At seasonal time scales, Copco TN retention as a percent of inflow was higher than TP and was consistently positive for all summarized periods, with values ranging between +2% to +16% (Table 8). Over the entire May 2005 to December 2007 study period, 431.4 metric tons (MT) or 7% ±3% of the total inflow load of 6301.4 MT of TN was retained (Table 8). Copco TN retention was +7% overall for the two May-May calendar years, +6% overall for the three May-December periods, +12% overall for the three May-September periods, and +6% for the December 2005-May 2006 period.

3.5.2 Iron Gate Reservoir

3.5.2.1 Phosphorus

Sampling period (generally bi-weekly) time series for major nutrient mass-balance terms for Iron Gate Reservoir are presented in Figure 25, Figure 26, and Appendix A3. On a whole-season basis the KRAI (Copco Outflow) contributed 98.1% of the TP load (Appendix A3).

Temporal patterns in TP inflow loading to Iron Gate were similar to Copco (Figure 25a). Loading 1) was highest during peak winter and spring high flows (May 2005, December 2005-June 2006), 2) decreased as flows fell to near stable summer lows, 3) increased through the summer- peaking with concentration in September (2005 and 2007) or October (2006), and 4) fell along with concentration to early December lows. Small tributaries (Jenny Creek, Fall Creek, and others) represented a maximum of 6.4% of the total TP load in the late December/early January sampling period, but typically contributed a much lower percent (Appendix A3). Atmospheric input was very low for all time periods, never exceeding 0.1% of total input load.

Seasonal patterns in Iron Gate Reservoir TP storage were very similar among years (Figure 25c). Storage began at seasonal lows of ~5 MT each May, rising rapidly to peak in August or September at ~15 MT before falling back near 5 MT again in December. In the December 2005 to April 2006 winter/spring period, storage remained relatively constant with the exception of a large spike during the extreme high flow event in early January 2006.

TP retention fluctuated between positive and negative values from May through December, with no consistent patterns among years (Figure 25d). Retention is highly negative in the mid-December 2005 to early January 2006 period during the extreme high flow event. In 2005, from late January to late April, TP retention is positive through the end of the study period in May. Positive retention during the winter and spring may be because both a large percent of the incoming phosphorus is in particulate form (Figure 15) that is more likely to settle out than the dissolved phosphorus that predominates during the rest of the year, and the anaerobic and higher temperature conditions that facilitate sediment P release are not present during this period.

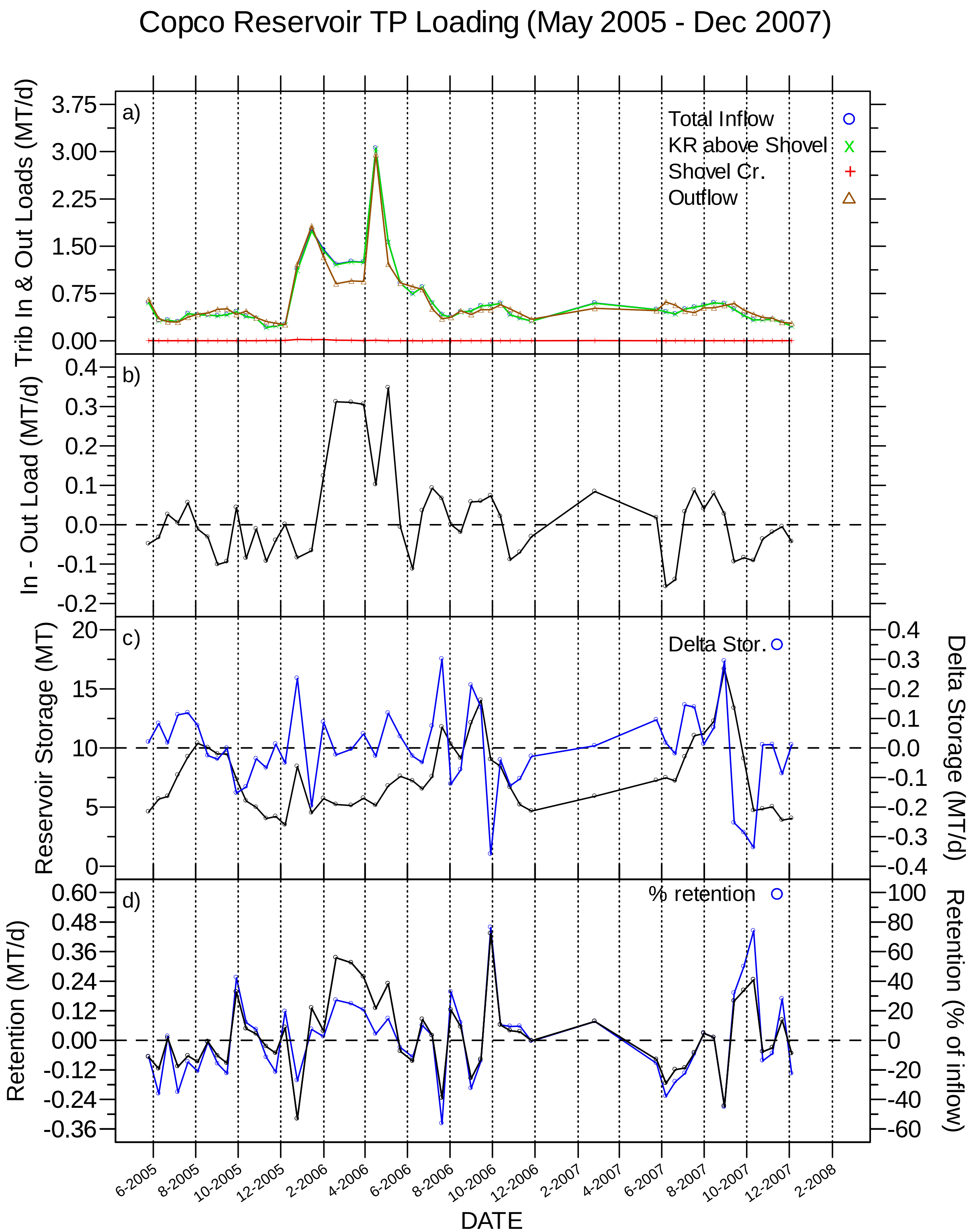

Figure 23. Time series of Copco Reservoir total phosphorus loading, May 2005 – Dec 2007. Each point represents data from an entire sampling interval (~biweekly) and is placed at the midpoint of the two adjacent sampling dates. Horizontal dashed lines are placed at zero for ΔStorage and retention.

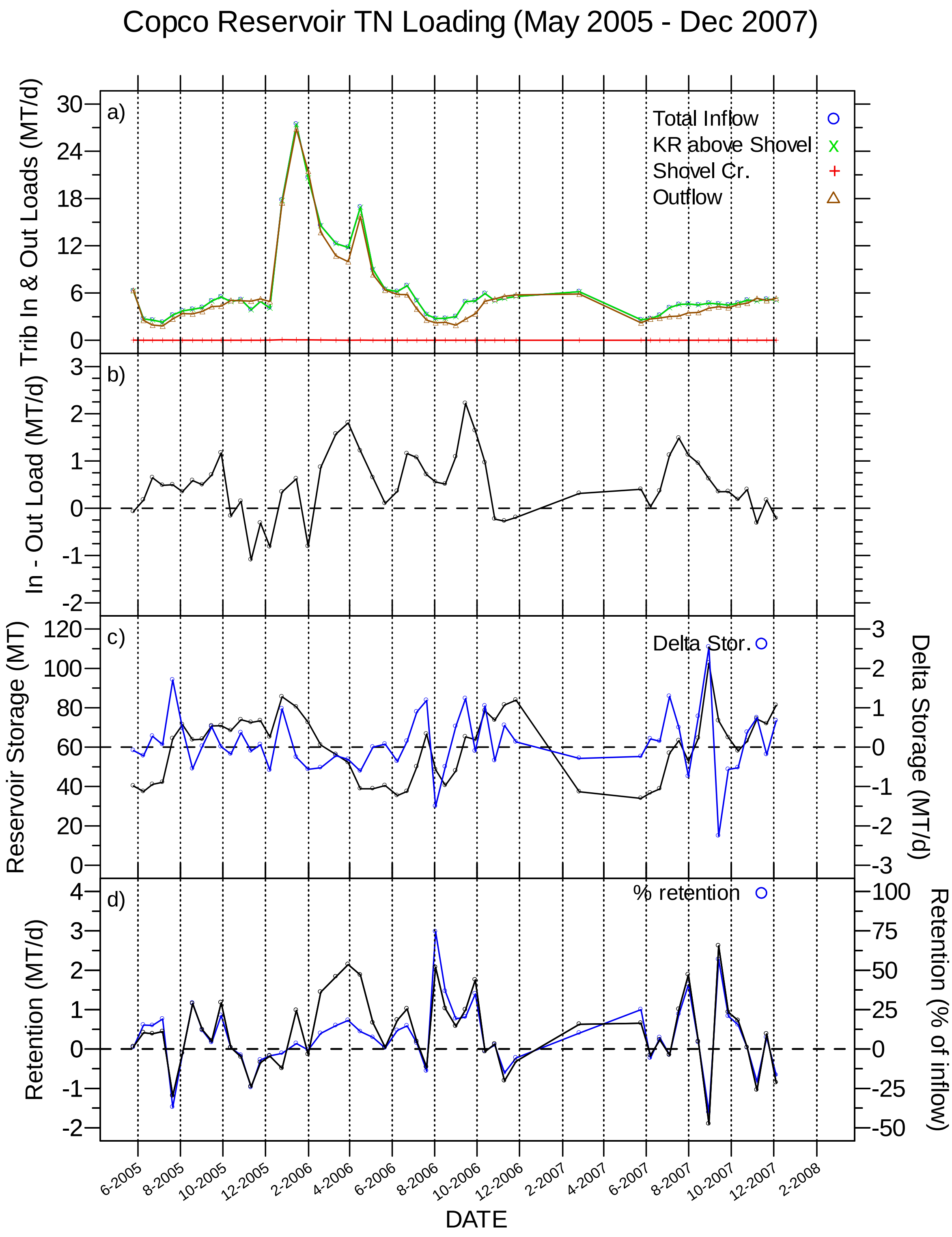

Figure 24. Time series of Copco Reservoir total nitrogen loading, May 2005 – Dec 2007. Each point represents data from an entire sampling interval (~biweekly) and is placed at the midpoint of the two adjacent sampling dates. Horizontal dashed lines are placed at zero for ΔStorage and retention.

At seasonal time scales, Iron Gate TP retention as a percent of inflow was generally low or negative, ranging from -6% to +16% across the summarized seasonal periods (Table 7). Over the entire May 2005 to December 2007 study period, 28 metric tons (MT) or 5±3% of the total inflow load of 606 MT of TP was retained (Table 7). Overall Iron Gate TP retention was positive but low for both May-May calendar years (+4%), near-zero for the May-December periods (+2%) and May-September periods (-1%), and positive (+4%) for the December 2005-May 2006 period.

3.5.2.2 Nitrogen

On a whole season basis KRAI (Copco Outflow) contributed 98.6% of the TN load to Iron Gate (Appendix A3). Unlike TP load, there was not a pronounced April 2005 loading peak (Figure 26b). TN loading followed a similar pattern to Copco, with seasonal lows in June or July (varied by year), and then rising until reaching highs in November or December. TN loading increased substantially with the onset of high flows in December 2006 and remained high until flows subsided in July 2006. Small tributaries (Jenny Creek, Fall Creek, and others) represented a maximum of 3.5% of the total TN load in the late April/early May 2005 sampling period (Appendix A3). Atmospheric input was very low for all time periods, never exceeding 0.6% of total input load. TN storage followed a similar temporal pattern as TN loading, except lows were in May instead of June/July.

From mid-May through December, retention fluctuated from period to period but was generally positive, with only limited periods with negative values.

At seasonal time scales, Iron Gate TN retention as a percent of inflow was higher than TP and positive for all summarized periods, with values ranging from +1% to +17% (Table 8). Over the entire May 2005 to December 2007 study period, 414 metric tons (MT) or 7±2% of the total inflow load of 5913 MT of TP was retained (Table 8, Figure 29). The overall Iron Gate TN retention was +6% for the two May-May calendar years, +9% for the three May-December periods, +14% for the three May-September periods, and +7% for the December 2005-May 2006 period.

3.5.3 Combined Analysis of Iron Gate and Copco Reservoirs

The above analyses for Copco and Iron Gate Reservoirs separately are intended to allow for evaluation of management actions that may apply to the reservoirs individually. However, the combined effect of the reservoirs in tandem was also evaluated by calculating net retention for the entire reservoir system by summing daily retention values for each reservoir. Combined retention as a percent of inflow was calculated as the combined retention divided by the sum of the external input loads (Klamath River above Copco + Shovel Creek + Copco other tributaries + Copco atmospheric input + Jenny Creek + Fall Creek + Iron Gate other tributaries + Iron Gate atmospheric input). Note that for purposes of this combined analysis, KRAI was not included because it is a linkage between the two reservoirs and not an additional external input.

The results of the combined retention, as well the individual retentions and inflows are shown in Table 7, Table 8, Figure 27, and Figure 28. Overall retention summaries including uncertainty estimates are shown in Figure 29 and Figure 30. Additionally, Appendix A5 contains charts with the same formatting as Figure 27 and Figure 28 but showing the various seasonal summary periods.

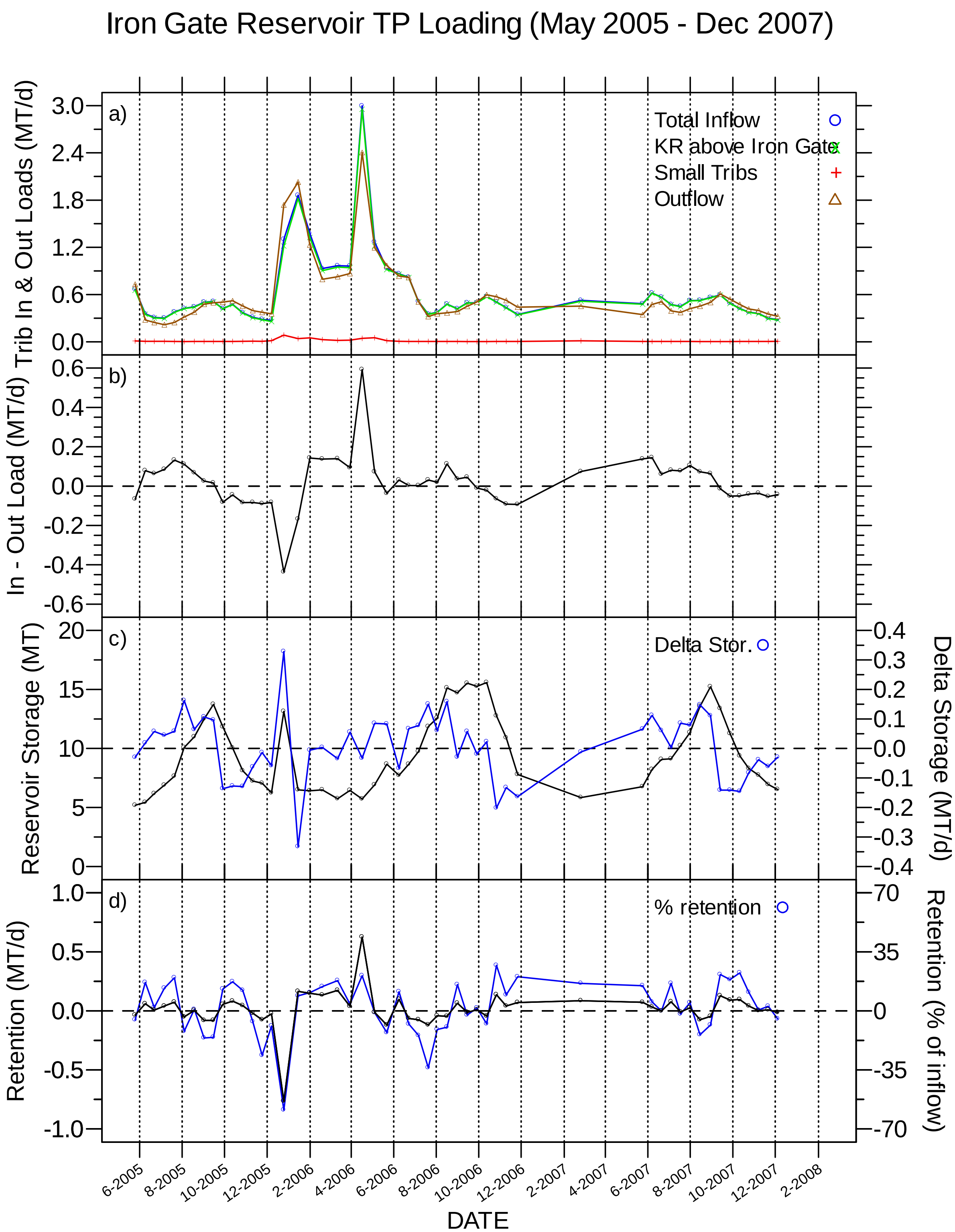

Figure 25. Time series of Iron Gate Reservoir total phosphorus loading, May 2005 – Dec 2007. Each point represents data from an entire sampling interval (~biweekly) and is placed at the midpoint of the two adjacent sampling dates. Horizontal dashed lines are placed at zero for ΔStorage and retention.

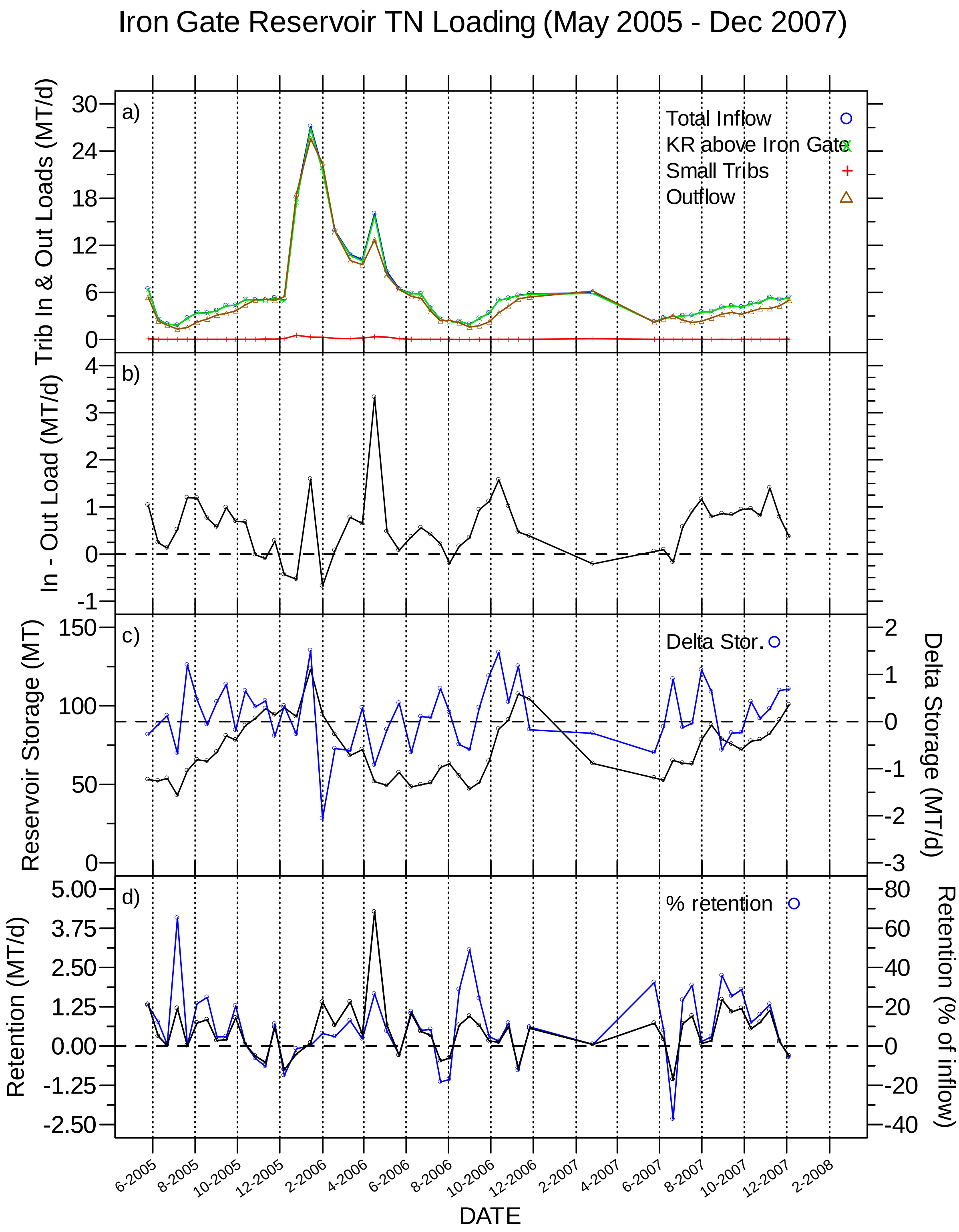

Figure 26. Time series of Iron Gate Reservoir total nitrogen loading, May 2005 – Dec 2007. Each point represents data from an entire sampling interval (~biweekly) and is placed at the midpoint of the two adjacent sampling dates. Horizontal dashed lines are placed at zero for ΔStorage and retention.

Seasonal patterns in retention were generally similar in Iron Gate and Copco, thus the combined retention of the two reservoirs is often, though not always, more positive or more negative than the separate retention of each reservoir. On a relative (as percent of inflow) basis at most seasonal time scales, TN retention was higher than relative TP retention, except for January through May 2006 when relative retention for TP and TN were similar and both were consistently positive. Although there was some variation among years in relative retention for the various summary periods for both TN and TP, these inter-annual differences in relative percent retention were generally less than 10% (Figure 29, Figure 30, Table 7, and Table 8). The only exception to this occurs when comparing the December 2005-May 2006 and December 2006-May 2007 periods; however, that result may be an artifact of the lack of samples collected during December 2006-May 2007. The standard error bars indicate that years were not significantly different from each other for the May – May and December – May periods (Figure 29, Figure 30).

Over the entire study period, Iron Gate and Copco Reservoirs retained 60 MT or 9±4% of the total 638 MT of TP inflow (Table 7, Figure 27), with the vast majority of that positive retention occurring in the winter and spring months. Combined TP retention was +11% for the two May-May calendar years (9±6% for May 2005-May 2006, 13±7% for May 2006-May 2007), 0% for the three May-December periods (-8±8% in 2005, 1±8% in 2006, 3±8% in 2007), -8% for the three May-September periods, and +17% for the December 2005-May 2006 period (Table 7, Figure 29).

Across the summary periods, flow-weighted average (calculated by dividing total load by total flow for both inputs and outputs to the combined complex of Iron Gate and Copco Reservoirs, including tributaries to account for dilution) outflow TP concentrations were often, but not always, lower than the combined inflow concentrations, with outflow concentrations ranging from 73 to 104% as a percent of inflow (Table 7, Figure 27). During the May-December period that encompasses turnover, TP concentrations were slightly higher than inflow in two of three years, and outflow concentrations were within 10% of inflow concentrations for each of the three May-Sep periods. As expected based on retention characteristics, the winter-spring periods (Dec-May) showed larger decreases in TP concentrations relative to summer –fall periods (Table 7).

Over the entire study period, Iron Gate and Copco Reservoirs retained 845 MT or 13±3% of the total 6384 MT of TN inflow (Table 8, Figure 28). Combined TN retention was +12% for the two May-May calendar years (12±4% for May 2005 to May 2006, 12±5% for May 2006 to May 2007), 15% for the three May-December periods (10±5% in 2005, 14±5% in 2006, 18±5% in 2007), 23% for the three May-September periods, and +13% for the December 2005-May 2006 period (Table 8, Figure 30).

In all summary periods, flow-weighted average Iron Gate outflow TN concentrations were lower than combined Iron Gate/Copco inflow concentrations, with outflow concentrations ranging from 68 to 97% as a percent of inflow (Table 8, Figure 28). For the entire study (May 2005-December 2007) outflow concentration was 85% of inflow concentration, with larger decreases in TN concentration occurring across the three May-September (outflow was 69% of inflow) and May-December (outflow was 77% of inflow) periods.

Total Phosphorus Mass Balances for Period: 5/18/2005 12/11/2007

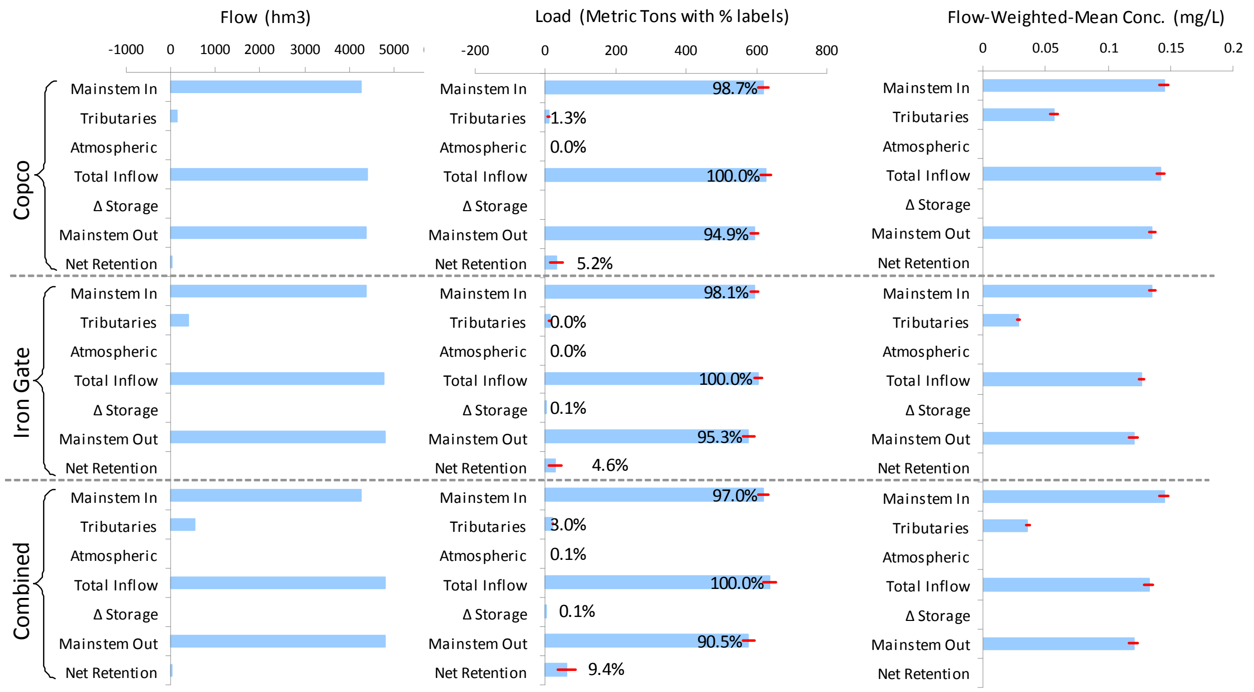

Figure 27. Summary of phosphorus mass-balances for the period 5/18/2005 to 12/11/2007 for Iron Gate, Copco, and the two reservoirs combined. Atmospheric is wetfall and dryfall (included only for load).

Total Nitrogen Mass Balances for Period: 5/18/2005 12/11/2007

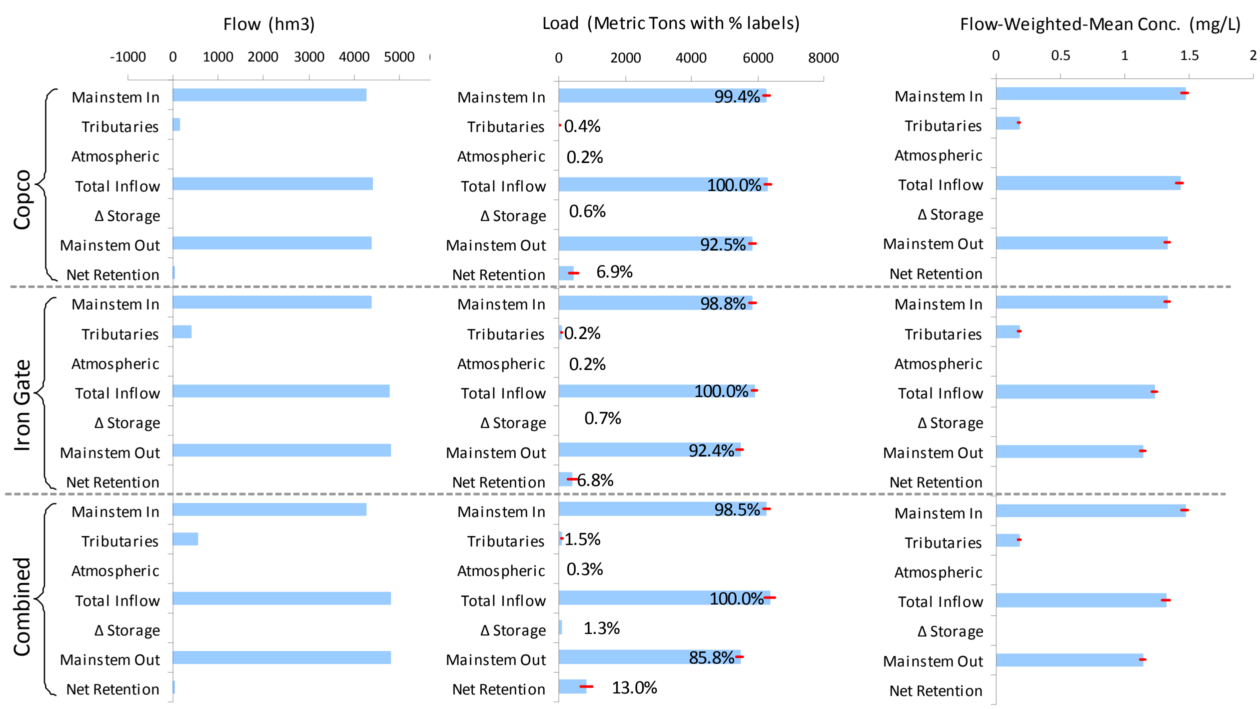

Figure 28. Summary of nitrogen mass-balances for the period 5/18/2005 to 12/11/2007 for Iron Gate, Copco, and the two reservoirs combined. Atmospheric is wetfall and dryfall (included only for load).

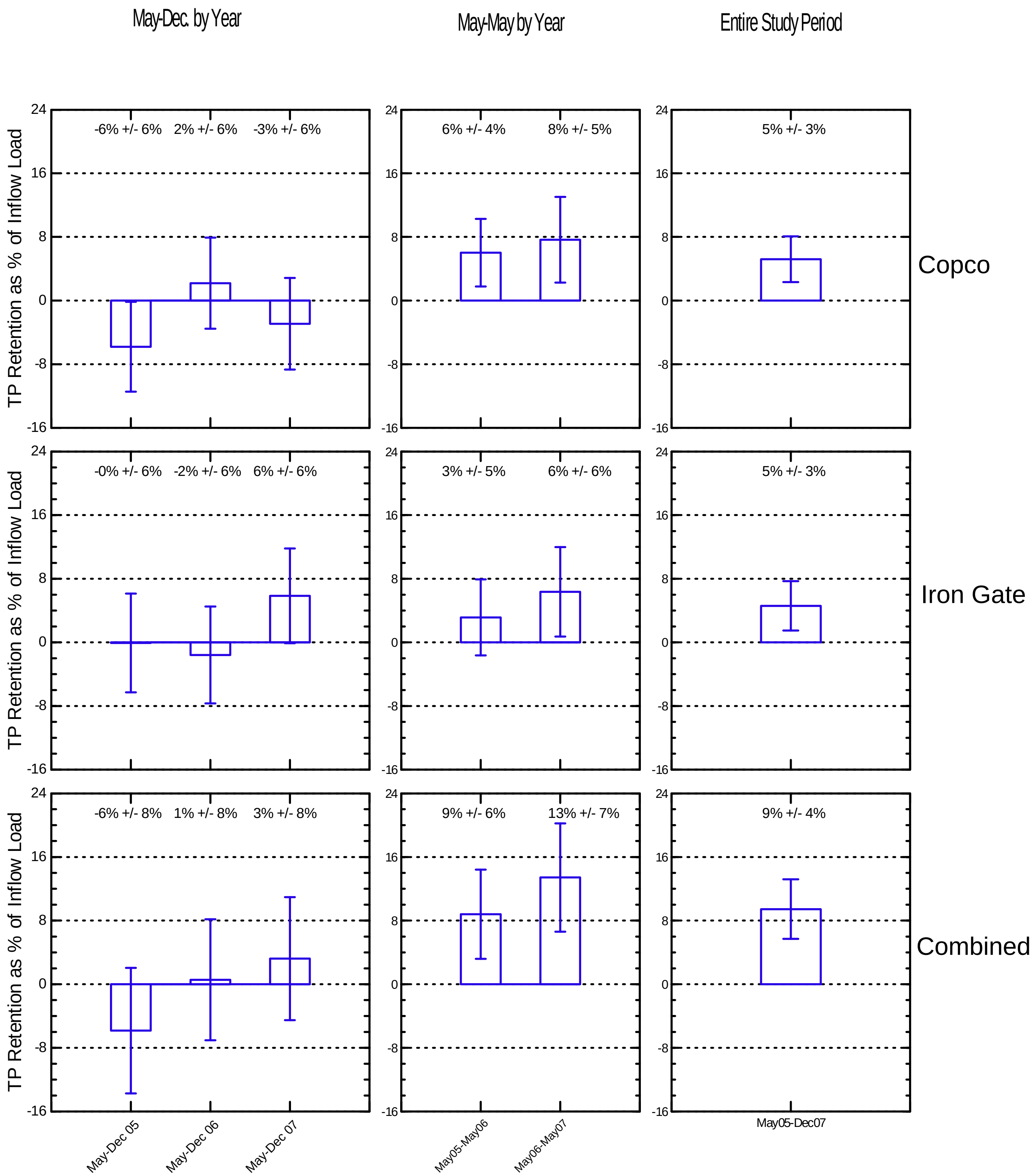

Figure 29. Summary of phosphorus retention in Iron Gate and Copco Reservoirs (separately and combined) for the various time periods: May-December of each year, May-May calendar years, and the entire study. Height of bars and labels on graphs are percent retention for the period (expressed as a percent of inflow), error bars are +/- one standard error.

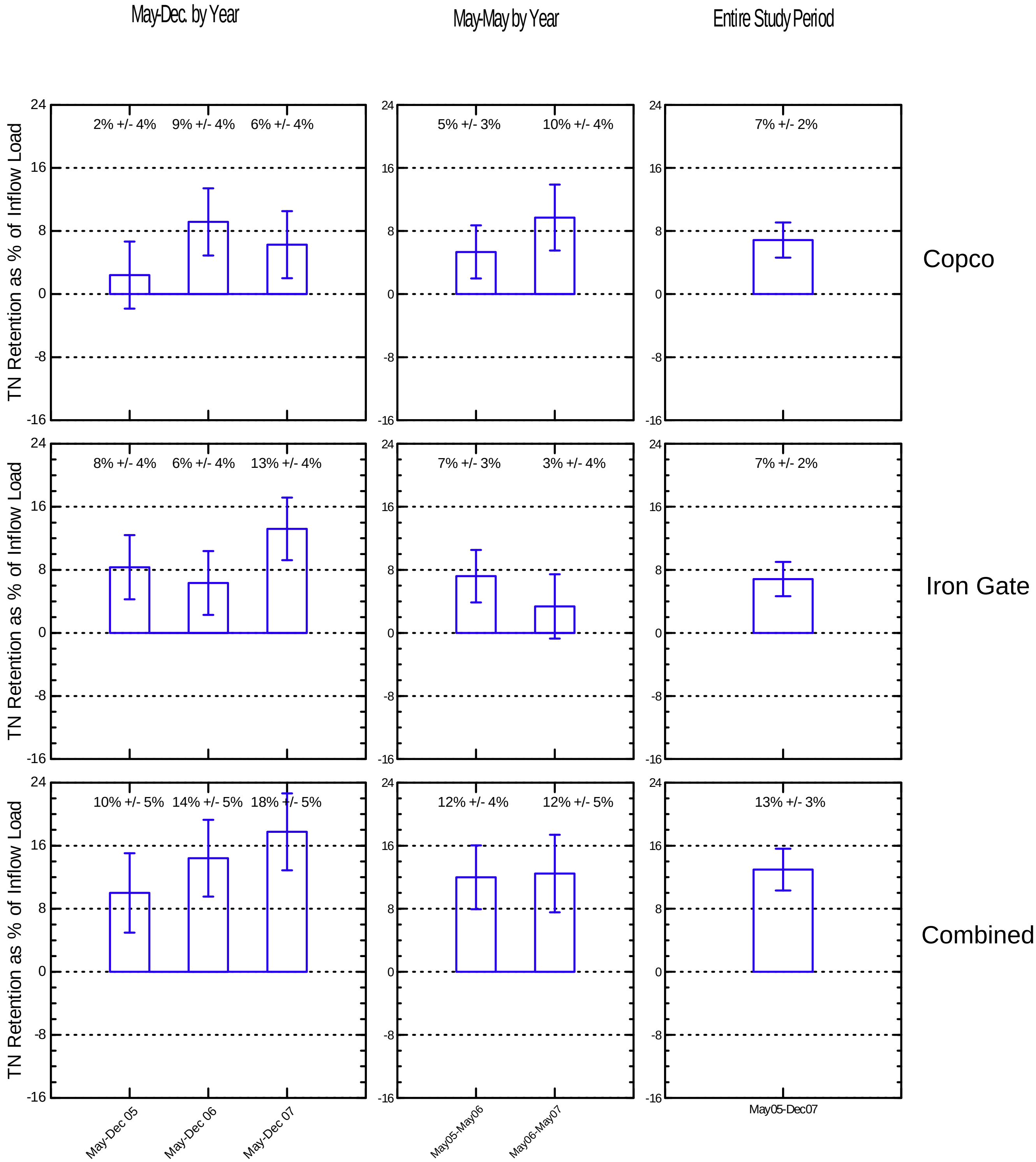

Figure 30. Summary of nitrogen retention in Iron Gate and Copco Reservoirs (separately and combined) for the various time periods: May-December of each year, May-May calendar years, and the entire study. Height of bars and labels on graphs are percent retention for the period (expressed as a percent of inflow), error bars are +/- one standard error.

Table 7. Total phosphorus flow-weighted average concentration, inflow, and retention for Copco and Iron Gate Reservoirs, May 2005 - December 2007, summarized by seasonal summary period.

				TP Flow-weighted Conc. for IG & Copco Combined			Total Phosphorus Inputs			Total Phosphorus Retention					
				(mg/L)		(%)	(total metric tons)			(total metric tons)			(percent of inflow)		
Summary Period	**Interval Start**	**Interval End**	**Days in Interval**	**In**	**Out**	**Out as % of In**	**Copco**	**Iron Gate**	**IG & Copco**	**Copco**	**Iron Gate**	**IG & Copco**	**Copco**	**Iron Gate**	**IG & Copco**
Entire study	5/17/05	12/11/07	939	0.133	0.120	90	626.51	605.80	638.06	32.5	28.0	60.5	5	5	9
may05may06	5/18/05	5/17/06	365	0.131	0.117	89	327.00	312.73	334.69	19.6	9.9	29.5	6	3	9
may06may07	5/18/06	5/17/07	365	0.131	0.115	88	207.28	195.34	210.29	15.7	12.4	28.1	8	6	13
may-may all	5/18/05	5/17/07	730	0.131	0.116	89	534.27	508.07	544.98	35.3	22.3	57.5	7	4	11
may-dec2005	5/18/05	12/11/05	208	0.120	0.125	104	78.12	84.48	79.45	-4.6	0.0	-4.7	-6	0	-6
may-dec2006	5/18/06	12/11/06	208	0.134	0.136	102	110.56	111.37	111.59	2.8	-0.7	2.1	3	-1	2
may-dec2007	5/18/07	12/11/07	208	0.148	0.146	98	92.23	97.73	93.08	-2.8	5.7	2.9	-3	6	3
may-dec all	5/18/05	12/11/07	624	0.134	0.135	101	280.90	293.58	284.13	-4.6	4.9	0.3	-2	2	0
may-sept2005	5/18/05	9/30/05	136	0.131	0.121	92	55.57	58.70	56.36	-6.3	-0.4	-6.7	-11	-1	-12
may-sept2006	5/18/06	9/30/06	136	0.134	0.126	94	80.86	78.98	81.59	-1.7	-4.7	-6.4	-2	-6	-8
may-sept2007	5/18/07	9/30/07	136	0.176	0.158	90	69.78	72.12	70.31	-6.3	3.5	-2.7	-9	5	-4
may-sept all	5/18/05	9/30/07	408	0.145	0.133	92	206.21	209.80	208.26	-14.3	-1.6	-15.8	-7	-1	-8
dec05-may06	12/12/05	5/17/06	157	0.136	0.115	85	248.88	228.25	255.24	24.2	9.9	34.1	10	4	13
dec06-may07*	12/12/06	5/17/07	157	0.127	0.092	73	96.72	83.97	98.69	12.9	13.1	26.0	13	16	26
dec-may all*	12/12/05	5/17/07	314	0.133	0.108	81	345.60	312.21	353.94	37.1	23.0	60.1	11	7	17

* No samples were collected from mid-December 2006 to mid-May 2007, so results for that period were estimated based on the multiple regression loading model and hence are less reliable than the rest of the time periods.

Table 8. Total nitrogen flow-weighted average concentration, inflow, and retention for Copco and Iron Gate Reservoirs, May 2005 - December 2007, summarized by seasonal summary period.

				Total Nitrogen Flow-weighted Concentration for IG & Copco Combined			**Total Nitrogen Inputs**			**Total Nitrogen Retention**					
				(mg/L)		**(%)**	**(total metric tons)**			**(total metric tons)**			**(percent of inflow)**		
Summary Period	**Interval Start**	**Interval End**	**Days in Interval**	**In**	**Out**	**Out as % of In**	**Copco**	**Iron Gate**	**IG & Copco**	**Copco**	**Iron Gate**	**IG & Copco**	**Copco**	**Iron Gate**	**IG & Copco**
Entire study	5/17/05	12/11/07	939	1.335	1.138	85	6301.4	5912.8	6383.8	431.4	413.9	845.3	7	7	13
may05may06	5/18/05	5/17/06	365	1.353	1.183	87	3389.5	3266.7	3442.7	180.5	238.9	419.4	5	7	12
may06may07	5/18/06	5/17/07	365	1.259	1.094	87	2003.0	1832.0	2025.7	193.6	65.0	258.6	10	4	13
may-may all	5/18/05	5/17/07	730	1.316	1.149	87	5392.5	5098.7	5468.4	374.0	303.9	678.0	7	6	12
may-dec2005	5/18/05	12/11/05	208	1.332	1.074	81	873.3	833.1	883.1	20.4	71.5	91.9	2	9	10
may-dec2006	5/18/06	12/11/06	208	1.235	0.944	76	1021.8	892.8	1029.2	97.7	59.4	157.1	10	7	15
may-dec2007	5/18/07	12/11/07	208	1.457	1.064	73	909.0	814.1	915.4	57.3	110.0	167.3	6	14	18
may-dec all	5/18/05	12/11/07	624	1.331	1.021	77	2804.1	2540.0	2827.6	175.5	240.9	416.3	6	9	15
may-sept2005	5/18/05	9/30/05	136	1.245	0.843	68	530.1	467.5	535.6	37.9	80.2	118.1	7	17	22
may-sept2006	5/18/06	9/30/06	136	1.050	0.758	72	633.0	508.1	637.8	101.7	44.0	145.6	16	9	23
may-sept2007	5/18/07	9/30/07	136	1.379	0.937	68	547.1	453.3	551.0	66.7	73.1	139.8	12	16	25
may-sept all	5/18/05	9/30/07	408	1.200	0.833	69	1710.3	1428.8	1724.4	206.2	197.3	403.5	12	14	23
dec05-may06	12/12/05	5/17/06	157	1.360	1.222	90	2516.1	2433.6	2559.6	160.0	167.5	327.5	6	7	13
dec06-may07*	12/12/06	5/17/07	157	1.285	1.253	97	981.2	939.2	996.5	95.9	5.6	101.5	10	1	10
dec-may all*	12/12/05	5/17/07	314	1.338	1.231	92	3497.4	3372.8	3556.1	255.9	173.1	429.0	7	5	12

* No samples were collected from mid-December 2006 to mid-May 2007, so results for that period were estimated based on the multiple regression loading model and hence are less reliable than the rest of the time periods.

3.5.4 Comparison with previous Klamath Reservoir and other literature studies

3.5.4.1 Previous Klamath Reservoir Studies

Previous mass-balance studies of the Iron Gate and Copco Reservoirs have included U.S. EPA (1978) and Kann and Asarian (2005), and are discussed in Kann and Asarian (2007).

Methodological improvements between this study and the previous Kann and Asarian (2007) study resulted in small changes (maximum absolute change was 8%) in estimated retention. For example, the combined Iron Gate and Copco retention for mid-May 2005 to mid-December 2005 decreased from +2% (Kann and Asarian 2007) to -6% (this study) for TP and from +17% to +10% for TN. From mid-May 2005 to mid-May 2006, the combined retention for Iron Gate and Copco decreased from +12% to +9% for TP and from 18% to 12% for TN. The retention differences are likely due to a more accurate accounting of the effects of hydropower peaking (resulting in decreased estimates for KRAC concentrations during most of 2005, see Appendix A2 for details), the incorporation of both ungaged flows between the Boyle USGS gage and KRAC and between the KRAC and KRBI), and use of multiple regression models to estimate load.

3.5.4.2 Other Literature Studies

Previously in Kann and Asarian (2007) observed retention was compared to estimated retention from a variety of cross-sectional lake and reservoir studies that developed empirical models to predict nutrient retention from a combination of parameters including annual hydraulic residence time (HRT), inflow nutrient load, volume-weighted mean inflow, and volume-weighted reservoir concentration (e.g., Walker 1985; Kronvang 2004). Similar to those comparisons, observed retention values in this study also fall within the range expected based upon systems with similar morphometric and hydraulic characteristics.

For example, maximum annual TP retention ranges as a percent of inflow observed in this study for Copco (2% to 13%) and Iron Gate (-2% to 12%) were within the range predicted by the Vollenweider and Canfield/Bachman models for natural lakes (Table 9). As noted in Kann and Asarian (2007), while the predictions using equations developed for reservoirs were higher than the observed values for Copco and Iron Gate, reasons for the lower values observed in this study include 1) likely P release from bottom sediments (a phenomenon known to occur in the type of prolonged anaerobic conditions observed in 2005-2007; Figure 6 and Figure 7), and 2) unlike many reservoirs that can efficiently trap particulate P, the dissolved fraction of inflow P (SRP) in this system is generally >70% (Figure 15) for much of the May-November period when retention was generally low and periodically negative.

Likewise, annual TN retention ranges as a percent of inflow observed in this study for Copco (2% to 14%) and Iron Gate (-1% to 10%) were also within the range predicted by both the Walker (1985) and Kronvang (2004) models (Table 9).

Table 9. Comparison of predicted Copco and Iron Gate retention as a percent of inflow[1] to observed retention values calculated from this study.

Model Source	Model	Retention as a % of Inflow: Copco	Retention as a % of Inflow: Iron Gate
		TP	
Walker (1985)	BATHTUB - Reservoirs	26%	27%
Walker (1985)	Vollenweider - Northern Natural Lakes	12%	14%
Walker (1985)	Canfield/Bachman – Reservoirs	29%	29%
Walker (1985)	Canfield/Bachman - Natural Lakes	11%	12%
Kronvang et al. (2004)	Tier 4 P retention model (equation 10, p. 40)	1.4%	-1.9%
		TN	
Walker (1985)	Model 05 (p72)	10.3%	9.4%
Kronvang et al. (2004)	Tier 3 N retention model (equation 3, p. 25)	8.7%	9.5%
		TP Range (±1SD)	
This Study May 2005 to December 2007	Computed from Mass Balance	2% to 8%	2% to 8%
This Study May 2005 to May 2006	Computed from Mass Balance	2% to 10%	-2% to 8%
This Study May 2006 to May 2007	Computed from Mass Balance	3% to 13%	0% to 12%
		TN Range (±1SD)	
This Study May 2005 to December 2007	Computed from Mass Balance	5% to 9%	5% to 9%
This Study May 2005 to May 2006	Computed from Mass Balance	2% to 8%	4% to 10%
This Study May 2006 to May 2007	Computed from Mass Balance	6% to 14%	-1% to 7%

[1] Predicted based on the above literature equations using May 2005 – May 2006 input parameters-- see Kann and Asarian 2007 for details,

4. CONCLUSIONS

The study described herein examined longitudinal, temporal, and depth trends in physical and chemical water quality in Copco and Iron Gate Reservoirs from May 2005 to December 2007.

Both reservoirs thermally stratified during the warm summer months, with the deeper waters (hypolimnion) in both reservoirs exhibiting low levels of dissolved oxygen as well as high concentrations of NH_3 and SRP. The upper water column layers (epilimnion) in both reservoirs hosted large blooms of phytoplankton (as evidenced by chlorophyll *a*) and had elevated pH. Concentrations of total nitrogen (TN) were consistently lower at Klamath River below Iron Gate than Klamath River above Copco for the July through October period, while total phosphorus (TP) concentrations were lower at Klamath River below Iron Gate for the mid-July through August period in 2005 and 2007, and from mid-July through September in 2006. This is likely due to 1) nutrient storage in the water column and sediments of the reservoirs, 2) penstock intakes that draw water from intermediate depths where concentrations are lower, and 3) possible atmospheric losses through denitrification (for nitrogen only). Higher TP concentrations were generally observed below Iron Gate than above Copco for the September-November period, likely reflecting internal loading and residence time.

Over the entire 31-month study period (May 2005-December 2007), the combined retention of Iron Gate and Copco Reservoirs was 9±4% of TP inflow. For the two years where May to May data were available, the total combined TP retention was 11% (9±6% for May 2005-May 2006, 13±7% for May 2006-May 2007), with a majority of that retention occurring in the winter and spring period of high flow when the percent of TP comprised of particulate P was high. During the main reservoir phytoplankton growing season (May 18-September 30 for 2005, 2006 and 2007) the total combined TP retention was -8% (-12% in 2005, -8% in 2006, -4% in 2007), while for the period encompassing turnover (May 18-December 11 for 2005, 2006 and 2007) it was 0% (-8±8% in 2005, 1±8% in 2006, 3±8% in 2007). Relatively low TP retention during the growing season period is likely due to a combination of two factors: 1) a high percentage of the incoming phosphorus load was in dissolved form, which is less likely to settle than particulate phosphorus, and 2) in many reservoirs, internal phosphorus loading commonly occurs during the type of low and prolonged dissolved oxygen conditions observed in this study. The pattern of flow-weighted average TP concentration was similar to that of retention, with outflow TP concentrations ranging from 73% to 104% of inflow concentrations across the various summary periods. During the May-December period that encompasses turnover, TP concentrations were slightly higher than inflow in two of three years, and outflow concentrations were within 10% of inflow concentrations for each of the three May-Sep periods.

Over the entire study period (May 2005-December 2007), the combined retention of Iron Gate and Copco Reservoirs was 13±3% of TN inflow. For the two May to May years, combined TN retention was 12% (12±4% for May 2005 to May 2006, 12±5% for May 2006 to May 2007). For the main reservoir phytoplankton growing season (May 18-September 30 for 2005, 2006 and 2007) total combined TN retention was 23% (22% in 2005, 23% in 2006, 25% in 2006), while for the period encompassing turnover (May 18-December 11 for 2005, 2006 and 2007) it was 15% (10±5% in 2005, 14±5% in 2006, 18±5% in 2007). Higher percent retention during summer months may reflect settling of organic matter and algal material, and/or denitrification. The pattern of flow-weighted average TN concentrations was similar to that of retention, with outflow TN concentrations ranging from 68% to 97% of inflow concentrations across the various summary periods. For the entire study (May 2005-December 2007) outflow concentration was 85% of inflow concentration, with larger decreases in TN concentration occurring across the three May-September (outflow was 69% of inflow) and May-December (outflow was 77% of inflow) periods. The relatively greater reduction in TN concentration vs. TP concentration in the outflow had the effect of lowering TN:TP ratios relative to upstream values.

For TN and TP, although variation in relative retention occurred among years for the various summary periods, these inter-annual differences were less than ~10% of inflow and uncertainty analysis indicates they were not significantly different.

Overall combined net retention accounted for a relatively low (11% for TP, and 12% for TN) percentage of inflow on an annual basis. However, observed values are generally within the range predicted using models developed from a broad range of lakes and reservoirs that incorporate inflow loading and other hydraulic characteristics. These retention values reflect the net effect of nutrient gains (e.g., fixation of atmospheric nitrogen by blue-green algae, ammonification of organic sediment material, and P release from sediments) and losses (e.g., settling of inorganic and organic matter or denitrification).

In summary, these results provide a robust assessment of nutrient loading and reservoir retention dynamics for the three year period from May 2005 through December 2007, and can be utilized to evaluate various Klamath River water quality management actions as well as the potential effects of current proposals to remove Copco and Iron Gate Reservoirs.

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