KLAMATH RIVER NUTRIENT LOADING AND RETENTION DYNAMICS IN FREE-FLOWING REACHES, 2005-2008

PREPARED FOR THE

YUROK TRIBE ENVIRONMENTAL PROGRAM

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EXECUTIVE SUMMARY

This study quantified nutrient retention (seasonal removal and/or release) rates in free-flowing reaches of the Klamath River during the months of June-October from 2005-2008. Understanding these processes will inform predictions of Klamath River water quality response subsequent to major management changes such as dam removal and alterations in upstream nutrient loads. High levels of nutrients (nitrogen [N] and phosphorus [P]) in some Klamath River reaches can cause excessive growths of algae, resulting in degraded water quality conditions (elevated pH and reduced dissolved oxygen levels) that are stressful to fish. Natural river processes such as denitrification, organic matter burial in bottom sediments, sediment sorption, and plant (attached algae and macrophytes) and microbial uptake can remove nutrients from rivers, resulting in improved downstream water quality.

The Klamath River of southern Oregon and northern California is one of the major salmon rivers of the western United States. The Klamath River is listed as an impaired water body on the Clean Water Act (CWA) Section 303(d) list. The U.S. Environmental Protection Agency (U.S. EPA), Oregon Department of Environmental Quality (ODEQ), and the California North Coast Regional Water Quality Control Board (NCRWQCB) are in the process of developing Total Maximum Daily Load (TMDL) regulations for the Klamath River, and PacifiCorp Energy, the owner and operator of the Klamath Hydroelectric Project (Project) is in the process of relicensing the Project with the Federal Energy Regulatory Commission.

The overall goals of this study were to 1) collect and analyze detailed nutrient and hydrologic data for the Klamath River, 2) construct mass-balance nutrient budgets to evaluate nutrient dynamics in various free-flowing reaches of the Klamath River, including longitudinal trends in absolute and relative retention of phosphorus and nitrogen, and 3) compare nutrient retention rates between free-flowing river reaches and reservoir reaches.

Hydrologic and nutrient data from the Karuk Tribe, Yurok Tribe, U.S. Geological Survey, PacifiCorp, U.S. Bureau of Reclamation, and ODEQ were assembled for mainstem and tributary stations to compute nutrient loading for various free-flowing Klamath River sites during June-October of 2005-2008. Nutrient parameters examined included total phosphorus (TP), soluble reactive phosphorus (SRP), particulate phosphorus (PP), total nitrogen (TN), total inorganic nitrogen (TIN), and organic nitrogen (ON). Sampling frequency varied by station and year, but generally occurred at monthly to weekly frequencies.

Sampling frequency generally increased over the years, with fewer samples collected in 2005 compared to 2008. Mass-balance nutrient budgets were constructed and summarized on seasonal time scales (June 1 - October 20 and July 1 - September 30) to assess temporal nutrient dynamics and the relative fate of nutrients in each of the assessed river reaches.

Unless otherwise noted, report results pertain to these seasonal time scales, not entire hydrologic or calendar years. The analyses reflect seasonal nutrient dynamics, not long-term loss or removal of nutrients at annual time scales. The five primary river reaches evaluated were: Keno Dam to Above Copco Reservoir (Reach 1), Iron Gate Dam to Seiad Valley (Reach 4), Seiad Valley to Orleans

(Reach 5), Orleans to Above Trinity (Reach 6), and Above Trinity to Turwar (Reach 7). Net nutrient retention for the various reaches was computed by parameter as the difference between inflow nutrient load [mainstem + gaged and un-gaged tributaries] and outflow nutrient load. Negative retention values denote a source from within the system (e.g., sediment or algal regeneration and nitrogen fixation), and positive values denote a sink (e.g., storage in algae/plant or bacterial biomass, denitrification, and ammonia volatilization).

By using improved methodologies (i.e., flow- and season-based multiple regression models for predicting daily nutrient concentrations and loads, and quantification of uncertainty), higher quality data (i.e., lower laboratory reporting limits and higher sampling frequency), and inclusion of nutrient parameters other than total nitrogen, the current study provides a more robust analysis than a previous study of 1998-2002 data (Asarian and Kann 2006).

Due to a combination of factors including tributary dilution and retention in reservoir and river reaches, flow-weighted average June-October concentrations of phosphorus parameters all exhibited large (~10x) decreases from Keno Dam to Turwar. Flow-weighted average June-October concentrations of nitrogen parameters also exhibited large (~10x for total nitrogen and organic nitrogen, ~40x for total inorganic nitrogen) decreases from Keno Dam to Turwar.

Mass-balance nutrient budgets for individual reaches indicated that mainstem inflows were the dominant budget term generally accounting for >90% of inflow load in 2008. Across the entire Iron Gate to Turwar aggregated reach (Reach 4+5+6+7) for June-October 2008 (used as an example, because it had sufficient data for all primary reaches), the mainstem Klamath at Iron Gate accounted for ~65-85% (varied by parameter) of total inflow load, gaged tributaries accounted for ~5-20%, and ungaged tributaries contributing the remaining ~5-10%.

Phosphorus retention varied by year and parameter. Across the entire study period (i.e., mean of all years that had adequate data for each site), TP and SRP retention during the June-October and July-September periods was positive for the five primary river reaches. Overall, there appeared to be a longitudinal trend of increasing TP and SRP retention with increasing distance downstream of Iron Gate, and decreasing (or more negative) PP retention. On both a relative and absolute basis, the furthest downstream reach (Reach 7: Above Trinity to Turwar) had the most positive SRP retention and most negative PP retention, suggesting a shift in form from dissolved to particulate as well as an overall retention of phosphorus (TP retention was positive) in Reach 7. TP retention appeared to be positive overall for Reach 1 (Keno to Copco); however, uncertainty was high (possibly due to highly variable Keno TP concentrations) indicating that calculated TP retention in that reach was likely not significantly different from zero.

Nitrogen retention parameters showed clearer longitudinal patterns with less year-to-year variability. For example, a strong declining downstream retention trend was observed on both a relative and absolute basis, with TN retention highest in Reach 1 (Keno to Copco; 24.69 kg/day per mile and 0.47 percent/mile) and lowest (negative) in Reach 7 (Above Trinity to Turwar) for the July-September period. With the exception of Reach 7 (Above Trinity to Turwar) for 2007-2008 (the only years of adequate data for that reach) and Reach 4 (Iron Gate to Seiad) in 2005, TN retention was positive for both the June-October and July-September periods for all other reaches and years.

On a relative basis TN retention was higher in the July-September period than in the June-October period at all five reaches; on an absolute basis it was higher at four of five reaches. TIN also showed a strong longitudinal trend, with higher absolute retention rates at the first two reaches below Iron Gate Dam (Reaches 4 [Iron Gate to Seiad] and 5 [Seiad to Orleans] where TIN was generally present at concentrations >0.05 mg/L), lower rates at Reach 6 (Orleans to Above Trinity), and negative rates at Reach 7 (Above Trinity to Turwar). Relative TIN retention rates within Reaches 4 and 5 were similar to each other (0.86±0.12 and 0.95±0.17 percent/mile for July-September, respectively), with remarkably low year-to-year variation. Both relative and absolute ON retention rates were generally lower than for TIN and TN in Reaches 4 and 5, but were higher in Reach 7. The results of this study largely confirm the trends of a previous analysis (Asarian and Kann 2006) of TN dynamics in free-flowing reaches of the Klamath River for the years 1998-2002. The current results are based on more robust dataset and analysis, but nonetheless, values are in a similar range and show similar longitudinal trends in retention.

The observed negative retention rates for TN and TIN in Reach 7 (Above Trinity to Turwar) are likely due in part to very low incoming concentrations of TIN (the form of nitrogen most easily assimilated by periphyton) leaving nearly zero TIN available for algal uptake in the reach. The lack of TIN in the water column likely provides a competitive advantage to nitrogen-fixing species (particularly the diatom *Epithemia sorex* that associates with endosymbiotic blue-green algae), which dominate the periphyton communities in the mainstem Klamath River from Orleans (and perhaps farther upstream, there are only very limited samples between Seiad and Orleans) to Turwar in the low-flow season.

For nitrogen parameters, reach inflow concentrations appeared to be a major driver of retention rates. On both an absolute and relative basis, TN retention showed a clear pattern of higher retention in reaches with higher inflow TN concentrations. ON retention exhibited a similar pattern, but with more scatter. A similar trend was evident for TIN on an absolute basis, not only between reaches (as with TN) but also within reaches. These results have important implications for potential management changes. For example, if dam removal results in an increase in nitrogen concentrations at Iron Gate Dam, downstream retention rates are likely to rise in response to the increased concentrations. These increased retention rates downstream would then partially offset the effects of increased Iron Gate load on nitrogen concentrations in reaches farther downstream. The influence of concentration on retention rates would also need to be factored in when determining the effect of upstream management efforts (i.e., treatment wetlands and/or reduced agricultural runoff) on downstream concentrations.

The effect of retention across longer river distances was evaluated by aggregating adjacent primary reaches. These analyses indicate that large quantities of nitrogen and phosphorus are retained when longer river lengths were considered. For example, the Iron Gate nutrient load was reduced by 24% for TP, 25% for SRP, 21% for PP, 41% for TN, 93% for TIN, and 21% for ON during July-September 2007-2008 in the 130 miles from Iron Gate to Orleans. Load reductions for the June-October period were lower: 16% of TP, 24% of SRP, -9% of PP, 34% of TN, 82% of TIN, and 15% ON. Both nutrient retention and tributary dilution contribute to reducing nutrient concentrations in the Klamath River as water flows downstream from Iron Gate Dam.

An evaluation of the relative effect of dilution/retention indicates that although tributary dilution generally has a proportionally greater effect on concentration reduction, retention is also an important factor. For example, in the July-September periods of 2007-2008, flow-weighted average TN concentrations decreased from 1.055 mg/L at Iron Gate to 0.388 mg/L at Orleans, a decline of 63%. Of that 63% decline, 65% was due to dilution and 35% due to retention. The percent reductions in concentration due to retention were lower for phosphorus parameters and ON than for TN, but higher for TIN. These results have important implications for Klamath River water quality computer models, because under-representation of natural retention processes in a model could substantially over-estimate nutrient concentrations in the lower Klamath River. For example, in the Iron Gate to Seiad TN example cited above, a dilution-only (no retention) model would predict an Orleans concentration of 0.620 mg/L, 60% higher than the measured value of 0.388 mg/L.

To provide a range of estimates for how TP and TN concentrations at Iron Gate Dam might change under a dam removal scenario, relative retention rates in river reaches were compared with results from a study of the Copco-Iron Gate Reservoir complex by Asarian et al. (2009). TP concentrations are predicted to rise only 2-12% (e.g., from 0.144 mg/L to 0.147-0.150 mg/L for the June-October period) under a dam removal scenario. Increases in TN concentrations under dam removal are predicted to be larger than for TP, approximately 37-42% (from 0.910 mg/L to 1.250-1.288 mg/L) for June-October and 48-55% (0.950 mg/L to 1.404-1.469 mg/L) for July-September. The method used to make these comparisons does not take into account other changes that would likely accompany the removal of Iron Gate and Copco Reservoirs, such as the elimination of hydropower peaking and the return of full flows to the J.C. Boyle Bypass Reach, which are expected to have a beneficial (i.e., reducing) effect on river nutrient concentrations.

The potential effect of increased concentrations in the mainstem Klamath River at Iron Gate Dam on downstream reaches was explored by routing the load downstream in a stepwise fashion under two scenarios (with differing retention rates) and comparing with existing conditions for the years 2007-2008. The results of this analysis indicate that dam removal will result in only a very small increase in TP concentration in the Klamath River between Iron Gate and Turwar. TN concentrations will increase more than for TP, although the magnitude of the increase diminishes with increasing distance downstream of Iron Gate. The effect is substantially diminished by Orleans and quite small at Turwar.

Although estimated nutrient concentrations are predicted to increase in the mainstem Klamath River downstream of the dams following dam removal, the resulting effects on algal and macrophyte growth are complex and may vary by reach. If periphyton in the Klamath River between Iron Gate to Seiad are not nitrogen (or phosphorus) limited (see discussion in Section 4.1.3 regarding lack of N-fixing periphyton species), increases in nitrogen concentrations will not necessarily result in increased periphyton biomass but the effect on periphyton and macrophyte species composition is unknown. Increased N concentration expected with dam removal would likely shift N-fixing algae farther downstream (from their current upstream limit of approximately Seiad Valley), and upstream flora could be replaced by non N-fixers.

These observations provide an important point to consider when evaluating the effect of dam removal. For example, the current periphytic flora may enable N-fixation, thereby off-setting the effect of decreased N concentrations (due to both reservoir and natural retention) on plant biomass, and it is not clear that biomass of the non-fixers would be greater than that of the current flora. This is especially true because P is not expected to increase appreciably with dam removal, and in fact may even decrease at times. Whether or not a shift to P-limitation would occur under such a scenario is unclear; however, such factors as increased N, stable or decreasing P, N:P ratios, and N-fixation must be considered when evaluating the effect of dam removal on projected plant biomass and water quality in the river below Iron Gate dam.

Other reach-specific factors such as substrate, flow velocity, shading, light, and water temperature also affect biomass trends independent of nutrient dynamics. Such factors must be evaluated when attempting to determine algal or macrophyte biomass following dam removal. Additionally, upstream nutrient reductions (i.e., from treatment wetlands and/or reduced agricultural runoff) could offset the increases in nutrient concentration caused by dam removal. Finally, in determining the effect of dam removal on algal and plant biomass, the direct effect of dam presence or removal on sediment transport (and substrate), hydrology, light limitation, and days of biomass accrual should be evaluated.

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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 and drain into Upper Klamath Lake, the Link River and Lake Ewauna, where the Klamath River proper begins. From this point the mainstem river flows through a series of impoundments, including Keno, J.C. Boyle, Copco, and Iron Gate Reservoirs. Below Iron Gate Dam, the river flows 190 miles to the Pacific Ocean.

This study focuses on the Klamath River between Iron Gate Dam and Turwar (just upstream of the Klamath Estuary), but also contains some analyses of the Klamath River between Keno and Copco Reservoirs, Copco Reservoir, and Iron Gate Reservoir (Figure 1 and Figure 2).

1.2 BACKGROUND

The Klamath River is designated on the Clean Water Act (CWA) Section 303(d) list as an impaired water body. The listed impairments vary by state and reach, but include water temperature, nutrients, organic enrichment/low dissolved oxygen, sedimentation/siltation, ammonia toxicity, and chlorophyll *a* (NCRWQCB 2010). The U.S. Environmental Protection Agency (U.S. EPA), Oregon Department of Environmental Quality (ODEQ), and the California North Coast Regional Water Quality Control Board (NCRWQCB) are in the process of developing Total Maximum Daily Load (TMDL) regulations for the Klamath River, and PacifiCorp Energy, the owner and operator of the Klamath Hydroelectric Project (Project) is in the process of relicensing the Project with the Federal Energy Regulatory Commission. The California State Water Resources Control Board has authority under section 401 of the Clean Water Act to issue water quality certification for the Project. The study was designed to provide critical information for the development of the technical TMDL, the TMDL implementation plan, and for the water quality certification process.

The report was prepared using funds provided to the Yurok Tribe by the U.S. EPA. Data analysis and report writing were conducted by Kier Associates, Aquatic Ecosystem Sciences LLC, and William W. Walker.

1.3 PREVIOUS AND CURRENT KLAMATH NUTRIENT STUDIES

Asarian and Kann (2006) calculated mass-balance budgets for free-flowing reaches of the Klamath River below Iron Gate Dam using data from the years 1998-2002. Utilizing improved methodologies (e.g., flow- and season-based multiple regression models for predicting daily nutrient concentrations and loads), higher quality data (lower laboratory reporting limits and higher sampling frequency), and inclusion of nutrient parameters other than total nitrogen, the current study provides a major improvement over the previous effort.

Additional recent investigations of Klamath River nutrient dynamics include a computation of nutrient budgets for Iron Gate and Copco Reservoirs for the years 2002 (Kann and Asarian 2005), 2005-2006 (Kann and Asarian 2007), 2005-2007 (Asarian et al. 2009), a high-frequency study of two short free-flowing Klamath River reaches (Deas 2008), and two synthesis reports (Butcher 2008 and PacifiCorp 2006).

1.4 STUDY GOALS

The overall goals of this study were to 1) acquire and analyze detailed nutrient and hydrologic data for the Klamath River, 2) construct mass-balance nutrient budgets to evaluate nutrient dynamics in various free-flowing reaches of the Klamath River, including longitudinal trends in absolute and relative retention of phosphorus and nitrogen, and 3) compare nutrient retention rates between free-flowing river reaches and reservoir reaches.

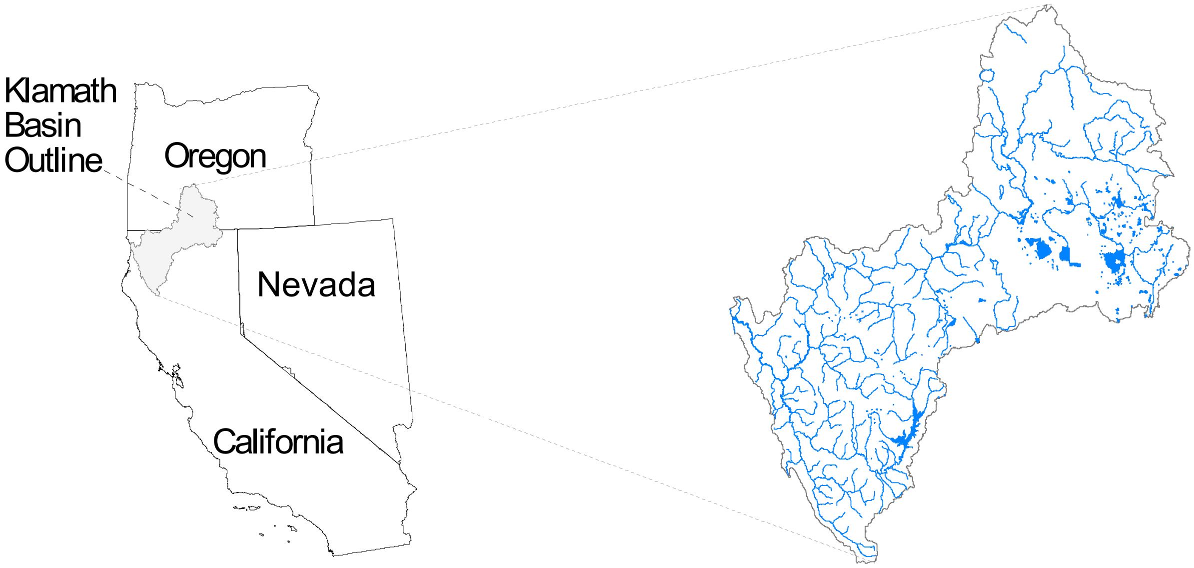

Figure 1. Regional location of the Klamath Basin.

2 METHODS

2.1 MASS-BALANCE ANALYSIS FOR WATER AND NUTRIENTS

Hydrologic (riverine discharge) and nutrient (various forms of nitrogen and phosphorus) data were collected and/or assembled for mainstem and tributary stations to estimate daily nutrient concentration and load for various free-flowing Klamath River reaches on a daily basis. Similar to Kann and Asarian (2007) and Asarian et al. (2009), nutrient budgets were constructed using the daily estimates and summarized on seasonal time scales to assess temporal nutrient dynamics and the relative fate of nutrients in the study reaches.

2.1.1 Nutrient Concentration

2.1.1.1 Sampling Locations and Parameters

Nutrient samples were collected at nine mainstem stations from just below Keno Dam (river mile 233.34) and Turwar (river mile 5.79, just upstream of the Klamath Estuary), and at four tributary stations (Shasta, Scott, Salmon, and Trinity rivers). Sampling stations and station codes used for this study are shown in Table 1 and Figure 2 and will be used throughout this report. Data were collected by a variety of entities, with methodology and results described in the following reports: Karuk Tribe (2007, 2008), Yurok Tribe (2007, 2008, 2009), Armstrong and Ward (2005), ARFO (2005), Raymond (2008, 2009), Deas (2008), Kann and Asarian (2007), and Asarian et al. (2009).

Sampling frequency varied by station and year, but generally occurred at monthly to weekly frequencies (Figure 3). Sampling frequency generally increased over the years, with fewer samples collected in 2005 compared to 2008.

Sample stations were fixed with the following exceptions: 1) location of the Yurok Tribe's Klamath River below Trinity was moved downstream four miles to Tully Creek starting in September 2007, and 2) for days when no samples were available for Klamath River below Keno Dam station, data were substituted from Keno Reservoir at Highway 66 Bridge station (comparison between the two stations showed that their general trends were similar enough to warrant using).

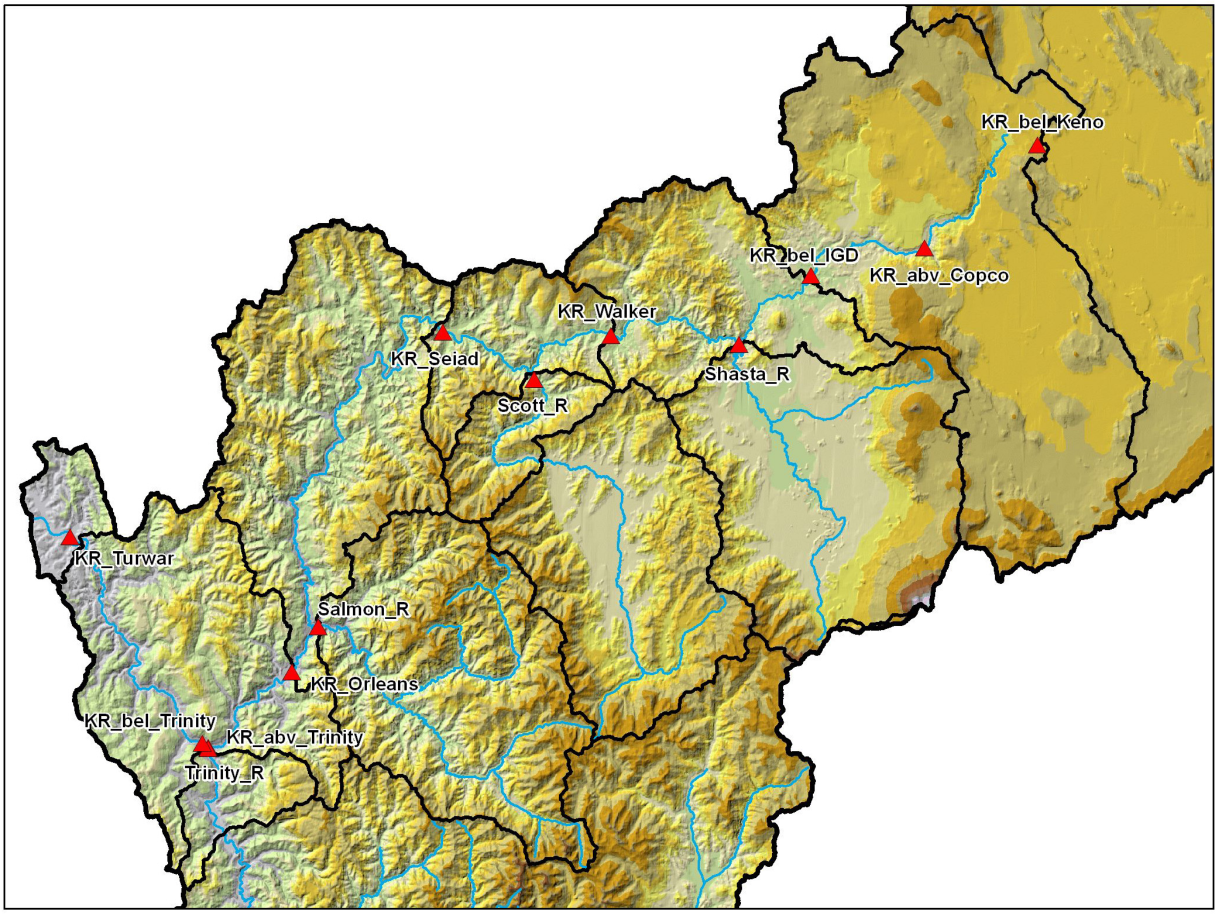

Figure 2. Location of nutrient sampling stations and associated watersheds (delineated by the black lines including the watershed area draining to a sample station).

Table 1. Nutrient and hydrologic sampling stations and reaches on the mainstem Klamath River and tributaries.

	Site Code	Site ID	River Mile	Station Description	Latitude	Longitude	Drainage Area (km^2)	Primary Reach	Supplemental Reach	Nutrient Data Sources and Years	Hydrologic Data Sources and Years
Mainstem Stations	KR_bel_Keno	KR23334	233.34	KR below Keno Dam	42.133333	-121.961111	10153	1 start		PacifiCorp: 2005 & 2007, USGS: 2006-2008, USBR: 2006, ODEQ: 2005-2008	USGS Keno
	KR_abv_Copco	KR20642	206.42	KR Above Copco	41.972417	-122.201683	10795	1 end		Karuk 2005-2008	Calculated as USGS Boyle plus accretions (based on reservoir water budgets)
	KR_bel_IGD	KR18973	189.73	KR Below Iron Gate	41.931083	-122.442200	11992	4 start	4A start	Karuk 2005-2008	USGS Iron Gate
	KR_Walker	KR15600	156.00	KR at Walker Bridge	41.837367	-122.864917	15225		4A end, 4B start	Karuk 2008	Calculated as USGS Iron Gate + accretions
	KR_Seiad	KR12858	128.58	KR at Seiad Valley	41.842683	-123.218867	17975	4 end, 5 start	4B end	Karuk 2005-2008	USGS Seiad
	KR_Orleans	KR05912	59.12	KR at Orleans	41.305600	-123.531583	21950	5 end, 6 start	6A start	Karuk 2005-2008	USGS Orleans
	KR_abv_Trin	KR04350	43.50	KR above Trinity	41.185833	-123.705556	22611	6 end, 7 start		Yurok 2005-2008	USGS Orleans+accretions
	KR_bel_Trin	KR04250	42.50	KR below Trinity	41.192500	-123.717778	30457		6A end, 7A start	Yurok 2005-2008	USGS Orleans + accretions + USGS Trinity
	KR_Turwar	KR00579	5.79	KR at Turwar	41.516111	-123.999167	31339	7 end	7A end	Yurok 2005-2008	USGS Turwar
Gaged Tribs	Shasta_R	SH00		Shasta River	41.823167	-122.595000	2054	4	4A	Karuk 2005-2008	USGS Shasta
	Scott_R	SCM		Scott River	41.768333	-123.026117	2107	4	4B	Karuk 2005-2008	USGS Scott + accretions
	Salmon_R	SA		Salmon River	41.376950	-123.477217	1945	5		Karuk 2005-2008	USGS Salmon
	Trinity_R	TR		Trinity River	41.184444	-123.705278	7685	7	6A	Yurok 2005-2008	USGS Trinity + accretions

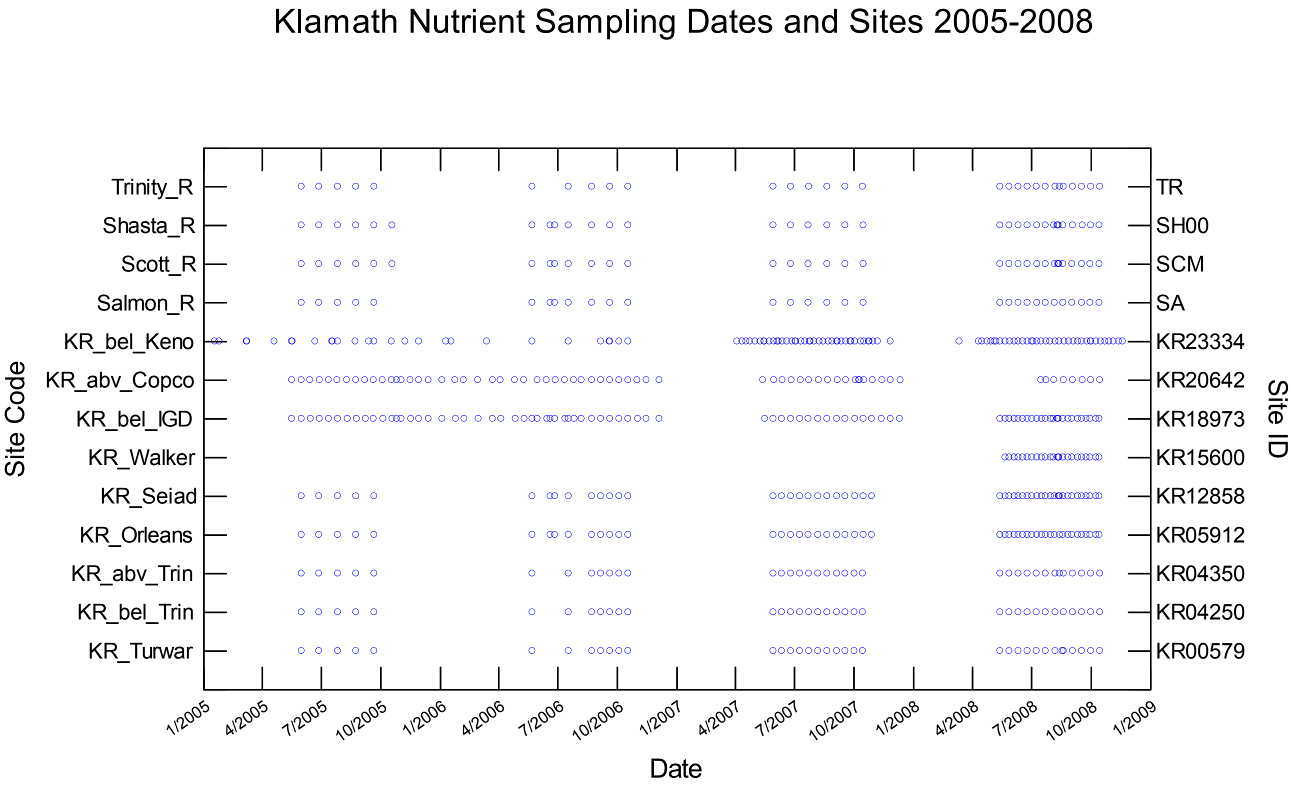

Figure 3. Timing of 2005 –2008 nutrient samples collected at mainstem Klamath River sites and tributaries.

Parameters analyzed included ammonia (NH_3), 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 NH_3 plus NO_3+NO_2, organic nitrogen (ON) was computed as TN minus NH_3 minus NO_3+NO_2, particulate phosphorus (PP) was calculated as TP minus SRP. Some data collection entities did not analyze TN, in which case TN was calculated as TKN+ NO_3+NO_2. In this report, nutrient concentrations are expressed in units of mg/L as N or mg/L as P.

Due to diel fluctuations in nutrient concentrations at the Klamath River above Copco station caused by hydropower peaking operations at the J.C. Boyle Powerhouse, TN and TP concentrations at that station were adjusted using the methods described in Asarian et al. (2009). Thus, flow-weighted average concentrations for each sampled day were computed; with adjustments ranging from -10% to +45% for TN and -5% to +25% for TP. Due to insufficient data, flow-weighted average concentrations for other parameters could not be computed and were therefore not used in nutrient budgets.

2.1.1.2 Nutrient Concentration for Ungaged Inflow

Iron Gate Dam to Turwar

Spatial and temporal resolution of samples collected at multiple ungaged tributaries (i.e., all tributaries of the Klamath River excluding the Shasta, Scott, Salmon, and Trinity Rivers) between

Iron Gate Dam and Turwar were not sufficient to predict differences between sites and season, or to determine flow-dependence. Thus, the 24 available nutrient samples[1] collected at these tributaries from 2005-2008 were pooled to calculate a single long-term average value representing all dates and sites for each parameter: TP=0.012 mg/L, SRP=0.008, PP=0.005, TN=0.081, NH_3=0.005, NO_3+NO_2=0.010, TIN=0.015 (Table 2).

Table 2. Summary statistics of nutrient concentration (in mg/L) calculated from 2005-2008 ungaged tributary samples.

Parameter	Number of Samples	Mean	Standard Deviation	Minimum	Percentiles 25	Percentiles 50	Percentiles 75	Maximum
TP	24	0.012	0.007	0.004	0.008	0.012	0.015	0.034
SRP	24	0.008	0.003	0.003	0.005	0.008	0.010	0.016
PP	24	0.005	0.005	0.000	0.002	0.003	0.005	0.021
TN	24	0.081	0.024	0.075	0.075	0.075	0.075	0.193
NO3+NO2	24	0.010	0.008	0.005	0.005	0.005	0.014	0.035
NH3	24	0.005	0.000	0.005	0.005	0.005	0.005	0.005
TIN	24	0.015	0.008	0.010	0.010	0.010	0.019	0.040

Keno Dam to Copco Reservoir

Ungaged accretion flow occurring between Keno Dam and Copco Reservoir is comprised of two primary sources: Spencer Creek and high-volume springs located between J.C. Boyle Dam and the J.C. Boyle Powerhouse. Although the high-volume springs contribute the majority of flow in this reach, nutrient concentrations in these springs have never been directly sampled.

IFR and PCFFA (2009) estimated long-term average nutrient concentrations of these springs using mixing equations and PacifiCorp's 2001-2007 nutrient sampling data from the top and bottom of the J.C. Boyle Peaking Reach (bracketing above and below the springs). For the 37 pairs of samples evaluated, median spring flow was 262 cfs and median concentrations (in units of mg/L) were TN=0.227, TIN=0.211, NO_3+NO_2=0.220, NH_3=0.002, TP=0.065, PO_4=0.043, and PP=0.016.

Using a similar (but less detailed) approach, Gard (2006) used 2001-2003 PacifiCorp data and mixing equations (assuming constant spring flows of 225 cfs) to calculate springs concentrations of 0.23 mg/L NO_3 and 0.08 PO_4, very similar to the IFR and PCFFA (2009) value for nitrogen but lower for phosphorus. Using values derived through model calibration for the year 2000, the Klamath TMDL model uses a TP concentration of 0.0688 mg/L and a TN concentration of 0.314 mg/L (TetraTech 2009). In this study, we use the values from IFR and PCFFA (2009), as they are derived from the most comprehensive analysis of available data.

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[1] The tributary samples utilized for this analysis were collected by the U.S. Fish and Wildlife Service, Karuk Tribe, and North Coast Regional Water Quality Control Board, and processed by the Aquatic Research Inc. laboratory. Samples collected by PacifiCorp as part of the Deas (2008) study were not used due to inadequate reporting limits for NH_3.

2.1.1.3 Estimation of Daily Nutrient Concentrations and Loads

In the analysis of 1998-2002 free-flowing river reaches (Asarian and Kann 2006), 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. 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 represents 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). Similar to Asarian et al. (2009), for each site and nutrient parameter (TN, TIN, TP, SRP, etc.), 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. 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 were incorporated to generate daily concentration and load series for use in the nutrient budgets.

The predictive equation utilized was:

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

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 (see Appendix A1)

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

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

where:

T = Total Load = ΣL_i
SE = Standard Error of Total Load Estimate
N = Fixed Total Samples for station i
S_i = Standard Deviation of difference between observed and regression predicted loads over all sampling dates for station i

The uncertainty analysis for load estimates presented in this report addresses only the uncertainty associated with the prediction of daily nutrient concentrations from the continuously measured flows and nutrient samples that were collected approximately biweekly. It does not incorporate additional sources of uncertainty such as potential errors in USGS flow measurements or laboratory processing of nutrient samples. For ungaged tributaries, relative standard error was set at 50% for all parameters.

2.1.2 Hydrologic Data

Streamflow data for the Klamath River gages listed in Table 1 were obtained online from the USGS Water Resources National Water Information System[2].

Because not all nutrient samples were taken at USGS stream gages, discharge was estimated at some locations using a watershed area accretion method similar to that used by PacifiCorp (2004), Tetra Tech (2009), and Asarian et al. (2009). The total watershed area contributing to the ungaged accretions (areas of gaged tributaries were excluded) between each mainstem USGS Gage (J.C. Boyle, Iron Gate, Seiad, Orleans, and Turwar) was determined using GIS, and the ratios of individual areas to the total accretion area were calculated (Table 1, Table 3, Figure 2)

Table 3. Drainage areas for ungaged accretions in each reach. See section 2.1.3 below for additional information about reach delineation.

Reach Number	Reach Name	Drainage Area of Ungaged Accretion (km^2)	Reach Length (mi)
1	Keno Dam to above Copco Reservoir	642	26.92
4	Iron Gate Dam to Seiad Valley	1,843	61.15
4A	Iron Gate Dam to Walker Bridge	1,180	33.73
4B	Walker Bridge to Seiad Valley	663	27.42
5	Seiad Valley to Orleans	2,031	69.46
6	Orleans to Above Trinity	661	15.62
7	Above Trinity to Turwar	1,039	37.71

Five-day moving averages of all gages were calculated and accretions for the reaches between the mainstem gages were developed by calculating the difference between the five-day moving averages of the upstream gage, downstream gage, and any gaged tributaries within the reach[3]. The accretion volume was then distributed to the nutrient sampling stations in proportion to their watershed area.

2.1.3 Selection of Reaches

Based on geographic location and data availability, the mainstem Klamath River was delineated into seven contiguous "primary" reaches from Keno Dam to Turwar (Figure 4, Table 1). Reach 1 spans from below Keno Dam to above Copco Reservoir, including J.C. Boyle Reservoir. J.C. Boyle

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

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

Reservoir has a short (compared to Iron Gate and Copco Reservoirs downstream) hydrologic residence time of about one day at the average flow of 1,600 cfs, and about 2.5 days at 700 cfs (PacifiCorp 2004). In addition hydropower peaking and bypass operations occur in the middle and lower portions of Reach 1, meaning that, unlike the reaches below Iron Gate Dam, Reach 1 is not strictly free-flowing. Mass-balances (for TN and TP only) for the two reservoir reaches, Iron Gate [Reach 2] and Copco [Reach 3]) were analyzed in Asarian et al. (2009) study, and are therefore not included here. The Klamath River between Iron Gate Dam and the Klamath Estuary (excluding the Estuary) were delineated into Reaches 4, 5, 6, and 7.

In addition, several "supplemental" non-contiguous reaches were delineated and analyzed to allow use of data from additional sites. These reaches include splitting Reach 4 (Iron Gate to Seiad) into two segments: 4A (Iron Gate Dam to Walker Bridge) and 4B (Walker Bridge to Seiad Valley). These reaches were only analyzed, however, for the year 2008 when sufficient data were available. Other supplemental reaches were 6A and 7A, which differed from Reaches 6 and 7 based upon inclusion of the Trinity River tributary (Figure 4). Only select results from the supplemental reaches are included here.

2.1.4 Construction of Nutrient Budgets

Estimates of daily nutrient concentration and flow were used in all subsequent determinations of nutrient load. The nutrient load for each surface inflow and outflow for delineated reaches was computed as the product of daily estimated nutrient concentration and daily mean discharge.

Net nutrient retention for each reach was calculated as the residual of the nutrient mass-balance equation as follows:

Net Retention = inflow load [mainstem + tributary] – outflow load

Net retention reflects 1) net losses from the water column resulting from sedimentation, 2) atmospheric fixation and denitrification (for nitrogen only), 3) net biologic uptake/release by periphyton and macrophytes, 4) nutrient releases from bottom sediments, and 5) the cumulative errors in the other mass-balance terms[4]. Negative retention values denote a source from within a reach.

Retention is expressed in several forms in this report, including absolute retention (in units of kg/day or kg/day per mile) and relative retention (in units of percent of inflow retained or percent of inflow retained per mile).

As noted above, although daily nutrient mass terms were generated for input to the mass-balance model it is not our 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. Thus, budgets were summarized for June 1 – October 20 (approximate beginning and

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[4] Many individual values (flows and concentrations for various sites) are combined to derive net retention. Each of those individual vales has some inherent error associated with it (e.g., laboratory precision for nutrient concentrations). Net retention therefore includes the accumulation of all of those errors.

end of nutrient sampling in each year)[5] and July 1 – September 30 (the approximate core growing season for periphyton in the river reaches).

Unless otherwise noted, report results pertain to these seasonal time scales, not entire hydrologic or calendar years. The analyses reflect seasonal retention of nutrients, and not long-term loss or removal of nutrients at annual time scales. Observed seasonal decreases in nutrient load with distance downstream may reflect both temporary retention (presumably occurring primarily through uptake by plants and algae) and permanent or semi-permanent losses (e.g. denitrification, ammonia volatilization, formation of insoluble precipitates, and export to floodplain soils). Nutrients that are temporarily retained by plants during June through October may be transported downstream during winter (in leaf litter and dead algae).

2.2 STREAM GRADIENT ANALYSIS

NHD Plus[6], a national dataset that combines digital elevation models with stream hydrography to facilitate hydrologic analysis, was used to evaluate potential effects of stream gradient on nutrient dynamics. NHD Plus pre-calculated statistics (including gradient) were used to delineate elevation and gradient profiles for the mainstem Klamath River.

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[5] In 2008, sampling ended on October 15, thus for that year only the October 16-20 period is excluded from the seasonal totals. The nutrient sampling season spans the June-October period because that is generally considered the period of nutrient-related water quality impairment and lowest flows.

[6] http://www.horizon-systems.com/nhdplus/

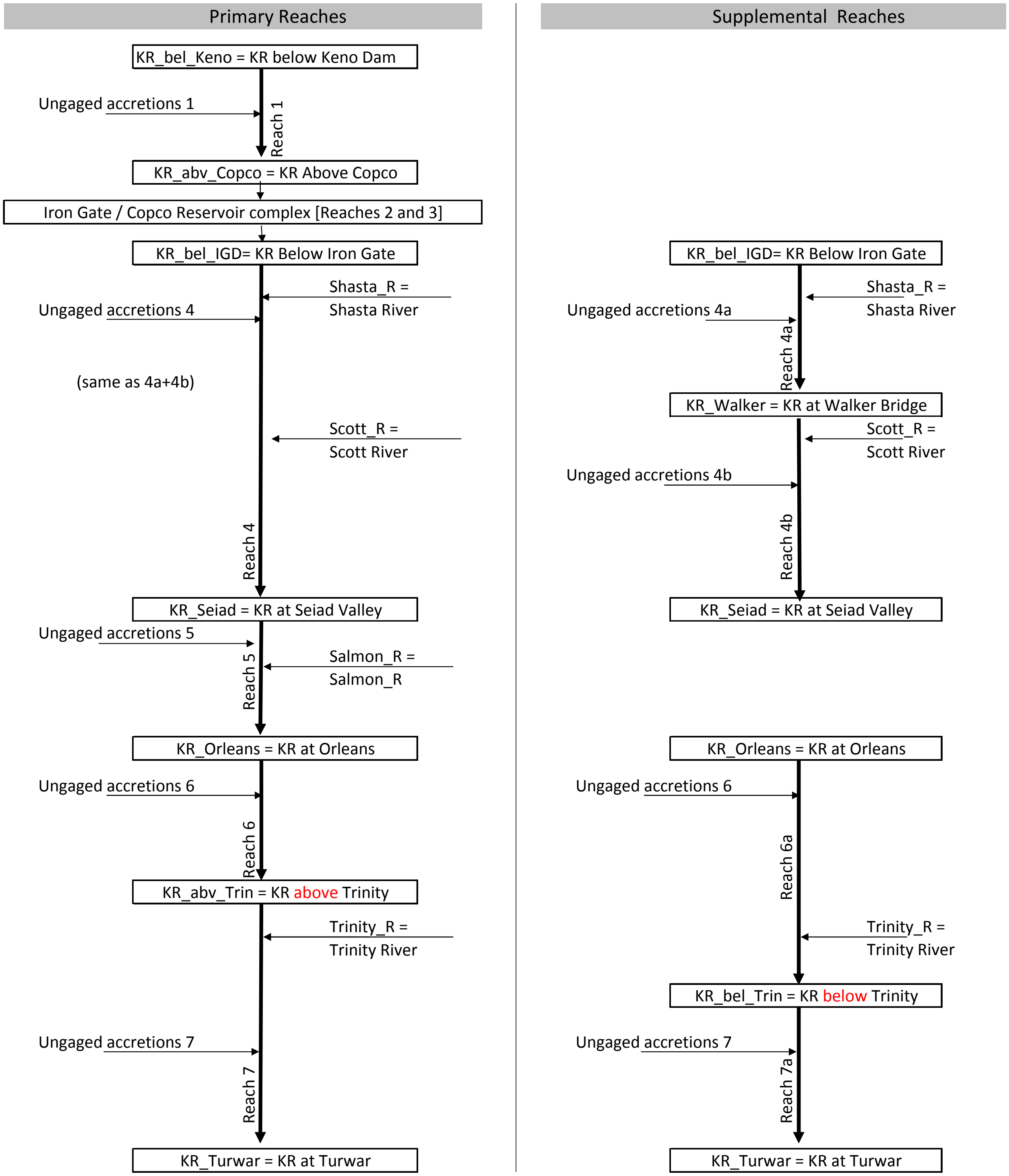

Figure 4. Schematic flow diagram of primary and supplemental study reaches and tributaries.

3 RESULTS

3.1 FLOW

Monthly average discharge data at six USGS flow gages on the mainstem Klamath River for hydrologic years (HY) 2005-2008 shows substantial variation among gages, seasons, and years (Figure 5). As expected, due to accretion from springs and tributaries, discharge increases with downstream distance. For example, the Scott River, Shasta River, and other smaller tributaries that enter between Iron Gate and Seiad Valley lead to substantially higher winter and springtime flows at Seiad Valley than occur at Iron Gate. In contrast, during the summer low-flow period, flows are only slightly higher at Seiad Valley than at Iron Gate.

Flows in HY 2006 were higher relative to other years for nearly all stations and months (an exception is October 2006, which was the first month of HY 2007). During the fall and winter period flows were generally highest in HY 2006, lowest in HY 2005, and intermediate in HY 2007-2008.

Inter-annual trends in spring and summer flows varied longitudinally; May-July flows were highest in 2006 (particularly important for this study are the high June and July flows) at upstream stations (Keno, J.C. Boyle, Iron Gate, and Seiad Valley), while for August and September at those upstream stations there were no clear inter-annual trends. At downstream stations (Orleans and Klamath Glen), summer flows were noticeably lower in 2007-2008 than in 2005-2006. At those two stations, spring flows were lowest in 2007.

3.2 MEASURED NUTRIENT CONCENTRATIONS

Time series of measured nutrient parameters for selected mainstem Klamath River stations are shown in Figure 6 through Figure 8.

3.2.1 Nitrogen

Measured total nitrogen (TN), total inorganic nitrogen (TIN), and organic nitrogen (ON) all followed a strong longitudinal trend, with concentrations highest at Keno Dam and decreasing with increasing distance downstream, apparently due to the combination of tributary dilution and in-river nitrogen removal processes (Figure 6). In addition, as outlined in Asarian et al. (2009), further decreases in nitrogen due to reservoir retention occur between the above Copco station and the below Iron Gate station.

Concentrations of NH_3 and NO_3+NO_2 followed more complex patterns due to site-specific factors. For example, NH_3 concentrations were almost always <0.03 mg/L for all mainstem free-flowing stations. However, due to the presence of anoxic reservoir layers immediately upstream, both Keno Dam (KR below Keno Dam) and Iron Gate Dam (KR below Iron Gate) stations showed higher concentrations, with NH_3 concentrations at Iron Gate generally between 0.01 and 0.05 mg/L from May through mid-September, then rising rapidly to seasonal highs of ~0.1 to 0.2 mg/L in October and November. At Keno, NH_3 concentrations were <0.25 mg/L in May-June, and then increased to ~0.5 to 1.5 mg/L for July-November (Figure 6). In warmer months, high concentrations of ammonia released from Keno Reservoir are rapidly nitrified (converted to NO_3+NO_2) in the turbulent oxygen-rich river between Keno Dam and Copco Reservoir (Deas 2008).

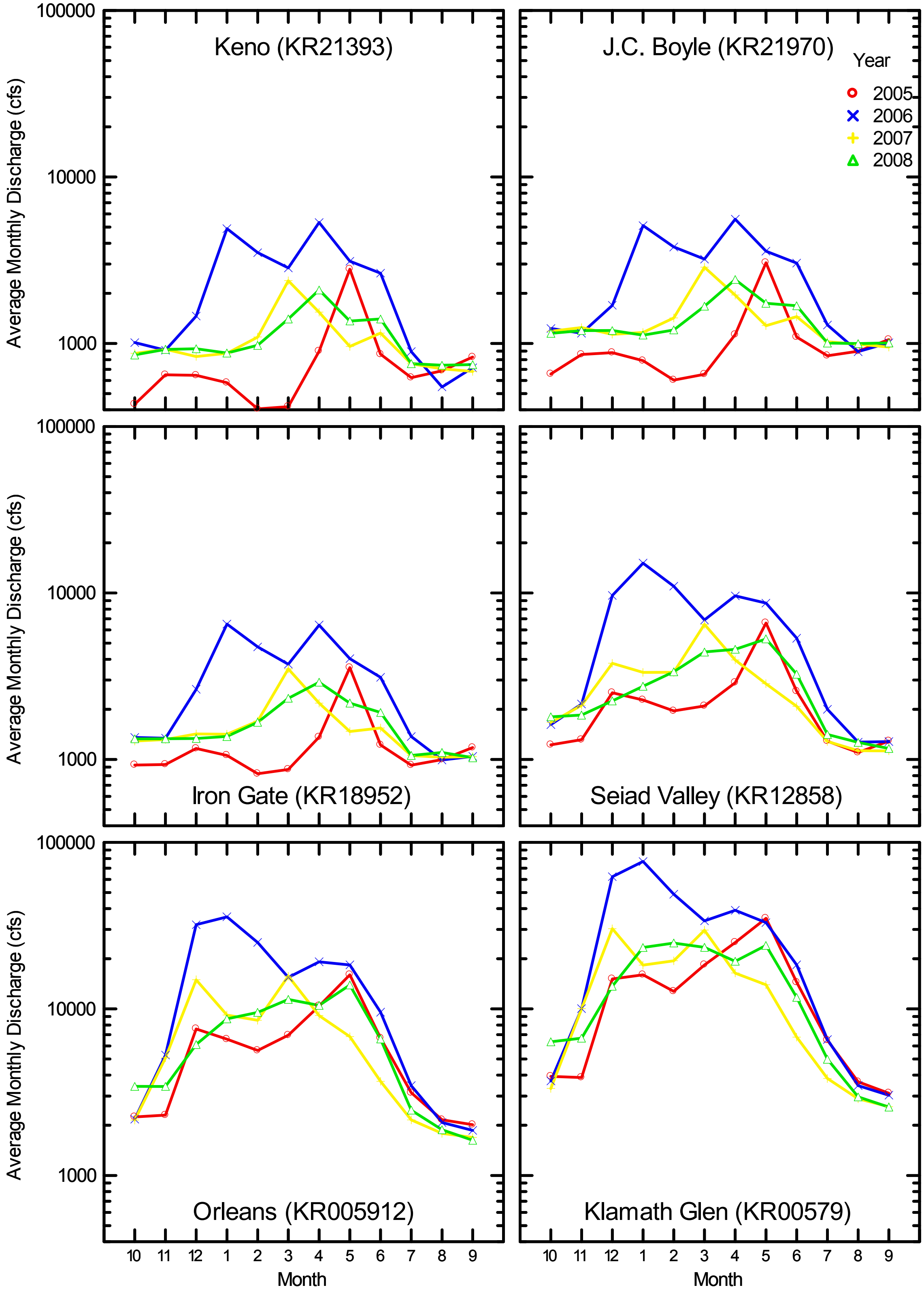

Figure 5. Monthly summaries of Klamath River discharge data for hydrologic years 2005-2008 at USGS flow gages.

Also, due to anoxia in Keno Reservoir, most inorganic nitrogen was in the form of NH_3, not NO_3+NO_2 at KR below Keno Dam during May-October, with NO_3+NO_2 concentrations less than 0.2 mg/L and often at levels not detected. (Figure 6). During May-November, NO_3+NO_2 concentrations at Iron Gate Dam ranged between ~0.1 to 0.6 mg/L, and then decreased rapidly downstream. NO_3+NO_2 levels typically remained above 0.05 mg/L at Walker Bridge and Seiad, but were at or near detection levels (<0.01) for Orleans and above Trinity. There was often a slight rise in NO_3+NO_2 concentrations from above Trinity to Turwar.

As noted above, organic nitrogen (ON) concentrations also showed a longitudinal trend, with decreasing ON concentrations with increasing distance downstream from below Keno Dam (Figure 6); however ON concentrations below Iron Gate Dam are periodically higher than those above Copco (Asarian et al. 2009). In 2005, 2006, and 2008, ON concentrations followed an overall increasing temporal trend (with variability) from June-October, but in 2007 ON concentrations peaked in September and then declined. ON generally comprised ≥50% (up to 95%) of the TN at all locations, with percent composition highest at Iron Gate and lowest at Orleans and above Trinity (Figure 8).

3.2.2 Phosphorus

Similar to nitrogen parameters, TP concentrations generally showed a decreasing longitudinal pattern (highest at Keno, lowest at Turwar) for TP, SRP, and PP (Figure 7). A frequent exception occurs during August-November, when concentrations are often higher at Iron Gate than they are at Keno and above Copco. As discussed in Kann and Asarian (2007) and Asarian et al. (2009), this reversal is likely the result of the combination of internally-driven nutrient dynamics in Copco and Iron Gate reservoirs and a temporal lag due to hydraulic retention 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. A substantial decline in maximum TP concentration occurred only in 2005.

Peak TP concentrations occurred between July and September (variable by year) at Keno Dam and above Copco, and then declined through the remainder of the fall months. For sites below Iron Gate Dam, peak TP concentrations occurred later (between mid-August and early October, variably by year), presumably due to the residence time in Iron Gate and Copco reservoirs, and were also followed by a decline which was steep in some years and gradual in others.

The percent of TP comprised of SRP was highly variable at Keno Dam, ranging from ~20-80% during May-November (Figure 8). During July-October, SRP accounted for a substantial majority (~60-90%, Figure 8) of the TP at sites from Iron Gate Dam to above Trinity. At Turwar, the percentage SRP was more variable and often <50% (as low as 25%) of TP, possibly due to the influence of the Trinity River tributary which has a relatively (compared to mainstem Klamath upstream of Trinity) low percent SRP composition. In May and June of 2006 and 2008, SRP was sometimes less than 50% of TP at Seiad, Orleans, above Trinity, and Turwar, apparently due to non-point source contributions of particulate P (PP) during high flow events.

SRP exhibited similar temporal and longitudinal dynamics as TP (Figure 7). Inversely, PP generally was only a minority of the TP during the July-October period, but comprised a majority of TP during the May-June 2006 and 2008 period when flows were high.

Total nitrogen to total phosphorus (TN:TP) and total inorganic nitrogen to SRP (TIN:SRP) ratios also showed a decreasing upstream to downstream longitudinal pattern. In particular, TN:TP and TIN:SRP were substantially higher at Keno Dam and above Copco than at sites downstream of Iron Gate (Figure 7). From May to mid-October, TIN:SRP ratios ranged from 0 to 6 and were substantially below the 7.2 Redfield Ratio (Smith et al. 1997) at sites from Iron Gate Dam and Turwar. TN:TP ratios were higher than TIN:SRP ratios, but were still generally below 7.2 from Iron Gate Dam to Turwar despite occasional exceedances at every site. Temporal patterns were evident also, with sites between Iron Gate Dam and Turwar displaying a "U"-shaped pattern of lowest ratios in mid summer.

Overall, these ratios indicate that nitrogen is potentially more limiting to algal growth than phosphorus; however, levels of N and P may be high enough in many reaches that neither nutrient is limiting. Additionally, as describe below in Section 4.1.3, nitrogen-fixing periphyton still thrive when there is a lack of N in the water column.

3.3 ESTIMATION OF DAILY NUTRIENT CONCENTRATIONS AND LOADS

3.3.1 Regression Model Outputs

Daily concentration and subsequent daily load estimates based on the multiple regression modeling method (Walker and Havens 2003) are contained in Appendix A5 (charts) and Appendix E1 (tables).

Regression coefficients are shown in Appendix A1. Coefficient of determination (R^2) and standard errors for the various stations and parameters are shown in Table 4. For TN, relative standard errors are less than 3% at all mainstem stations except Keno Dam (7.6%) where concentrations were highly variable (see Appendix A5 for time-series plots), and less than 5% at tributary stations except Salmon River (18.1%). For TP, relative standard errors generally increased with increasing distance downstream of Iron Gate, were less than 5% at all mainstem stations, and were 5-7% at tributary stations except Salmon River (10.1%).

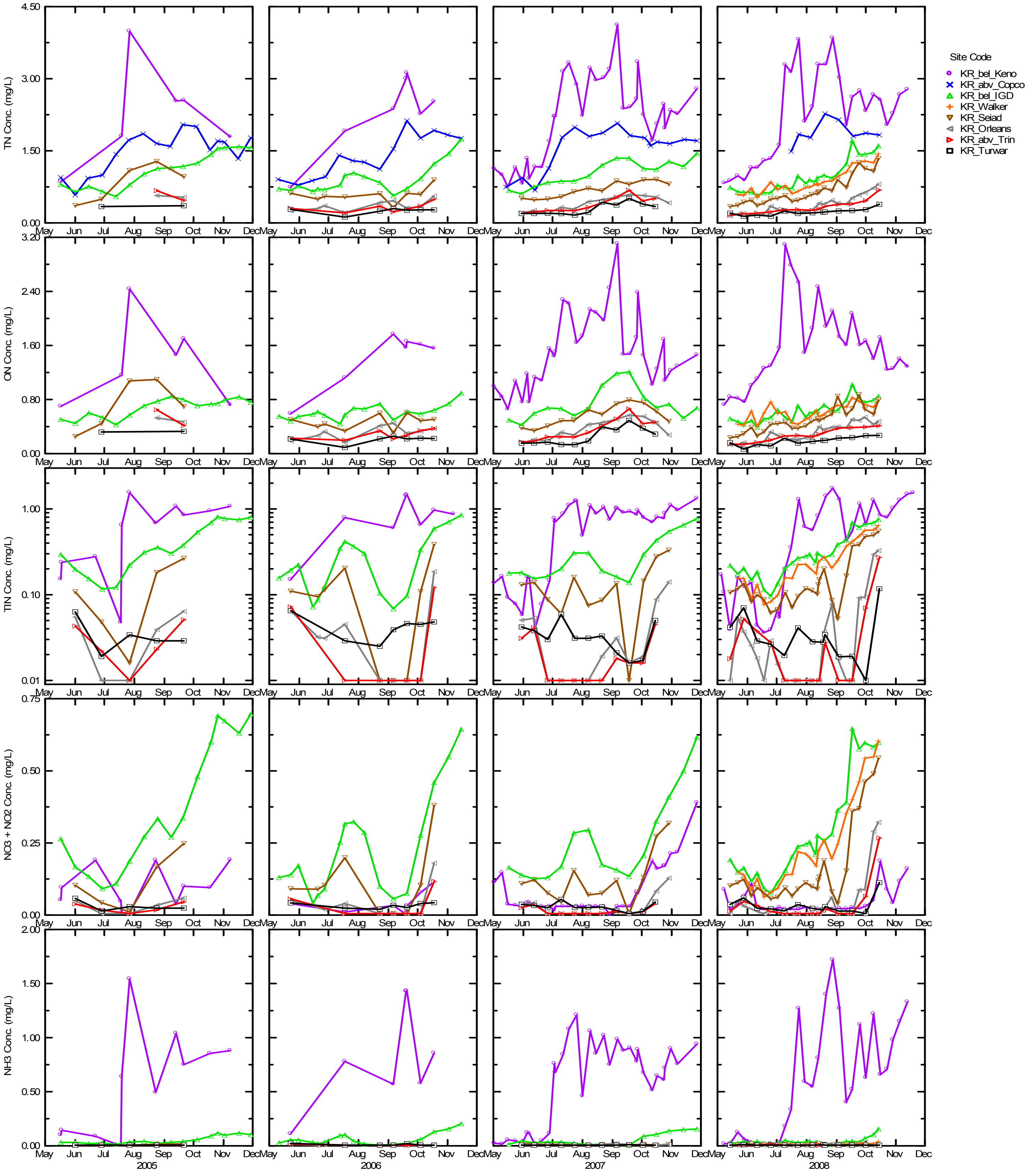

Figure 6. Time series of nitrogen concentrations for selected mainstem Klamath sites from Keno Dam to Turwar, May 2005 – November 2008.

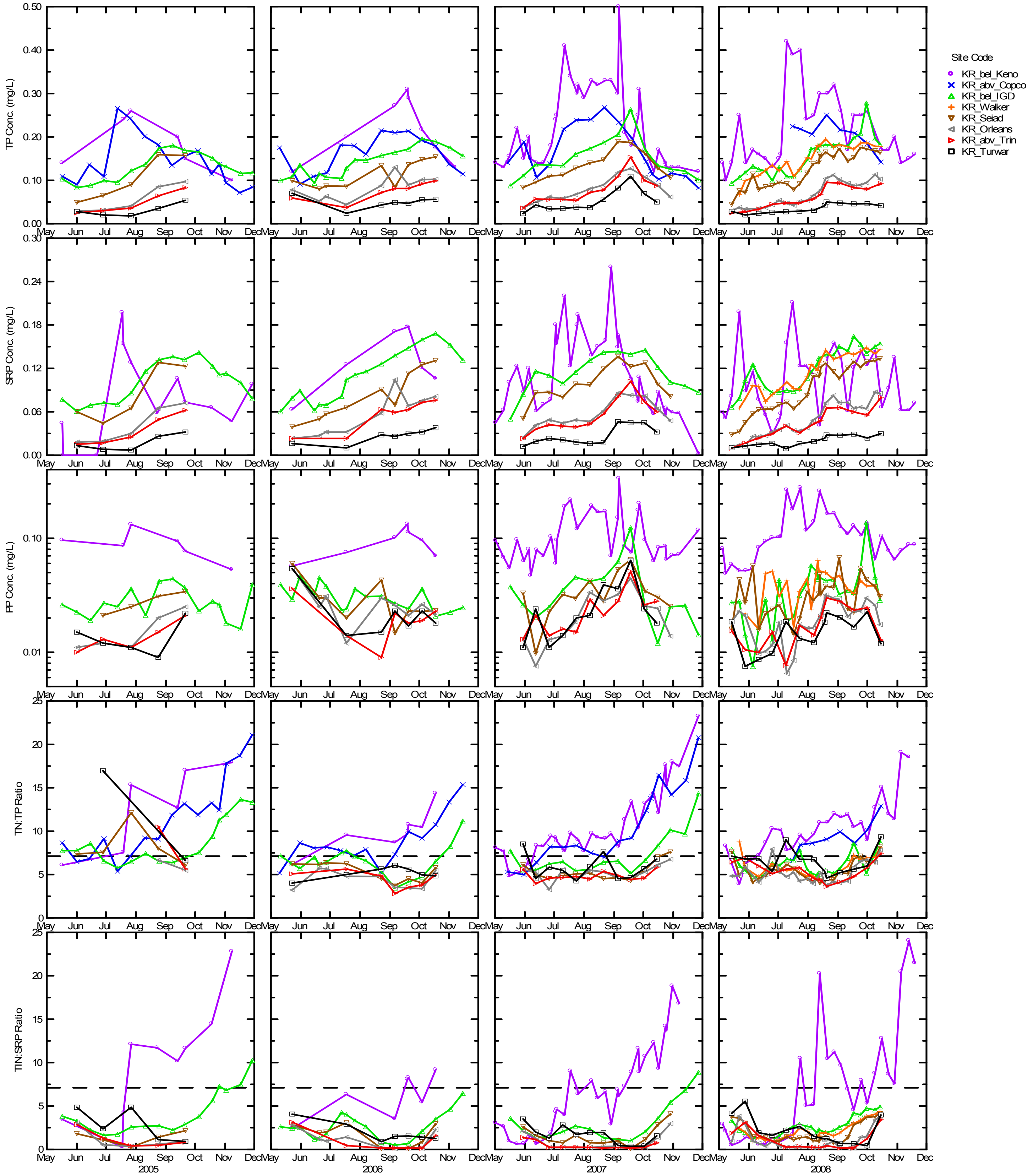

Figure 7. Time series of phosphorus concentrations and nitrogen:phosphorus ratios for selected mainstem Klamath sites from Keno Dam to Turwar, May 2005 – November 2008. The Redfield Ratio of 7.2 (Smith et al. 1997) is shown for TN:TP and TIN:SRP.

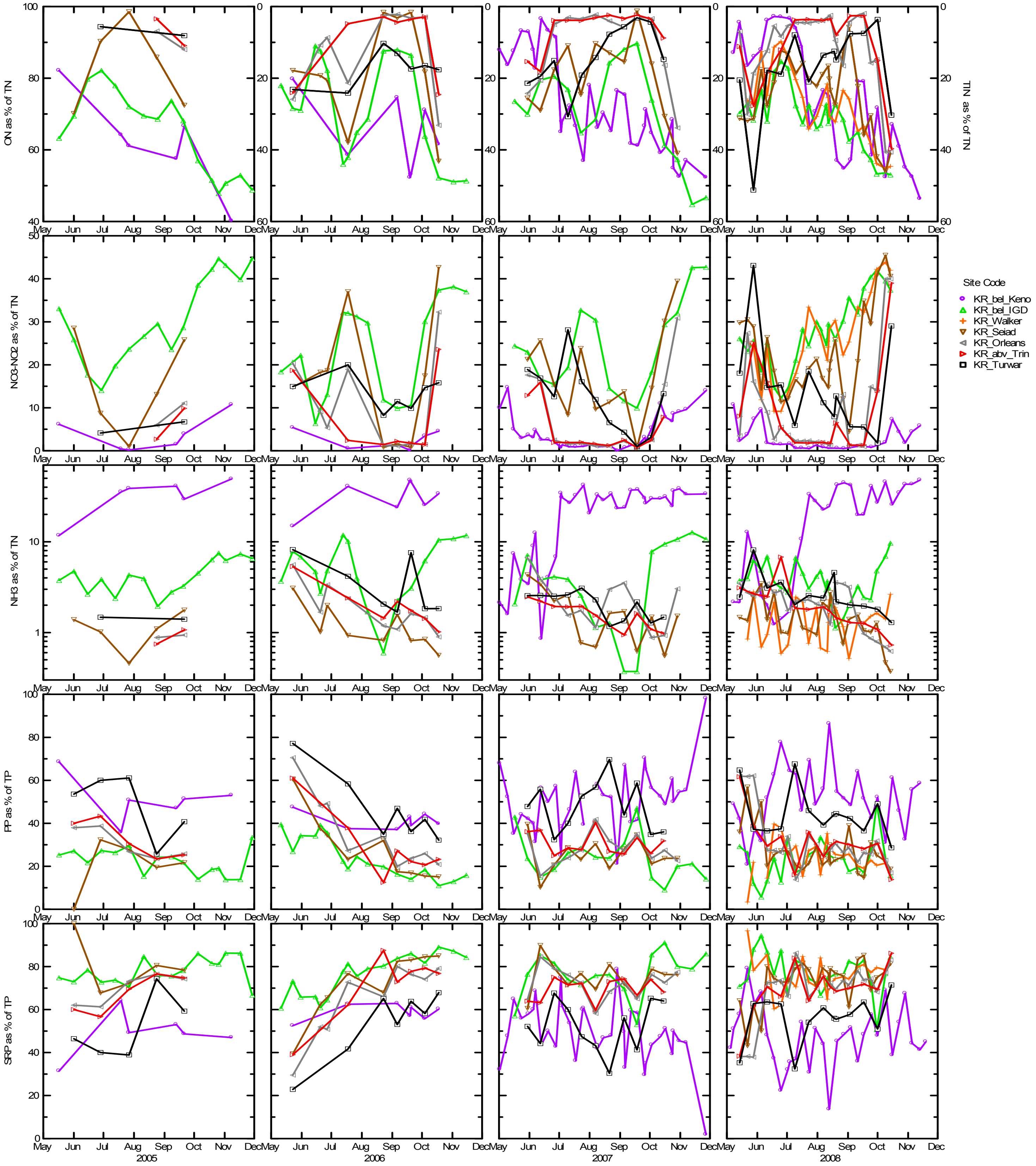

Figure 8. Time series of percent composition of nitrogen and phosphorus species for selected mainstem Klamath sites from Keno Dam to Turwar, May 2005 – November 2008.

3.3.2 Comparison of Five Methods for Calculating Nutrient Loads

Alternative load calculation algorithms were applied for comparison (Table 4 and Appendix A2) and for the entire monitoring period estimated loads were shown to be relatively insensitive to calculation method. For example, a comparison of Method 3 (simple linear interpolation of concentrations between sampling dates) used in Asarian and Kann (2006) and Method 5 (regression with residual interpolation) used in this study shows that total TN and TP load did not differ by more than 5% at any mainstem station.

Table 4. Comparison of mean daily TN and TP loads at mainstem and major tributary stations calculated using the five algorithms (descriptions of algorithms provided below table). Mean daily loads were calculated only for sites, years, and parameters when sampling frequency was adequate (i.e., monthly or better, see section 3.5.2.1 below for more details); thus, the number of years included in the mean daily load values vary by site and parameter (range is between one and four years). Standard error and regression R^2 are for method 5 only.

		Mean Daily Load (metric tons/day)						Method 5	
Para-meter	**Site**	**Method 1**	**Method 2**	**Method 3**	**Method 4**	**Method 5**	**M3 Load as % of M5 Load**	**Relative Std Error**	**Regression R^2**
TP	KR_bel_Keno	0.4475	0.4513	0.4969	0.5209	0.5004	99.3%	7.6%	0.6340
	KR_abv_Copco	0.4717	0.4814	0.5210	0.4986	0.4969	104.8%	2.4%	0.7355
	KR_bel_IGD	0.4227	0.4392	0.4656	0.4647	0.4656	100.0%	2.1%	0.8044
	KR_Walker	0.5131	0.5351	0.5311	0.5372	0.5361	99.1%	1.5%	0.9386
	KR_Seiad	0.4546	0.4989	0.4905	0.4818	0.4827	101.6%	2.1%	0.7993
	KR_Orleans	0.4678	0.5018	0.4954	0.5016	0.4973	99.6%	2.8%	0.8887
	KR_abv_Trin	0.3776	0.4330	0.4351	0.4231	0.4302	101.1%	2.6%	0.9033
	KR_bel_Trin	0.4454	0.4644	0.4711	0.4623	0.4616	102.1%	2.1%	0.8947
	KR_Turwar	0.4312	0.4427	0.4560	0.4385	0.4515	101.0%	2.8%	0.8336
	Shasta_R	0.0312	0.0313	0.0315	0.0317	0.0316	99.8%	1.4%	0.6225
	Scott_R	0.0146	0.0124	0.0092	0.0081	0.0075	123.0%	4.1%	0.7016
	Salmon_R	0.0105	0.0108	0.0105	0.0122	0.0115	91.2%	18.1%	0.4778
	Trinity_R	0.0551	0.0370	0.0390	0.0364	0.0366	106.3%	3.0%	0.9423
TN	KR_bel_Keno	3.8323	4.2694	4.8199	4.8448	4.7893	100.6%	2.5%	0.8549
	KR_abv_Copco	4.7357	4.8690	4.4496	4.3721	4.3260	102.9%	1.8%	0.8093
	KR_bel_IGD	3.2693	3.3356	2.8999	2.9139	2.8961	100.1%	1.4%	0.7923
	KR_Walker	2.9650	3.0403	3.0890	3.0670	3.0585	101.0%	2.4%	0.9166
	KR_Seiad	2.6942	2.9729	2.8540	2.7857	2.8295	100.9%	2.5%	0.7101
	KR_Orleans	2.4052	2.6056	2.5633	2.5992	2.5723	99.7%	3.6%	0.7509
	KR_abv_Trin	2.1048	2.2819	2.3388	2.2290	2.3104	101.2%	3.9%	0.6869
	KR_bel_Trin	2.4566	2.5135	2.5667	2.4359	2.4804	103.5%	4.1%	0.7027
	KR_Turwar	2.6533	2.7568	2.7448	2.6937	2.7513	99.8%	4.9%	0.5504
	Shasta_R	0.0917	0.0829	0.0834	0.0874	0.0848	98.4%	5.1%	0.5900
	Scott_R	0.1269	0.1273	0.1301	0.1450	0.1308	99.4%	6.5%	0.5820
	Salmon_R	0.1000	0.0926	0.0987	0.1008	0.0925	108.2%	10.1%	0.5481
	Trinity_R	0.5404	0.3651	0.3694	0.2170	0.2173	104.8%	6.1%	0.7221

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 (used in Asarian and Kann [2006]), 4 = Regression without residual interpolation (similar to method 5, but without the residual interpolation), 5 = Regression with residual interpolation (final method utilized herein).

Differences between Method 3 and Method 5 were generally higher at tributary stations (especially for TN and TP in the Trinity and Salmon Rivers, and for TP in Scott River) than at mainstem stations, likely due to a stronger influence of flow on concentration in tributaries. The maximum difference found between Method 3 and Method 5 for TN or TP at any station was Scott River TP, where Method 3 overestimated load by 23% (Table 4).

3.4 SEASONAL SUMMARIES OF NUTRIENT CONCENTRATION AND LOAD

This section examines longitudinal trends and inter-annual comparisons by presenting seasonal summaries of nutrient concentration and load outputs from the regression model. A summary of flow, flow-weighted average concentration, and load for various N and P parameters for June 1 – October 20 periods of 2005-2008 are presented in Figure 9 through Figure 11.

As noted in Section 3.1, above, flows in 2006 were the highest of any year at all stations for the June-October period (Figure 9, Figure 5). At upstream stations (Keno, J.C. Boyle, Iron Gate, and Seiad Valley), flows were relatively similar for 2005, 2007, and 2008. At downstream stations (Orleans, Above Trinity, Below Trinity, and Turwar) summer flows were noticeably lower in 2007-2008 than they were in 2005-2006, with 2007 showing lowest flows.

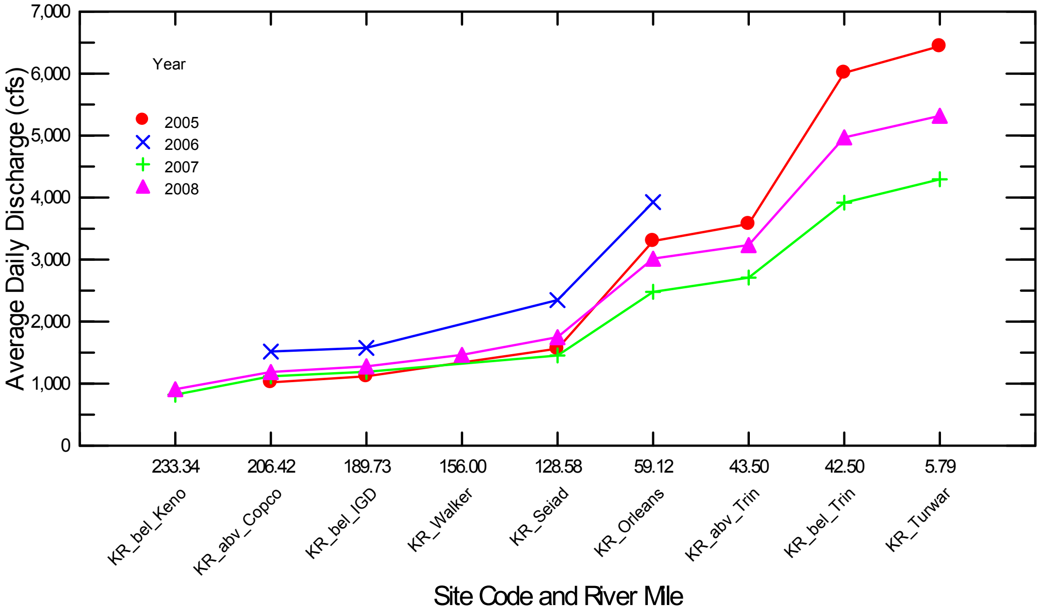

Figure 9. Summary of average daily discharge at mainstem Klamath River sites from Keno Dam to Turwar for the months of June-October, years 2005-2008. Data are only presented for years and sites in which there are available nutrient data (so values correspond with data in Figure 10 and Figure 11)

Due to a combination of factors including dilution and retention in reservoir and river reaches, flow-weighted average June-October concentrations of phosphorus parameters all exhibited large (~10x) decreases from Keno Dam to Turwar (Figure 10). Longitudinal (upstream to downstream) trends in average daily phosphorus load were variable by parameter and year; TP increased or was relatively stable in 2005-2007, but decreased in 2008. SRP decreased in all years, and PP showed a "U" shaped longitudinal pattern with a decrease from Keno to Iron Gate followed by an increase to Turwar.

Substantial conversion of phosphorus from particulate to dissolved forms occurred in the turbulent river reach between Keno Dam and Copco Reservoir. This transformation is clearly evident even within the short 5-mile reach between Keno Dam and above J.C. Boyle Reservoir (Deas 2008), and presumably continues downstream to Copco Reservoir. Data were not available, however, to evaluate the effects of hydropower peaking on diel fluctuations of PP and SRP concentrations above Copco. This confounded the calculation of seasonal loads presented in Figure 10 and negated the ability to attribute the portions of SRP and PP change to either the Keno to above Copco reach or the above Copco to below Iron Gate reach. Although high-volume springs downstream of J.C. Boyle Dam dilute TP and SRP concentrations they also contribute load. The net effect of these processes, as well as the dynamics of Copco and Iron Gate Reservoirs, is that between Keno Dam and Iron Gate Dam PP concentrations and load decrease by >50%, while SRP concentrations increase slightly. In addition, SRP loads approximately double, TP concentrations decrease, and TP load increases slightly.

Flow-weighted average June-October concentrations of nitrogen parameters also exhibited large (~10x for TN and ON, ~40x for TIN) decreases from Keno Dam to Turwar (Figure 11). As noted above regarding phosphorus, these trends are caused by the combination of dilution and retention in reservoir/river reaches. Between Keno Dam and Iron Gate Dam large concentration decreases occurred for TN, ON, and TIN. However, because tributary dilution decreases only concentration and not load, smaller proportional decreases were observed in TN, ON, and TIN load. Longitudinal depletion of TIN concentrations to near-zero occurred between Seiad and Orleans.

In contrast to the observed pattern for TP (increasing, stable, or decreasing pattern varying by year), the inter-annual pattern in TN load was more consistent. TN load generally reached a minimum at Orleans, stayed stable to above the Trinity, and increased below the Trinity and again at Turwar. The inter-annual pattern in TIN load was also consistent, reaching a minimum at Orleans or above the Trinity, before increasing to Turwar. Loading of ON was more variable, increasing from below Iron Gate to Seiad in 2005, 2006, and 2008 (although only slightly in 2008), but decreasing slightly in 2007. In 2007 and 2008 ON loading then increased downstream to Turwar, although the increase was less pronounced in 2008.

The observed longitudinal patterns in load and concentration for nitrogen parameters were relatively consistent between the years examined in this study (2005-2008). Additionally, the patterns were similar to the 1996-2004 data shown in Asarian and Kann (2006, see Figure 7 in that document) for TN (the only parameter analyzed in that study).

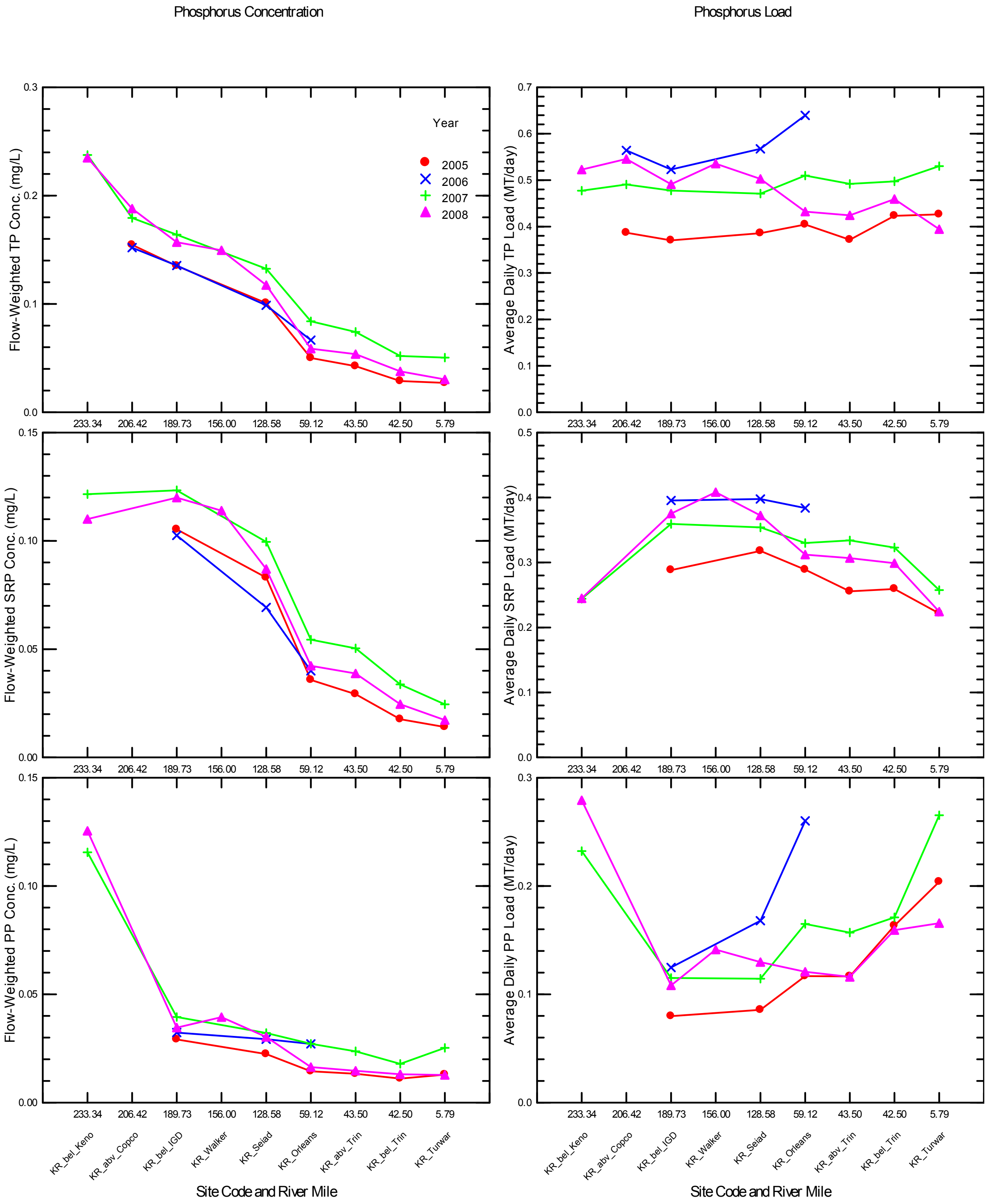

Figure 10. Summary of flow-weighted mean concentration (mg/L) and mean daily loads (metric tons/day) for phosphorus parameters at mainstem Klamath River sites from Keno Dam to Turwar, for the months of June-October, years 2005-2008.

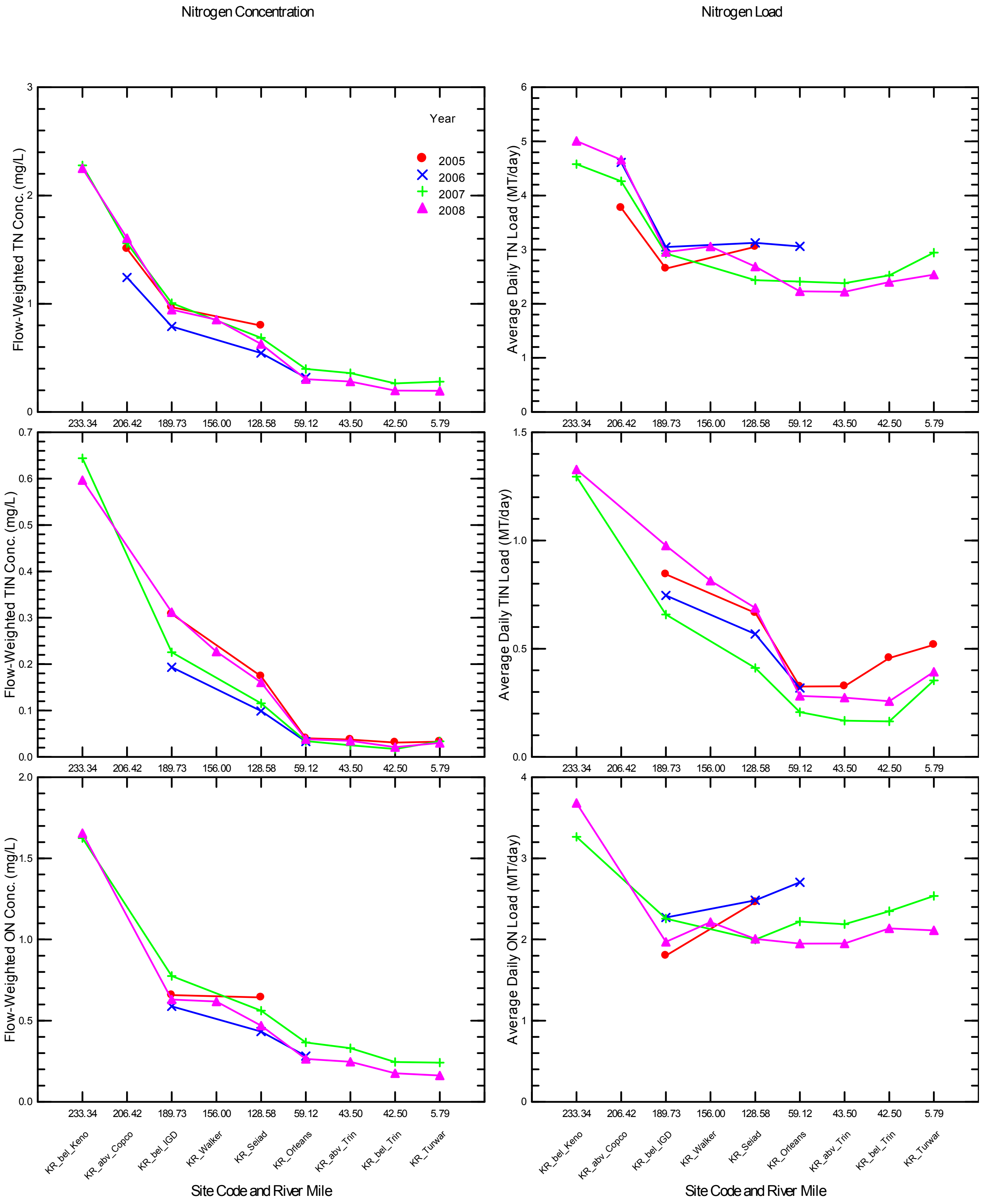

Figure 11. Summary of flow-weighted mean concentration (mg/L) and mean daily loads (metric tons/day) for nitrogen parameters at mainstem Klamath River sites from Keno Dam to Turwar**,** for the months of June-October, years 2005-2008.

3.5 NUTRIENT BUDGETS

3.5.1 Budget Components

As described above, loading estimates were derived for reach mainstem station as well as gaged and ungaged tributaries. On a reach-by-reach basis the mainstem inflow load plus gaged and ungaged tributary loads constitute the total inflow load to a specific reach (Figure 4).

Nutrient budget components for June-October 2008 (used as an example, because it had sufficient data for all primary reaches) are shown in Figure 12 (data for all years/reaches/parameters/seasons are contained Appendix A3). With the exception of Reach 7 for TIN and PP, mainstem inflows were the dominant budget term generally accounting for >90% of inflow load in 2008, (Figure 12). In Reaches 1 (Keno to Copco), 5 (Seiad to Orleans), and 6 (Orleans to Above Trinity), ungaged tributaries represented a greater percentage of incoming load than gaged tributaries; the reverse occurred in Reaches 4 (Iron Gate to Seiad) and 7 (Above Trinity to Turwar). The percent of incoming load from mainstem inflow was higher in the June-October season than July-October, reflecting lower tributary flows during the low-flow season (Appendix A3). Due to low nutrient concentrations in the mainstem Klamath and large quantities of water contributed by the Trinity River, Reach 7 was the only primary reach where tributary inflow accounted for >20% of total inflow load (for TIN and PP only)(Figure 12 and Appendix A3).

Across the entire Iron Gate to Turwar aggregated reach (Reach 4+5+6+7) for June-October 2008, the mainstem Klamath at Iron Gate accounted for 81.4% of TP, 86.0% of SRP, 68.0% of PP, 79.0% of TN, 83.0% of TIN, and 77.2% of ON inflows, with gaged tributaries contributing ~50-80% of the remainder depending upon the parameter (Figure 12 and Appendix A3).

3.5.2 Retention

Net retention for the various reaches was computed as the difference between inflow load [mainstem + gaged and un-gaged tributaries] and outflow load, and was computed for TP, SRP, PP, TN, TIN, and ON. Negative retention values denote a source from within the system (e.g., sediment or algal regeneration and nitrogen fixation), and positive values denote a sink (e.g., storage in algae/plant or bacterial biomass, adsorption to sediments, denitrification, and ammonia volatilization).

3.5.2.1 Seasonal Summaries for Primary Reaches

For each year and reach of the study, nutrient budgets were summarized for June 1 – October 20 (approximate beginning and end of sampling in each year) and July 1 – September 30 (the approximate core growing season for periphyton in the river reaches). Per-mile retention rates were than calculated on both an absolute (kilograms per day per mile retained) and relative (as percent of inflow retained per mile) basis. The relative retention rates for each parameter (TP, SRP, PP, TN, TIN, ON) in primary reaches (1, 4, 5, 6, and 7) are presented in Figure 15-Figure 20. Seasonal summaries were only calculated when the sampling frequency was adequate (i.e., monthly or better); thus, many sites/parameters were not summarized for each of the four seasons (2005-2008) and appear as blanks in Figure 15-Figure 20.

The results were then summarized on both a relative and absolute basis for each reach and parameter as an aggregate of all years of adequate data, (Table 5, Figure 13, and Figure 14).

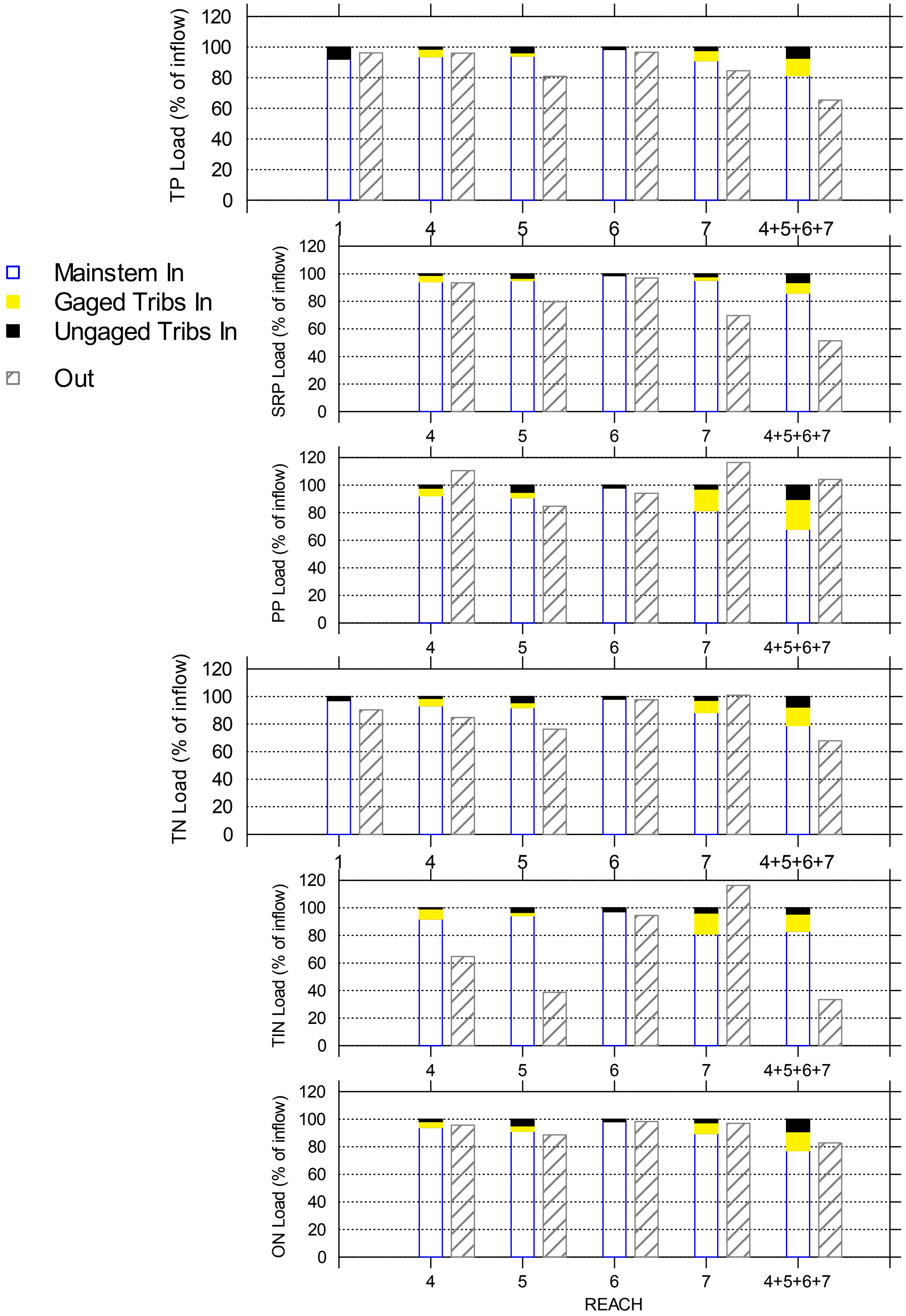

Figure 12. Nutrient budget components for primary Klamath River reaches for June-October 2008.

Phosphorus

Phosphorus retention varied by year and parameter. Across the entire study period (i.e., mean of all years that had adequate data for each site), TP and SRP retention during the June-October and July-September periods was positive for all primary river reaches (Figure 13 and Figure 14). There were no consistent across-reach differences when comparing June-October vs. July-September TP and SRP retention. On both a relative and absolute basis, TP and SRP retention were lowest at Reaches 4 (Iron Gate to Seiad) and 5 (Seiad to Orleans). In contrast to TP and SRP, PP retention was negative or near zero at three of four reaches for June-October and two of four reaches for July-September.

Overall, there appeared to be a longitudinal trend of increasing TP and SRP retention with increasing distance downstream of Iron Gate, and decreasing (or more negative) PP retention. On both a relative and absolute basis, the furthest downstream reach (Reach 7: Above Trinity to Turwar) had the most positive SRP retention and most negative PP retention, suggesting a shift in form in that reach from dissolved to particulate as well as an overall retention of phosphorus in that reach (TP retention was positive). Year-to-year variability for TP and SRP relative retention was high at Reach 6 (Orleans to Above Trinity; Figure 15 and Figure 16).

TP retention appeared to be positive overall for Reach 1 (Keno to Copco); however, uncertainty was high (possibly due to highly variable Keno TP concentrations; see Appendix A5) indicating that calculated TP retention in that reach was likely not significantly different from zero (Figure 15).

Nitrogen

Nitrogen retention parameters showed clearer longitudinal patterns (Figure 13-Figure 14) with less year-to-year variability (Figure 18-Figure 20). For example, a strong declining downstream retention trend was observed on both a relative and absolute basis (Figure 13-Figure 14), with TN retention highest in Reach 1 (Keno to Copco; 24.69 kg/day per and 0.47 percent/mile) and lowest (negative) in Reach 7 (Above Trinity to Turwar) for the July-September period (Table 5). The longitudinal trend in relative TN retention was not as pronounced as that for absolute retention.

With the exception of Reach 7 (Above Trinity to Turwar) for 2007-2008 (the only years of adequate data for that reach) and Reach 4 (Iron Gate to Seiad) in 2005, TN retention was positive for both the June-October and July-September periods for all other reaches and years (Figure 18). The negative retention value for Reach 4 in 2005 appears to be an outlier due to insufficient sample frequency (only two samples) and potential laboratory issues[7]. On a relative basis TN retention was higher in the July-September period than in the June-October period at all five reaches (Figure 14); on an absolute basis it was higher at four of five reaches (Figure 13).

TIN also showed a strong longitudinal trend, with higher absolute retention rates at the more upstream reaches (Reaches 4 [Iron Gate to Seiad] and 5 [Seiad to Orleans] where TIN was generally

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[7] In June-August 2005 at sites from Seiad to Turwar samples were analyzed for TKN rather than TN (TN was analyzed from Seiad to Turwar starting in September 2005 through the end of 2008 and for all 2005-2008 samples at Iron Gate). TN was then calculated by summing TKN and NO_3+NO_2. Of the 51 days in which samples were collected at Seiad in the years 2005-2008, the July and August 2005 samples (one per month) are the only samples for which Seiad TN concentrations are higher than Iron Gate concentrations. Thus, the 2005 TN and ON (affected by the same TKN issue) data were excluded from the overall averages presented in Table 5.

present at concentrations >0.05 mg/L), lower rates at Reach 6 (Orleans to Above Trinity), and negative rates at Reach 7 (Above Trinity to Turwar) (Figure 14). Unlike absolute TIN retention, relative TIN retention was more stable or even increased in the Seiad to Above Trinity reaches before declining in Reach 7. Relative TIN retention rates were higher in the July-September period than in the June-October period at three of four reaches (the exception being Reach 7); on an absolute basis no clear trend was observed. Relative TIN retention rates within Reaches 4 and 5 were similar to each other (0.86±0.12 and 0.95±0.17 for July-September, respectively) (Table 5), with remarkably low year-to-year variation (Figure 19).

Both relative and absolute ON retention values were generally lower than for TIN and TN in Reaches 4 and 5, but were higher in Reach 7. Although absolute and relative ON retention for Reach 7 was lower than Reach 4, Reaches 5, 6, and 7 showed no clear longitudinal trend (Figure 13-Figure 14).

3.5.2.2 Seasonal Summaries for Secondary Reaches

As noted above, in addition to contiguous primary reaches, several supplemental non-contiguous reaches were also evaluated (Figure 4).

For the year 2008 only, primary Reach 4 (Iron Gate to Seiad) was split into two supplemental reaches: Reach 4A (Iron Gate to Walker Bridge) and 4B (Walker Bridge to Seiad Valley). Results indicate that retention rates for all parameters are much higher in 4B (Walker to Seiad) than Reach 4A (Iron Gate to Walker) (Table 6). A possible explanation for this pattern includes the potential overestimation of flow at Walker, for which no mainstem gage exists[8].

Alternatively, if the retention difference between sub-reaches 4A and 4B is real, aquatic macrophyte dominance patterns provide another possible explanation. For example, aquatic macrophytes dominate the algal/plant community from Iron Gate Dam to the Scott River (~10 miles below Walker Bridge), whereas below the Scott River composition shifts towards periphyton, and macrophytes only occur in quiescent backwater areas (PacifiCorp, 2005). These differences are likely caused by a shift from a relatively geomorphically stable channel to a more active alluvial channel (PacifiCorp 2005) due to a combination of natural (i.e., historical lack of gravel) and human-caused factors (i.e., dams interrupting sediment transport and resulting in streambed armoring). Because rooted macrophytes can obtain nutrients from streambed sediments rather than relying solely on water column sources, biomass sloughing during the growing season could convey sediment nutrients, leading to the low or negative retention that was observed at the Walker station. Because these streambed sediments may have been deposited during the winter and spring, this phenomenon may be an example of a difference between seasonal retention and annual loss rates (i.e., sedimentation with subsequent macrophyte uptake and sloughing may only cause a temporal lag in the downstream movement of nutrients, but does not serve as a source or sink at an annual time scale).

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[8] The ungaged accretion between the Iron Gate and Seiad Valley USGS gages was distributed in proportion to watershed area (see section 2.1.2 above), yet the lower elevation eastern portion (Figure 2) has lower precipitation along with greater agricultural land area. Thus, if actual water yield is lower than estimated water yield at Walker, load would be overestimated in our calculations which would have the effect of underestimating retention in Reach 4A and overestimating it in Reach 4B.

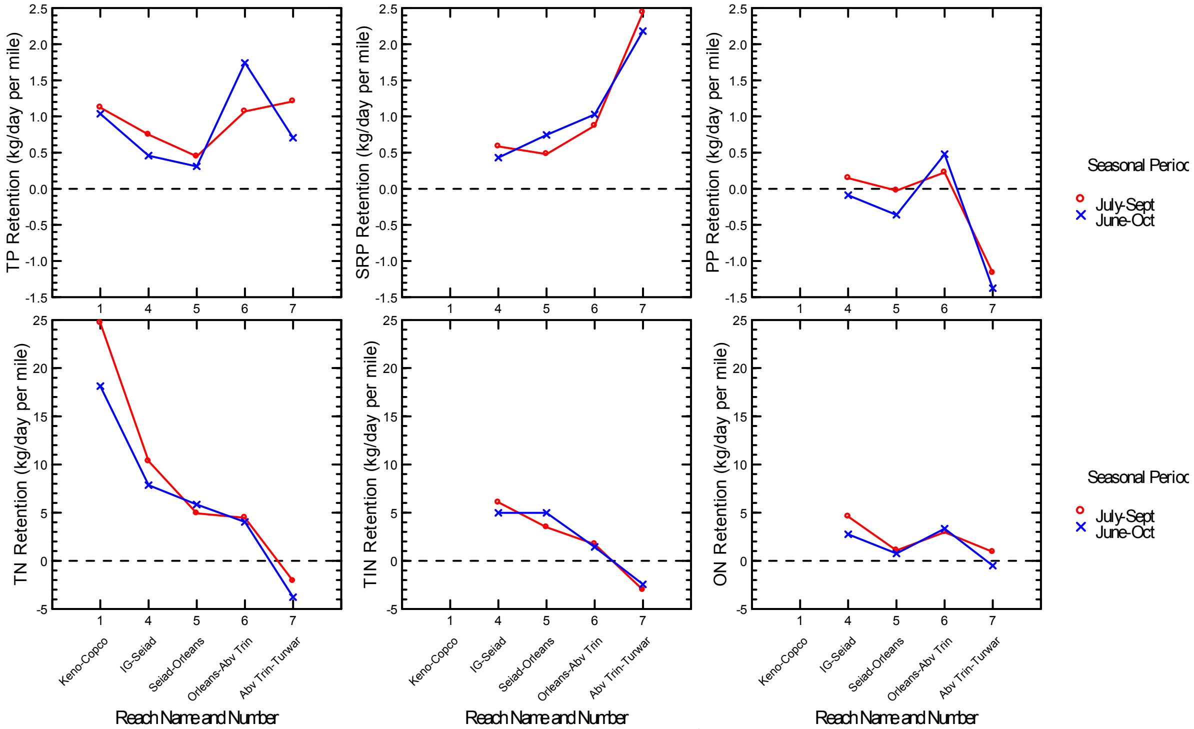

Figure 13. Comparison of absolute retention rates (units: kg/day per mile) for nitrogen and phosphorus parameters for primary river reaches during the seasonal periods of June-October and July-September. Values shown represent the overall period of available data for each site and parameter (i.e., 2007 and 2008 for Reach 1 TN).

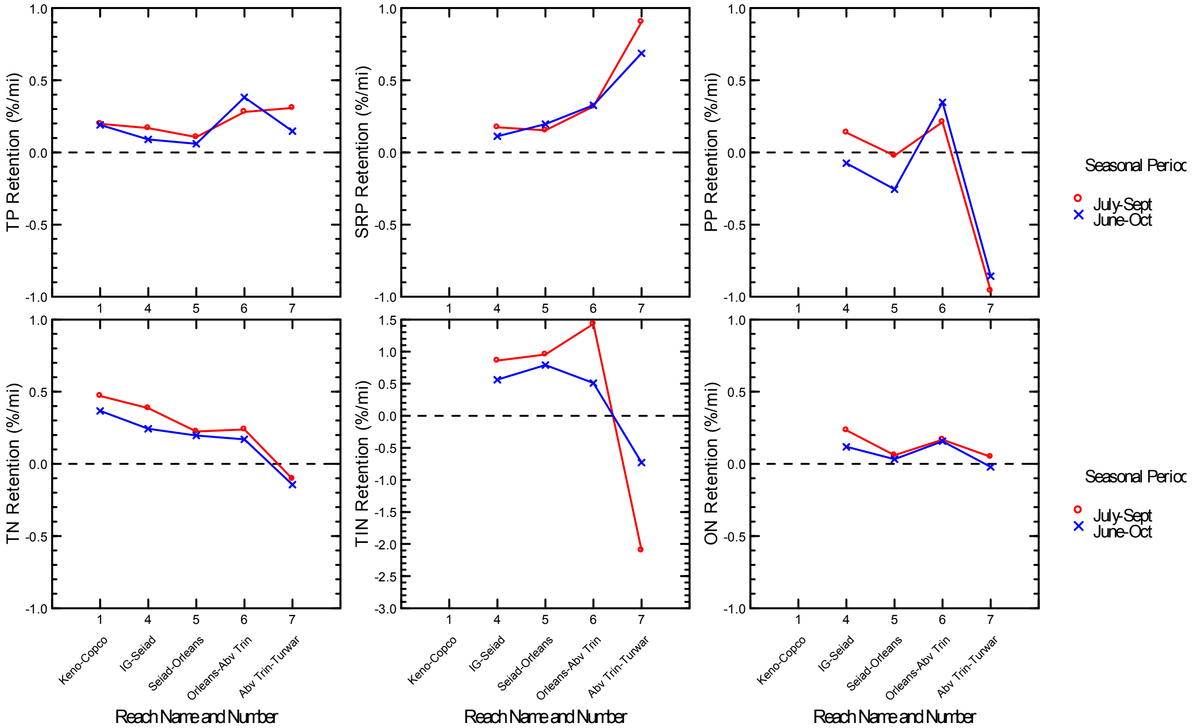

Figure 14. Comparison of relative retention rates (units: %/mile) for nitrogen and phosphorus parameters for primary reaches during the seasonal periods of June-October and July-September. Values shown represent the overall period of available data for each site and parameter (i.e., 2007 and 2008 for Reach 1 TN).

Table 5. Summary of absolute (kg/day per mile) and relative (%/mi) retention rates in primary river reaches for June-October and July-September periods. Values shown represent the overall period of available data, spanning two to four years depending upon site and parameter. These data points are shown graphically in Figure 13 and Figure 14 above. Note that TN and ON data for Reach 4 in 2005 are excluded from these summaries (for details, see footnote #7 above). The ± values represent standard errors calculated from the regression model. Standard errors were only calculated for each year individually, as well as 2005-2008 and 2006-2008; thus, standards errors are displayed here only for Reaches 4 and 5 due to the lack of 2006 data in Reaches 6 and 7.

		Reach 1 Keno – Copco (26.92 miles)		**Reach 4 IG - Seiad** (61.15 miles)		**Reach 5 Seiad - Orleans** (69.46 miles)		**Reach 6 Orleans-Above Trinity** (15.62 miles)		**Reach 7 Above Trinity-Turwar** (37.71 miles)		**Reach 4+5+6+7 Iron Gate - Turwar** (183.94 miles)	
Metric & Units	**Para-meter**	**June-Oct**	**July-Sept**	**June-Oct**	**July-Sept**	**June-Oct**	**July-Sept**	**June-Oct**	**July-Sept**	**June-Oct**	**July-Sept**	**June-Oct**	**July-Sept**
Retention Rate (kg/day per mile)	**TP**	1.04	1.12	0.46 ± 0.27	0.75 ± 0.30	0.31 ± 0.32	0.45 ± 0.30	1.74	1.07	0.70	1.21	0.65	0.83
	SRP			0.43 ± 0.30	0.59 ± 0.33	0.74 ± 0.22	0.48 ± 0.22	1.03	0.87	2.18	2.44	0.96	0.96
	PP			-0.09 ± 0.23	0.15 ± 0.27	-0.36 ± 0.16	-0.03 ± 0.14	0.48	0.23	-1.38	-1.16	-0.30	-0.13
	TN	18.13	24.69	7.85 ± 1.60	10.34 ± 1.55	5.85 ± 2.07	4.93 ± 1.83	4.03	4.46	-3.77	-2.09	4.99	5.92
	TIN			4.98 ± 1.02	6.07 ± 0.87	4.98 ± 0.90	3.49 ± 0.61	1.43	1.73	-2.44	-3.02	3.22	3.07
	ON			2.75 ± 1.43	4.60 ± 1.44	0.76 ± 1.73	1.08 ± 1.60	3.34	2.98	-0.50	0.92	1.85	2.74
Relative Retention Rate (%/mile)	**TP**	0.19	0.20	0.09 ± 0.05	0.17 ± 0.07	0.06 ± 0.06	0.11 ± 0.07	0.38	0.28	0.15	0.31	0.11	0.17
	SRP			0.11 ± 0.08	0.17 ± 0.10	0.20 ± 0.06	0.15 ± 0.07	0.33	0.32	0.69	0.90	0.23	0.27
	PP			-0.07 ± 0.20	0.14 ± 0.25	-0.26 ± 0.12	-0.02 ± 0.13	0.35	0.21	-0.86	-0.96	-0.19	-0.09
	TN	0.37	0.47	0.24 ± 0.05	0.39 ± 0.06	0.20 ± 0.07	0.22 ± 0.08	0.17	0.24	-0.14	-0.10	0.14	0.19
	TIN			0.56 ± 0.11	0.86 ± 0.12	0.79 ± 0.14	0.95 ± 0.17	0.51	1.43	-0.73	-2.10	0.32	0.37
	ON			0.12 ± 0.06	0.23 ± 0.07	0.03 ± 0.07	0.06 ± 0.09	0.16	0.17	-0.02	0.05	0.07	0.12

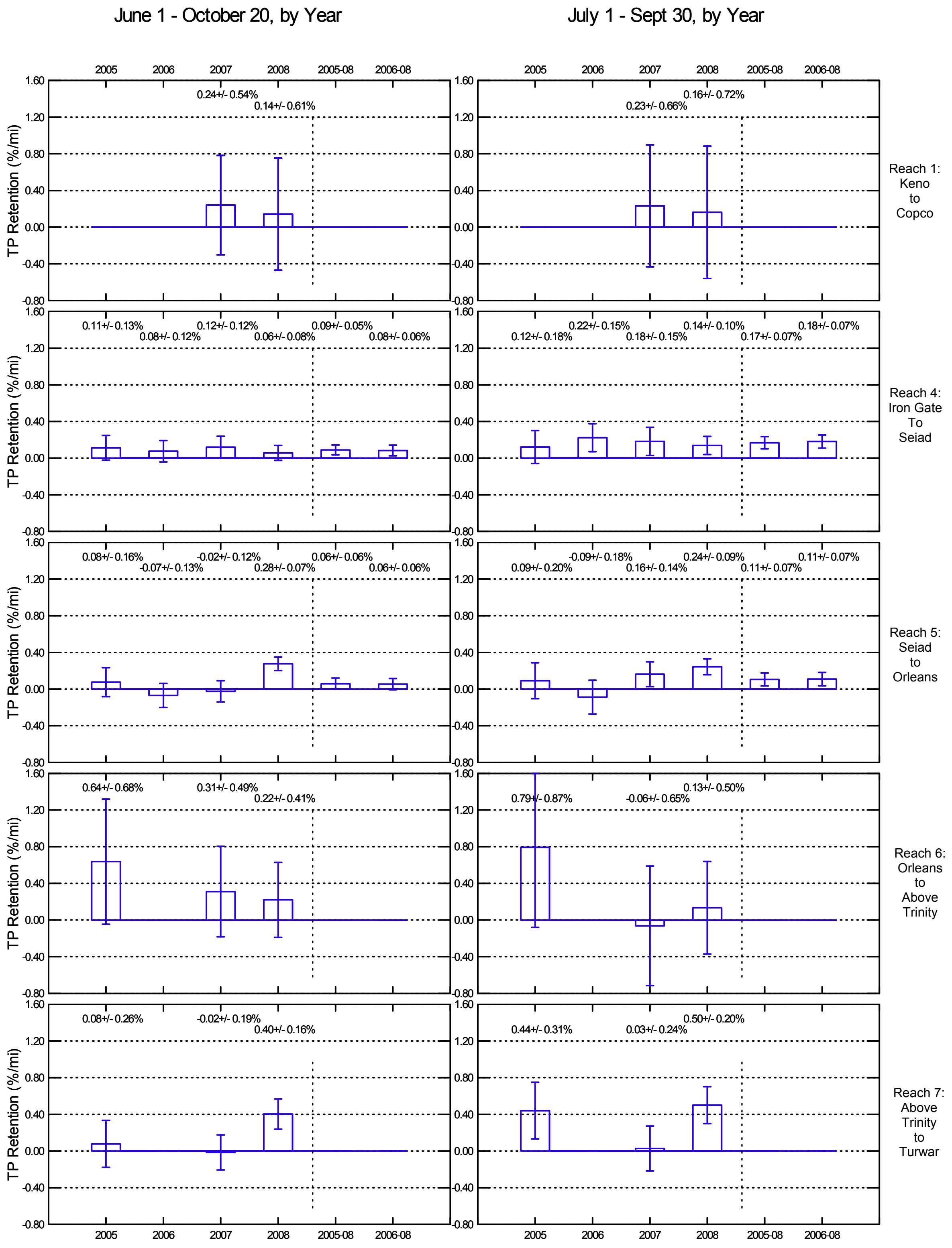

Figure 15. Total phosphorus (TP) relative (as a percent of inflow) retention rates per mile in primary river reaches for the June-October and July-September periods of each year with available data. Error bars are +/- one standard error (based on regression model).

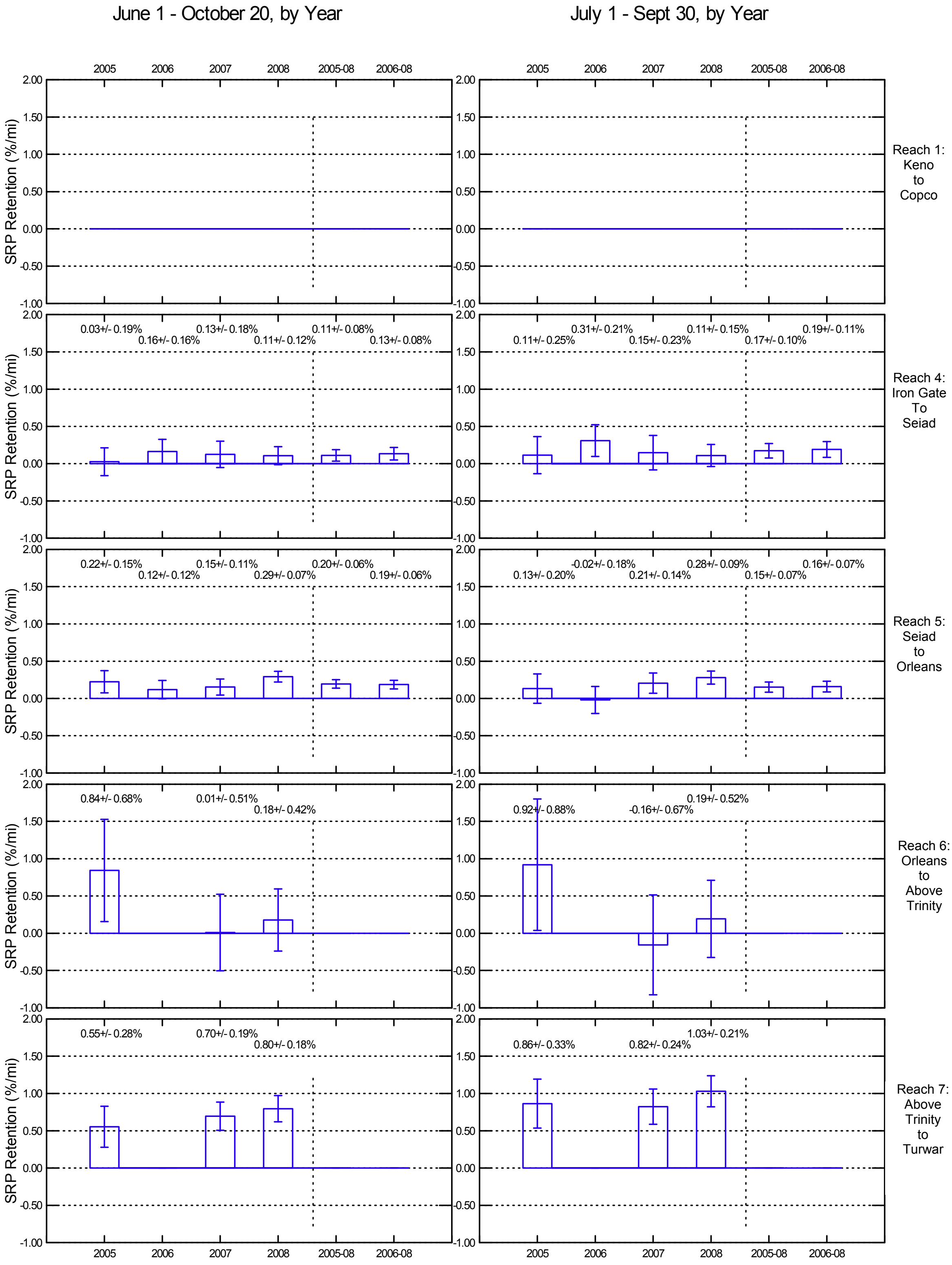

Figure 16. Soluble reactive phosphorus (SRP) relative (as a percent of inflow) retention rates per mile in primary river reaches for the June-October and July-September periods of each year with available data. Error bars are +/- one standard error (based on regression model).

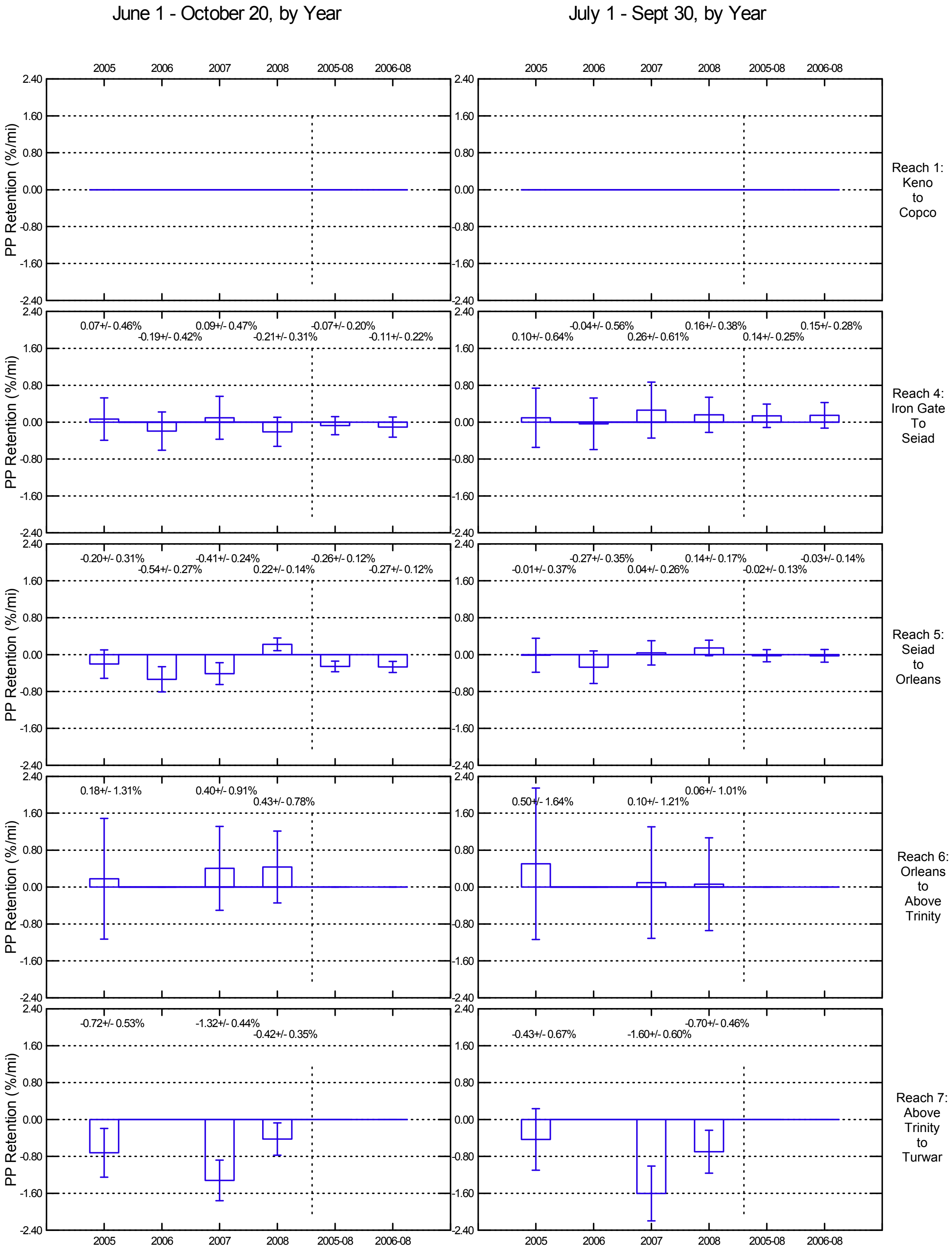

Figure 17. Summary of particulate phosphorus (PP) relative (as a percent of inflow) retention rates per mile in primary river reaches for the June-October and July-September periods of each year with available data. Error bars are +/- one standard error (based on regression model).

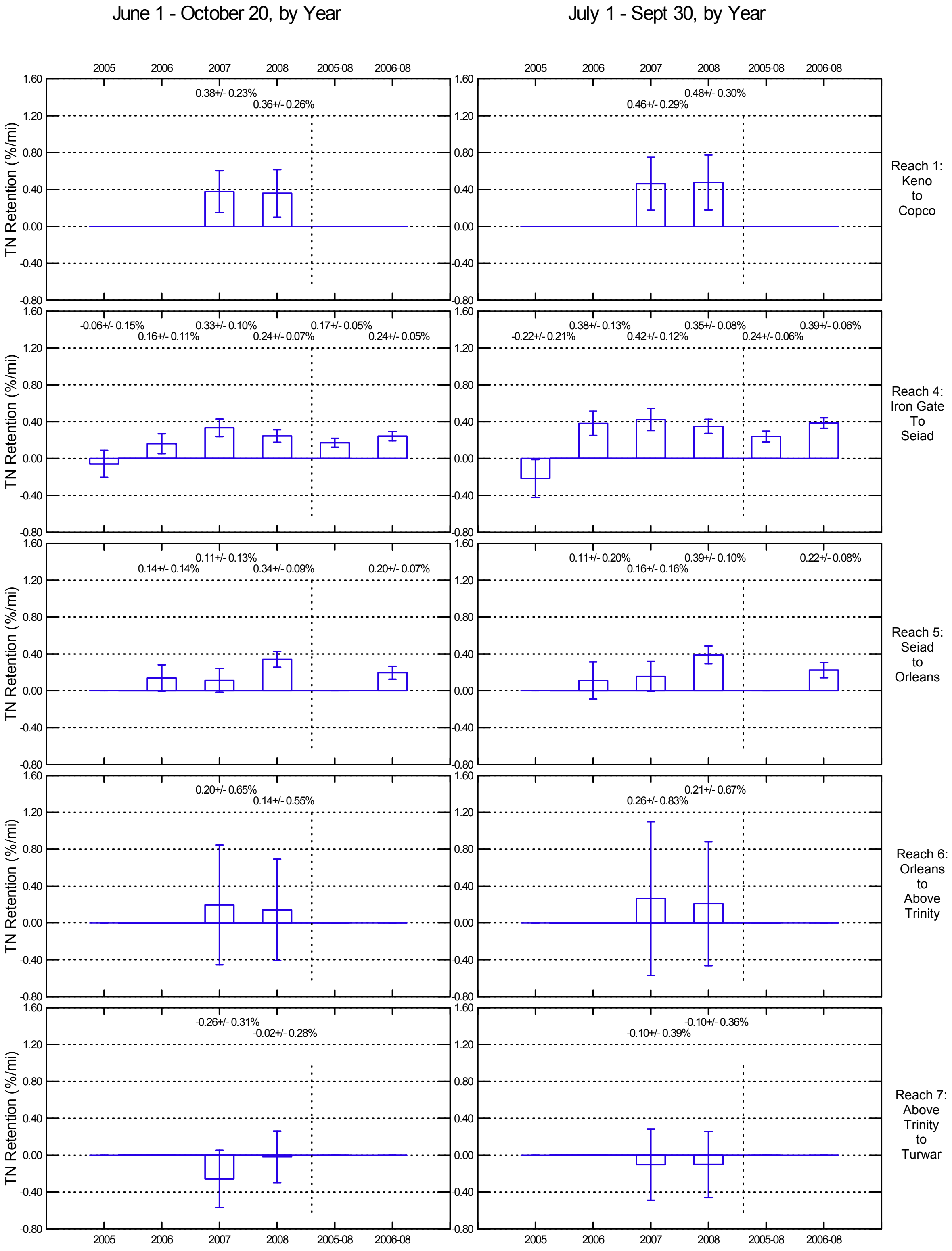

Figure 18. Summary of total nitrogen (TN) relative (as a percent of inflow) retention rates per mile in primary river reaches for the June-October and July-September periods of each year with available data. Error bars are +/- one standard error (based on regression model).

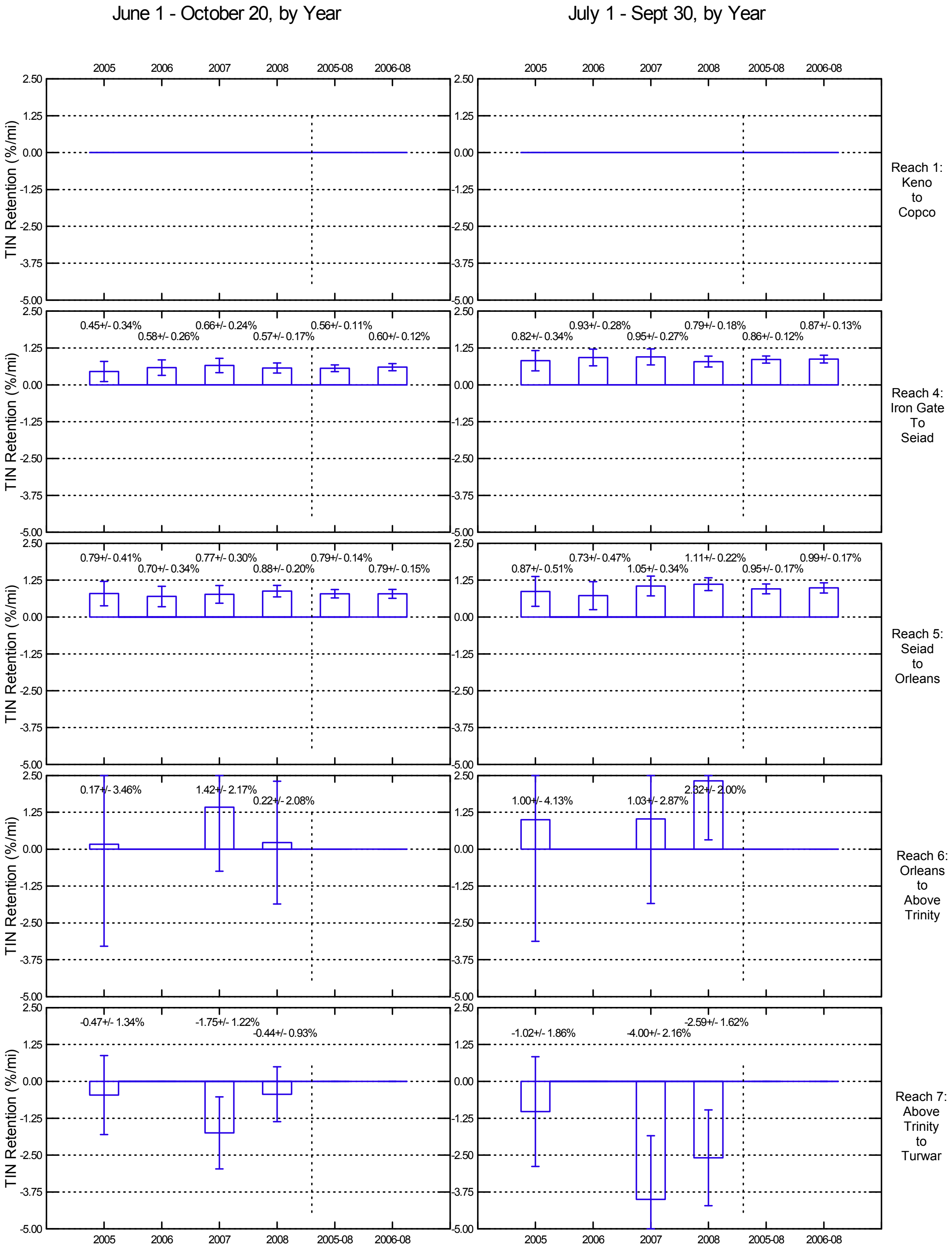

Figure 19. Summary of total inorganic nitrogen (TIN) relative (as a percent of inflow) retention rates per mile in primary river reaches for the June-October and July-September periods of each year with available data. Error bars are +/- one standard error (based on regression model).

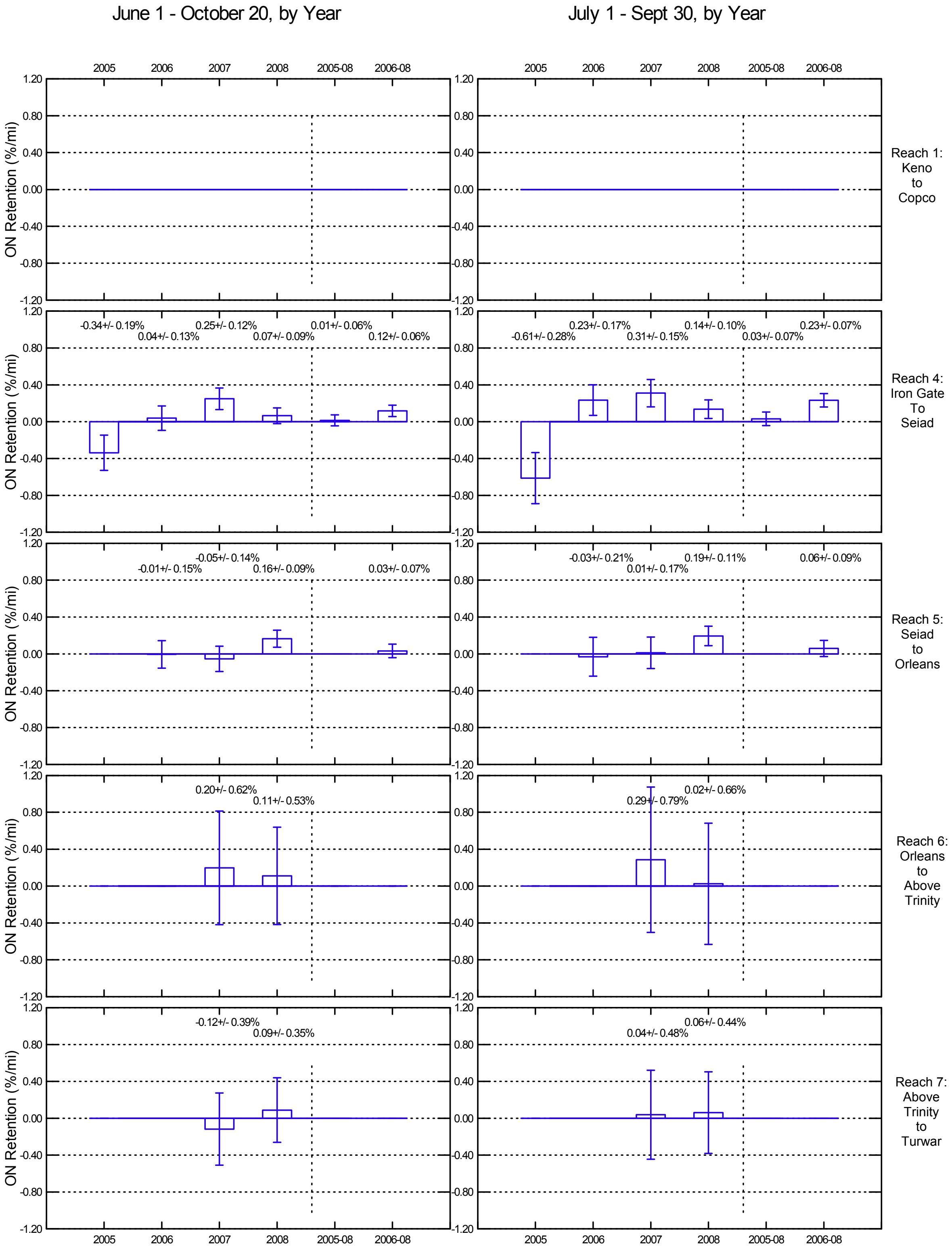

Figure 20. Summary of organic N (ON) relative (as a percent of inflow) retention rates per mile in primary river reaches for the June-October and July-September periods of each year with available data. Error bars are +/- one standard error (based on regression model).

Table 6. Comparison of seasonal retention rates at Reaches 4 (Iron Gate to Walker), Reach 4A (Iron Gate to Walker), and 4B (Walker to Seiad), for 2008.

Parameter	Relative Retention Rate (%/mile)					
	June-October 2008			July-September 2008		
	Reach 4: IG-Seiad	Reach 4A: IG-Walker	Reach 4B: Walker-Seiad	Reach 4: IG-Seiad	Reach 4A: IG-Walker	Reach 4B: Walker-Seiad
TP	0.06	-0.11	0.27	0.15	-0.14	0.48
TN	0.25	-0.02	0.57	0.35	0.21	0.57
TIN	0.58	0.51	0.83	0.78	0.57	1.31
SRP	0.11	-0.09	0.34	0.11	-0.15	0.41
PP	-0.17	-0.78	0.42	0.20	-0.53	0.92
ON	0.07	-0.24	0.41	0.14	0.04	0.26

Supplemental reach 7A (Below Trinity to Turwar), an alternate configuration of Reach 7 (Above Trinity to Turwar) utilizes the Below Trinity station as the upstream boundary, rather than Trinity River and Klamath River above Trinity. While some retention differences were observed between the two reaches (Appendix A3), overall they showed similar patterns, providing a partially independent (different upstream boundary) dataset to confirm the Reach 7 results.

3.5.2.3 Retention Monthly Comparisons for Primary Reaches

In addition to summarizing the nutrient budgets for the June-October and July-September periods, monthly summaries were also calculated to provide further detail on seasonal nutrient dynamics (Figure 21). Depending upon the parameter, reach, and month, there are two to four years of available data. Given that the sample size for any individual month is relatively small, caution should be exercised in interpreting these results; however, the results show consistent patterns among years for some parameters and reaches and thus are included here.

In both Reaches 4 (Iron Gate to Seiad) and 7 (Above Trinity to Turwar), TP retention was negative in June and positive for July-October. SRP retention was positive for all reaches and months except for June in Reach 4 (Iron Gate to Seiad). PP retention was negative for many reaches and months, including every month at Reach 7 (Above Trinity to Turwar).

For all N parameters, Reach 6 (Orleans to Above Trinity) June-July retention was always negative. TN and TIN retention at Reach 4 (Iron Gate to Seiad) and Reach 5 were positive for each month. In contrast, Reaches 6 and 7 (Above Trinity to Turwar) consistently showed negative retention for TN and TIN negative in the months June-September (not October). TIN retention at Reach 4 (Iron Gate to Seiad) shows a bell-shaped pattern, with higher rates in July-September than in June and October. To a lesser degree this TIN pattern was also present at Reach 5 (Seiad to Orleans). As evidenced by error bars there was relatively little inter-annual variation in TIN retention rates for any month for Reaches 4 and 5.

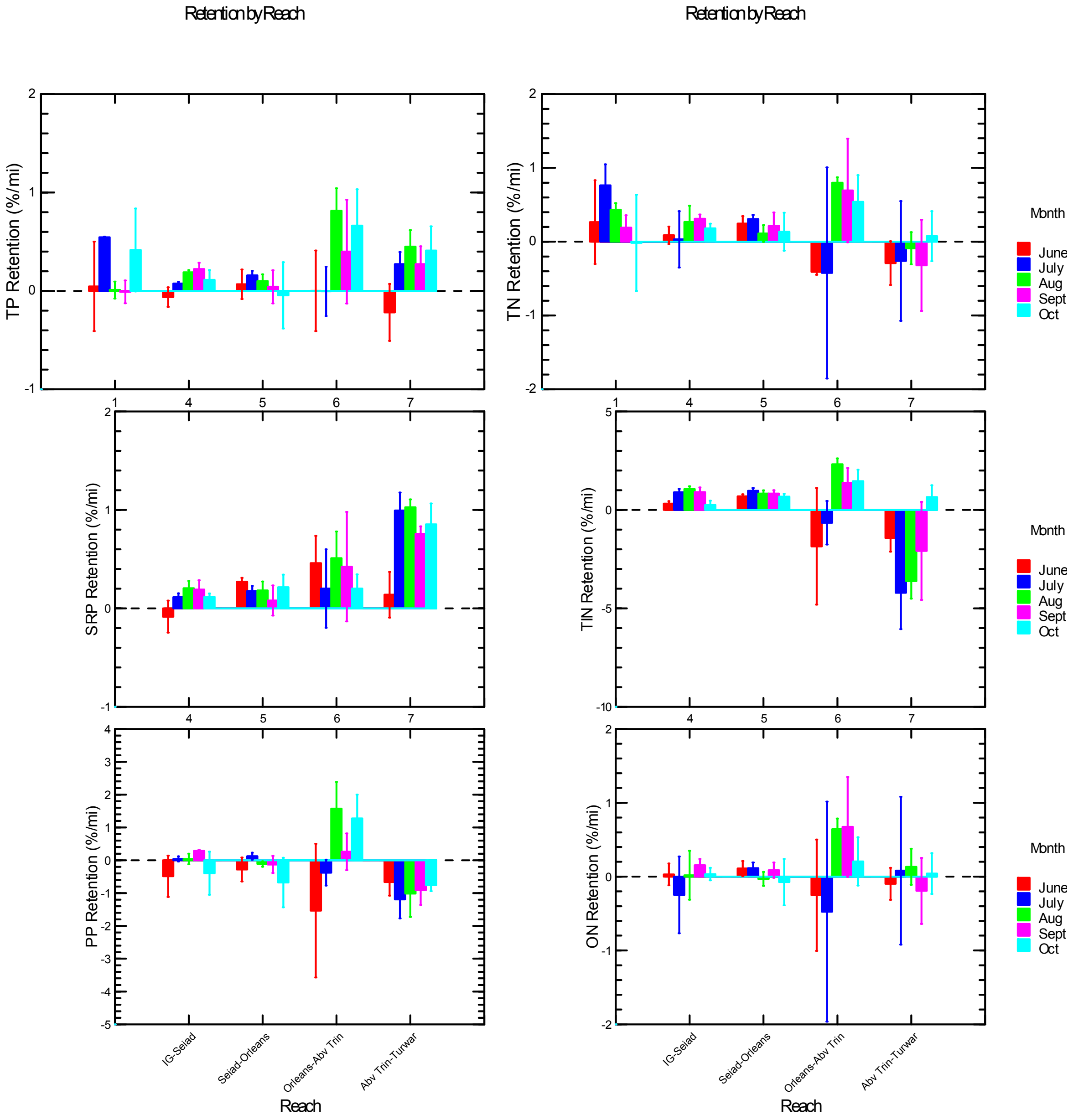

Figure 21. Comparison of relative (percent of inflow) retention by month for primary river reaches. Nutrient budgets were summarized on a monthly basis, resulting in one data point for each unique combination of parameter, reach, and year of available data. The mean of the years (there were two to four years depending upon site and parameter) was then calculated and is shown as the bar height in the graphs. *Error bars on the graphs represent the standard error of the mean of the years, thus indicating variation between individual years* (note: this is different than error bars used elsewhere in this report, which represent variation across the entire period of available data with all years combined together).

3.5.3 Effects of Retention at River-wide Scales

The effect of nutrient retention across longer river distances was evaluated by aggregating adjacent primary reaches.

These analyses indicate that large quantities of nitrogen and phosphorus were retained when longer river lengths were considered (Figure 22). For example, the Iron Gate nutrient load was reduced by 24% for TP, 25% for SRP, 21% for PP, 41% for TN, 93% for TIN, and 21% for ON during July-September 2007-2008 in the 130 miles from Iron Gate to Orleans (Figure 22 and Appendix E2). Load reductions for the June-October period were lower: 16% of TP, 24% of SRP, -9% of PP, 34% of TN, 82% of TIN, and 15% ON (Appendix E2).

As noted earlier, both nutrient retention and tributary dilution contribute to reducing nutrient concentrations in the Klamath River as water flows downstream from Iron Gate Dam. An evaluation of the relative effect of dilution versus retention indicates that although tributary dilution generally has a proportionally greater effect on concentration reduction, retention is also an important factor (Figure 23). For example, in the July-September periods of 2007-2008 flow-weighted average TN concentrations decreased from 1.055 mg/L at Iron Gate to 0.388 mg/L at Orleans, a decline of 63% (Figure 23). Of that 63% decline, 65% was due to dilution and 35% due to retention (Figure 24). For TIN, where the 93% decrease in TIN concentrations between Iron Gate and Orleans was due 54% to retention and 46% to dilution (Figure 24), the effect of retention was higher than that of dilution. The longitudinal trajectory of the effect of retention on TP concentration was similar to TN, although the percent reductions were slightly lower than for TN (Figure 24).

There appears to be a longitudinal trend in the relative contribution of retention to concentrations decreases, with retention contribution higher at Seiad, intermediate at Orleans and Above Trinity, and lower at Turwar (Figure 24). This longitudinal trend can be explained by both low tributary inflow from Iron Gate to Seiad (translating to a small dilution effect) and higher retention rates in upstream reaches (Figure 13).

These evaluations of the relative effects of dilution and retention have important implications for Klamath River water quality computer models, because under-representation of natural retention processes in a model could substantially over-estimate nutrient concentrations in the lower Klamath River. For example, in the Iron Gate to Seiad TN example cited above, a dilution-only (no retention) model would predict an Orleans concentration of 0.620 mg/L, 60% higher than the actual value of 0.388 mg/L.

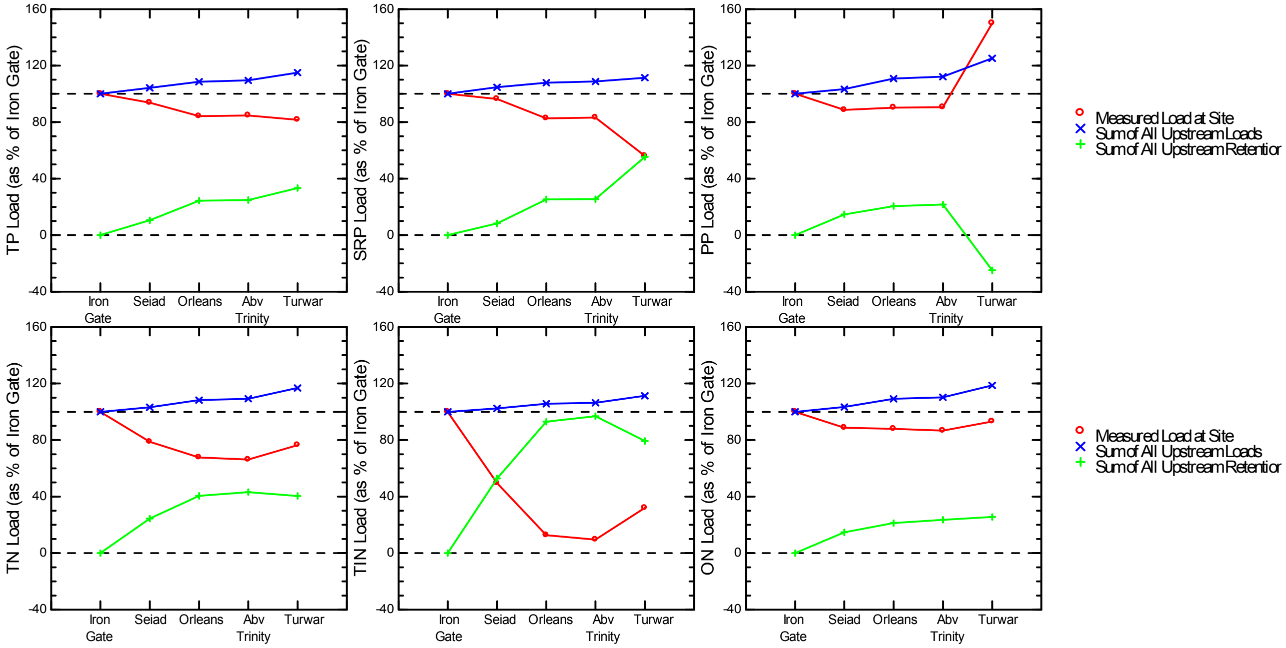

Figure 22. Measured nutrient load (implicitly includes the effects of retention), cumulative upstream load (this parameter equals expected load absent any retention), and upstream load retained (this parameter is the difference between cumulative and measured load) for sites from Iron Gate to Turwar for July-September 2007-2008. All values are expressed as a percent of load at Iron Gate Dam.

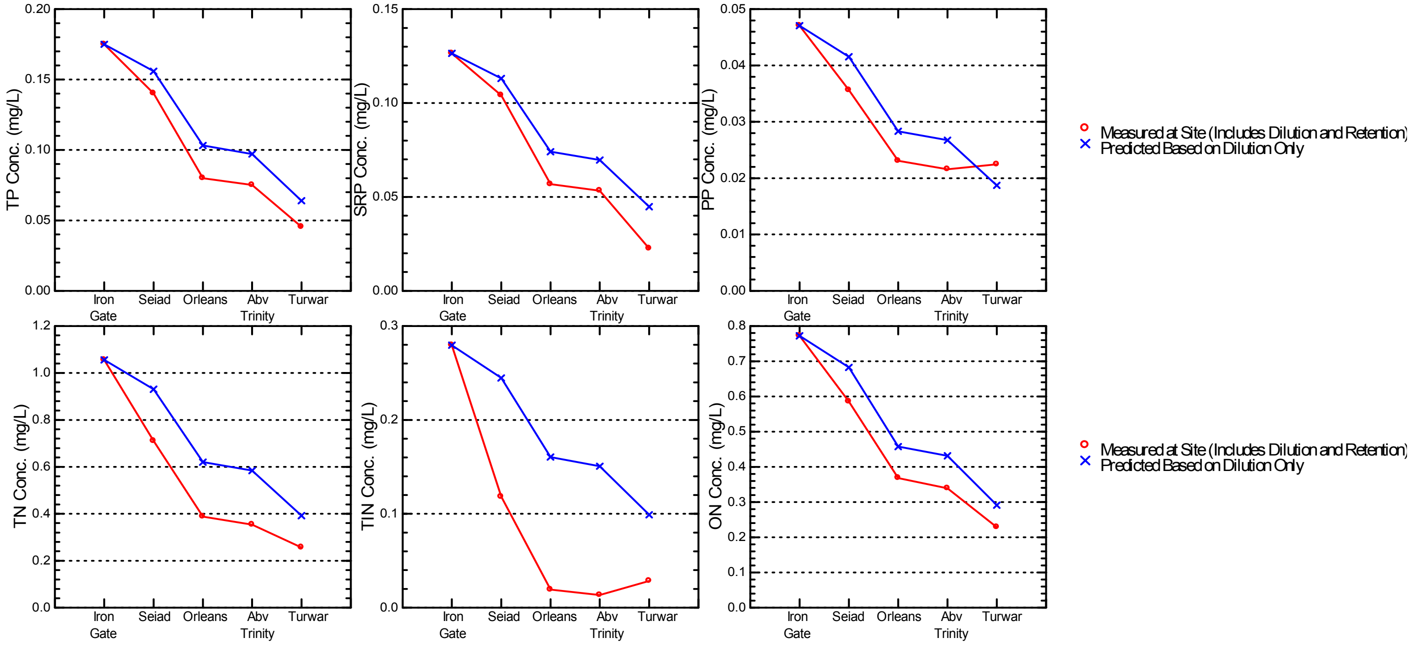

Figure 23. Comparison of measured flow-weighted average concentrations (decreasing trend due to combination of dilution and retention) and predicted flow-weighted average concentration without in-river retention (decreasing trend below Iron Gate due solely to tributary dilution of nutrient loads) at sites from Iron Gate to Turwar for July-Sept. 2007-08. The difference between the two lines is the effect of retention. Predicted flow-weighted average concentration without in-river retention was calculated as the cumulative upstream input load (i.e., mainstem Klamath at Iron Gate plus all applicable gaged and ungaged tributaries for the July-Sept. 2007-08 period) divided by total water volume for the same period.

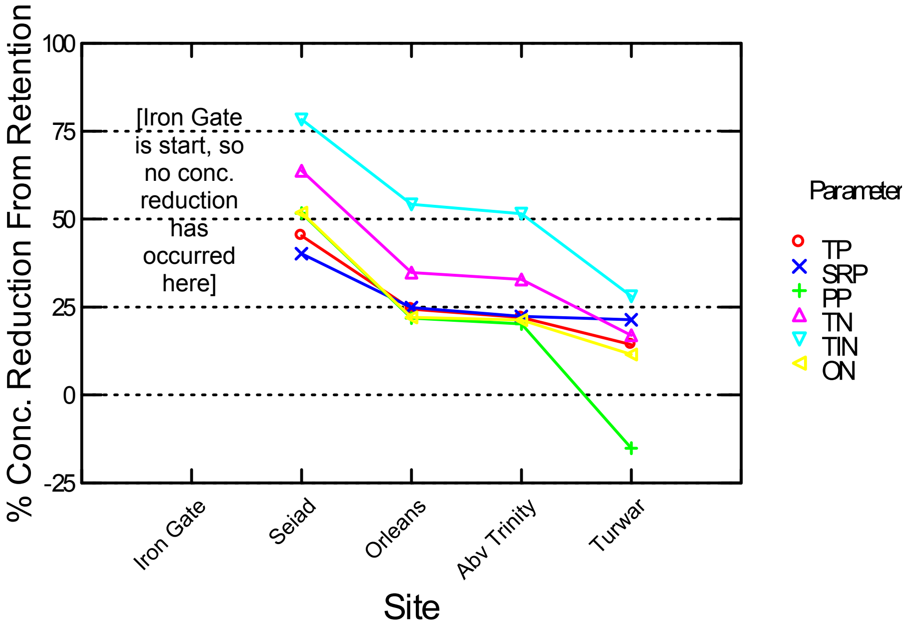

Figure 24. Percent of the reduction in nutrient concentration due to nutrient retention alone, between Iron Gate Dam and sites downstream for the July-September periods of 2007-2008.

4 DISCUSSION

The study results indicate that although nutrient retention rates on the mainstem Klamath River varied by parameter, reach, year, season, and month during 2005-2008, temporal and spatial patterns were also evident. Although comprehensive investigation of the causative factors for these patterns is beyond the scope of this report, the following section explores several of these potential factors. In addition, we provide context for how the study results can inform nutrient and algal biomass management as related to the TMDLs currently under development and hydropower relicensing, as well as comparisons to previously calculated reservoir retention in Reaches 2 and 3.

4.1 POTENTIAL FACTORS ACCOUNTING FOR RETENTION PATTERNS

4.1.1 River Gradient

Several aspects of gradient can impact nutrient dynamics in riverine systems. For example, lower gradient reaches are likely to have more alluvial features and consequently may have higher rates of hyporheic exchange and potentially higher denitrification rates (Sjodin 1997). Lower water velocities typical in low-gradient reaches can promote settling of nutrient-containing particulates. Faster velocities and confined channels in steep reaches may cause more scour, limiting periphyton biomass accrual. In addition, steeper gradient reaches are typically associated with canyons and therefore may experience greater topographic shading and more scour than lower-gradient reaches, potentially impairing periphyton growth.

The elevational and gradient profile of the Klamath River (Figure 25) suggests four discrete reaches of differing gradients: a nearly flat reach between Link Dam and Keno Dam, a high-gradient reach between Keno Dam and Iron Gate Dam (although the gradient beneath inundated areas of Iron Gate and Copco Reservoirs is lower than upstream reaches), a moderate gradient reach from Iron Gate Dam to below the Trinity River, and then a low-gradient reach from below the Trinity River to the Klamath River estuary (Figure 25). In addition, short low-gradient segments are present at various points along the Klamath River, including Frain Ranch (~ 5 miles below J.C. Boyle Dam), immediately above the Shasta River, ~5 miles above the Scott River, ~5 miles above the Salmon River, and ~5 miles above the Trinity River.

The factors identified above suggest that nutrient retention might be expected to be higher in low-gradient reaches and lower in high gradient reaches. However, the opposite pattern appears to be occurring for nitrogen in the Klamath River. Reach 1 (Keno to Copco) spans the steepest reach in the entire mainstem Klamath River, yet had the highest rates of TN retention (on both a relative and absolute basis). In addition, the only reach with consistent negative retention in the June-October and July-September periods for TN and TIN was Reach 7 (Above Trinity to Turwar), which has the lowest gradient of any reach evaluated. Thus, it is likely that factors other than gradient may be driving nitrogen dynamics.

Some examples include:

- High retention nitrogen rates in Reach 1 (Keno to Copco) may be due to ammonia volatilization in the steep, well aerated section between Keno Dam and J.C. Boyle reservoir. In most flowing waters ammonia concentrations and pH are not high enough for ammonia volatilization to occur at substantial rates (Bernot and Dodds 2005); however, when pH is high (>8), volatilization of ammonia can be an important process (McCutcheon 1989). Both ammonia concentrations and pH are high during the summer months at Keno Dam (the upstream extent of Reach 1), with both parameters diminishing downstream to J.C. Boyle Reservoir (Deas 2008). In addition to a substantial conversion of nitrogen form (NH_3 to NO_3+NO_2) in that reach, data[9] from Deas (2008) indicate that, although variable, TN concentrations were 4% lower overall at the bottom of the reach during the July-August period of high pH (computed from mean of 4 July and 4 August dates in 2007). The 2007-2008 results for Reach 1 (Keno to Copco) also indicate that TN retention rates were higher in July and August than other months (Figure 21). These data indicate that ammonia volatilization may account for at least a portion of the retention that occurs in Reach 1; however, additional data and analysis are needed to confirm this potential trend.

- It is possible that J.C. Boyle Reservoir could be contributing to the high nitrogen retention rates observed in Reach 1 (Keno to Copco), despite the reservoir's low hydraulic retention time.

- Reach 7 (which had low to negative retention rates) is influenced by coastal fog, and although not evaluated here, a potential decrease in water temperature and sunlight could explain the decreased retention by algal or plant uptake in this reach.

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[9] http://www.pacificorp.com/content/dam/pacificorp/doc/Energy_Sources/Hydro/Hydro_Licensing/Klamath_River/Klamath_Water_Quality_Data_2007.xls

- Although width-to-depth ratios begin to increase in Reach 7, overall maximum depths were higher than upstream sections which may reduce the amount of light reaching the riverbed and hence limit retention associated with primary production (Figure 26). However, the effect of increased depth on light extinction could be offset by increased light penetration due to a potential increase in water clarity below the Trinity River confluence. PacifiCorp (2008) suggested that light availability may be a potential limiting factor for periphyton in the Klamath River below the Trinity River (and between Keno Dam and Copco Reservoir), but light measurement data are scarce[10] in the Klamath River.

- As noted above, TN and TIN concentrations followed a strong longitudinal trend, with lowest concentrations in downstream portions of the river such as Reach 7. Thus, as examined in the following section, low or negative TN and TIN retention rates in Reach 7 may be the result of very low inflow N concentrations.

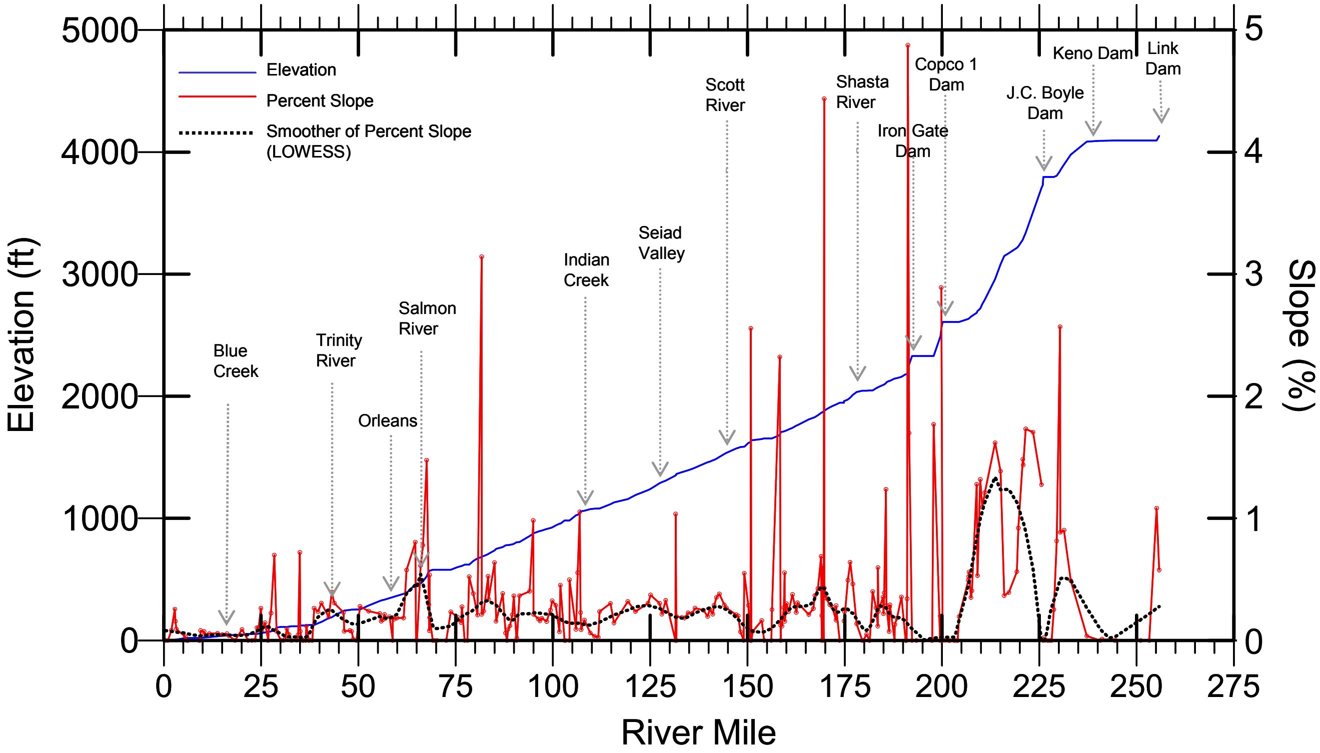

Figure 25. Elevational and gradient profile of the Klamath River. Nodes (points) along the slope line represent where tributaries enter. Note: the river miles shown in this figure differ slightly from those typically used for the Klamath River and shown in Table 1.

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[10] Data from early September 2004 indicate that most mainstem Klamath River sites had a 50% or greater reduction in light availability between the surface and 0.3 meters depth (Eilers 2005). Light extinction rates measured at mainstem Klamath River sites in August 2004 indicate water clarity increases substantially between Keno Dam and the Trinity River confluence (no data available are below the Trinity River), with Ke values ranging from ~2.5 m^{-1} and ~0.5 m^{-1} (PacifiCorp 2008).

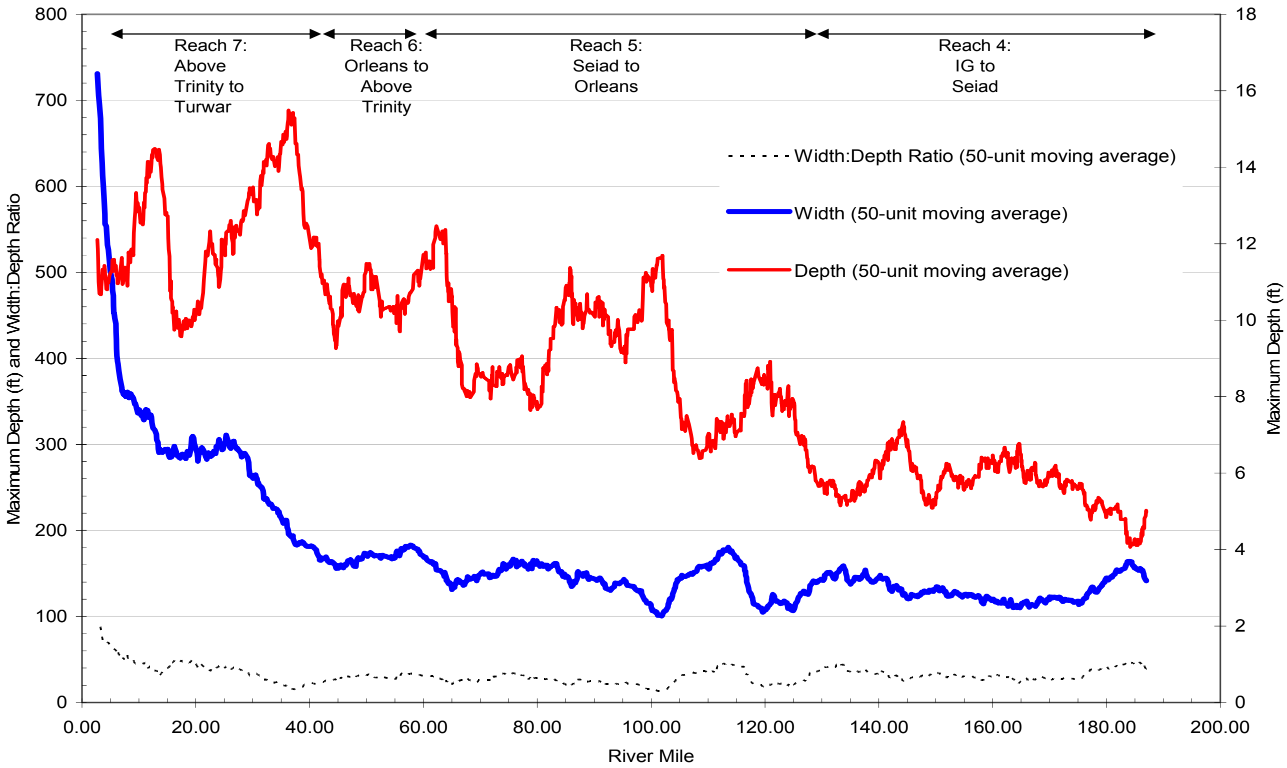

Figure 26. Maximum width, maximum depth, and width:depth ratios in Klamath River meso-habitat units from Iron Gate Dam to the river's mouth. Mean depth and mean width are not available. Data from U.S. Fish and Wildlife Service, Arcata Office.

4.1.2 Inflow Concentration

Scatterplots of the relationship between retention rates and inflow concentrations for the July-September period are shown in Figure 27 and Figure 28. The figures allow graphical evaluation of trends both between and within reaches (similar plots with load on the x-axis instead of concentration showed similar results and thus are not included here).

On both an absolute and relative basis TN retention showed a clear pattern of higher retention with higher inflow TN concentrations (Figure 28). ON retention exhibited a similar pattern, but with more scatter (Figure 28). A similar trend was evident for TIN on an absolute basis, not only between reaches (as with TN) but also within reaches (Figure 28). For reaches 4 (Iron Gate to Seiad) and 5 (Seiad to Orleans), years with higher TIN concentrations had higher TIN retention on an absolute basis. On a relative basis, reaches Reaches 4, 5, and 6 (Orleans to Above Trinity) were similar to each other (regardless of TIN inflow concentration) and there was remarkably little inter-annual variation, with ten of eleven reach-years showing TIN retentions from 0.70 to 1.1 percent/mile (Figure 28).

These results have important implications for potential management changes. For example, if dam removal results in increased nitrogen concentration at Iron Gate Dam (see section 4.3.1), the above analysis suggests that downstream retention rates are likely to rise in response to the increased concentration. These increased retention rates downstream would then partially offset the effects of increased Iron Gate load on nitrogen concentrations in reaches farther downstream. The influence of concentration on retention rates would also need to be factored in when determining the effect of upstream management efforts (i.e., treatment wetlands and/or reduced agricultural runoff) on downstream concentrations.

Whereas absolute retention for N parameters was generally lower at reaches with lower incoming N concentrations, the opposite pattern is evident for TP and SRP (Figure 27). Some of the highest rates of TP and SRP retention occurred in Reaches 6 (Orleans to Above Trinity) and 7 (Above Trinity to Orleans) in years with low incoming concentrations. There are not strongly apparent patterns in the relationship of PP retention to inflow concentration.

Scatterplots of the relationship between retention rates and inflow concentrations for the June-October period are shown in Appendix A4. The results exhibit similar trends as those of the June-October period but with more scatter, particularly for the PP and ON.

4.1.3 Nitrogen-Fixing Periphyton

Diatoms in the family Epithemiaceae, including the genera *Epithemia* and *Rhopalodia*, can fix nitrogen through endosymbiotic blue-green algae (Floener and Bothe 1980, Bahls and Weber 1988, DeYoe et al. 1992), and their presence can indicate nitrogen limitation (Power 1990). Diatoms with associated endosymbiotic blue-green algae and other nitrogen-fixing blue-green algae have been found to be important components of the periphyton community in other rivers in the region such as the North Fork Umpqua River (Anderson and Carpenter 1998) and the Clackamas River (Carpenter 2002).

Nitrogen fixation via periphyton is another factor that could explain the negative retention for N parameters in Reach 7 (Above Trinity to Turwar), and this phenomenon may be offsetting retention in other reaches. Monthly periphyton samples collected by the Yurok Tribe from ~May-October (shorter sampling season in some years) in 2006-2008 at Above Trinity and Turwar show that the periphyton species with the highest biomass was the diatom *Epithemia sorex* (51% of total biomass at Above Trinity and 35% at Turwar). Other N-fixing taxa (or those associated with N-fixing endosymbionts) present in periphyton at those sites included the blue-green algae *Calothrix sp.*, *Rivularia sp.*, and *Aphanizomenon flos-aquae*, and the diatom *Rhopalodia gibba* at Turwar.

Overall, the percentage of total periphyton biomass potentially associated with nitrogen-fixation was 66% at Above Trinity and 35% at Turwar. Periphyton sampling in 2004 found that *Epithemia sorex* was the dominant periphyton species in the lower 100 miles (from Happy Campy downstream) of the Klamath River in mid/late summer (HVTEPA 2008). Similar patterns were observed in periphyton sampling at Iron Gate, Seiad Valley, and Orleans by the Karuk Tribe in June-September 2008, where diatoms associated with N-fixation dominated (up to ~80% in some samples) July-September periphyton biomass at Orleans, were present at low/moderate levels at Seiad Valley (up to ~25%), and were absent at Iron Gate. In general, TN:TP ratios were below the 7.2 Redfield ratio also indicating potential N limitation (Figure 7) and consistent with the presence of N-fixing organisms in these river reaches.

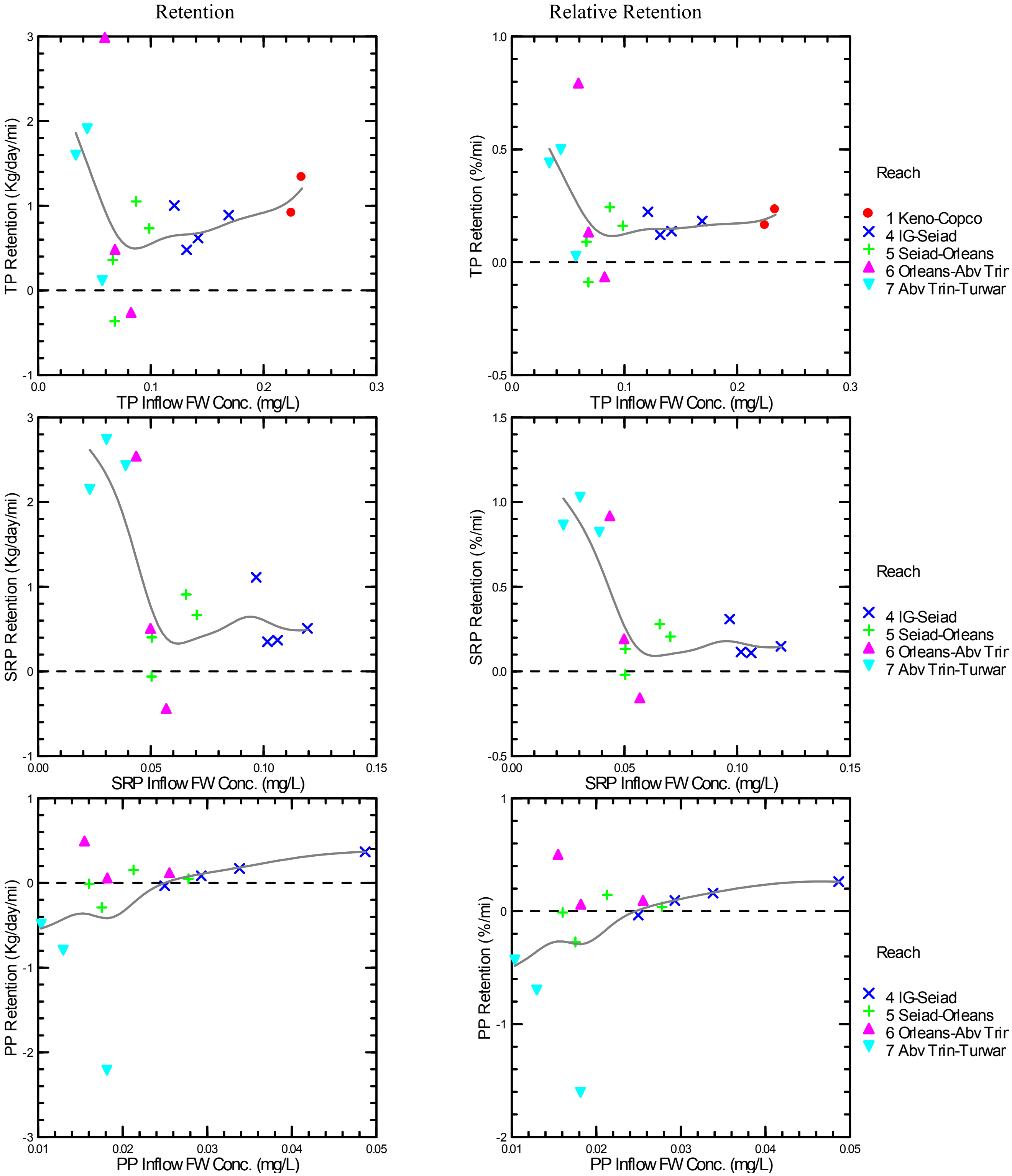

Figure 27. Relationship of retention to flow-weighted average inflow concentrations for phosphorus parameters in river reaches for the July-September period. Each data point is a summary of one season and site, providing a comparison between years and sites. DWLS smoother is displayed as a visual aid.

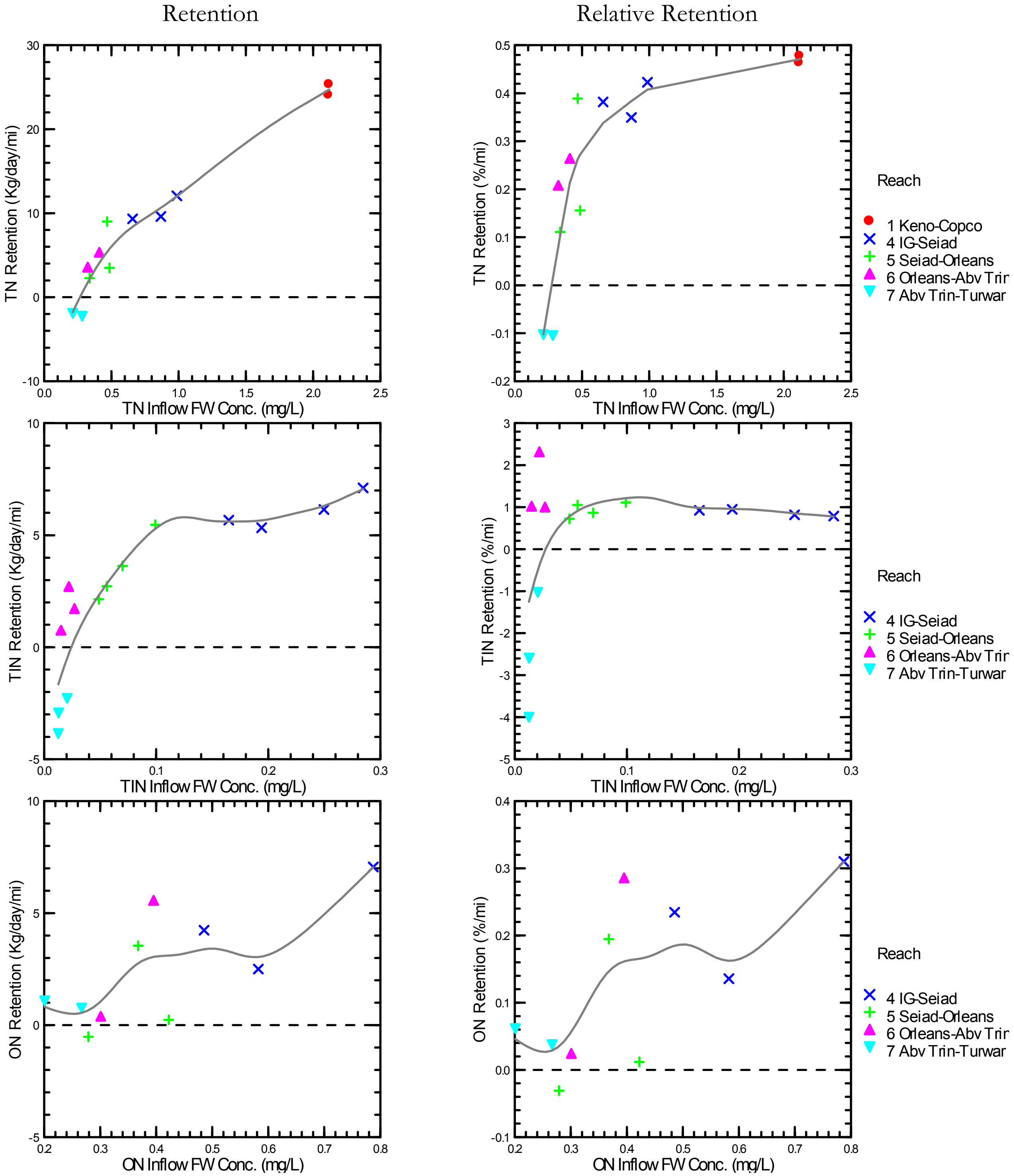

Figure 28. Relationship of retention to flow-weighted average inflow concentrations for nitrogen parameters in river reaches for the July-September period. Each data point is a summary of one season and site, providing a comparison between years and sites. DWLS smoother is displayed as a visual aid on all plots except TN relative retention (uses LOWESS smoother). TN and ON data for Reach 4 in 2005 are excluded because that data point appeared to be an outlier (see footnote 7 above for details).

4.2 COMPARISONS WITH A PREVIOUS STUDY OF NITROGEN IN FREE-FLOWING REACHES OF THE KLAMATH RIVER

The results presented here largely confirm the trends of a previous analysis (Asarian and Kann 2006) of TN dynamics in free-flowing reaches of the Klamath River for the years 1998-2002[11]. The current results are based on more robust data and analysis, but nonetheless, values are within a similar range and show similar longitudinal trends in nutrient retention.

For example, mean TN retention in 1998-2002 for the Iron Gate to Seiad reach was 0.41%/mile for July-September and 0.31%/mile June-October (Table 7), compared with 0.39%/mile and 0.24%/mile, respectively, for the mean of 2005-2008 data. A known factor contributing to these differences is that the Asarian and Kann (2006) study used a slightly higher TN concentration for ungaged tributaries (0.11 mg/L) than the 0.081 mg/L used in the current study.

Both studies also found that reaches between Iron Gate to Orleans generally had positive TN retention (Figure 14 , Figure 18, Table 5, Table 7). The only exception was 2002 (one of two years) for the Seiad Valley to Happy Camp reach (Table 7); however when the Seiad Valley to Happy Camp reach is summed with the adjacent Happy Camp to Orleans reach to result in a Seiad Valley to Orleans reach equivalent to Reach 5 of the current study, both 2001 and 2002 show positive TN retention.

Direct comparisons between the two studies were not made below Orleans due to high laboratory detection limits for nitrogen parameters in the previous study[12]. Due to low TN below Orleans as well as low TN in Trinity River inflows, many samples below Orleans were non-detect for nitrogen parameters, rendering the results of nutrients budgets for downstream reaches less reliable than for upstream reaches.

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[11] TN was only parameter analyzed by Asarian and Kann (2006).

[12] TN was calculated as TKN + NO3. In the 2001-2002 dataset for which TN budgets were calculated for reaches downstream of Orleans, NO3 detection limits for most samples were 0.05 mg/L or 0.1 mg/L and the TKN detection limit was 0.1 mg/L (Asarian and Kann 2006)

Table 7. Summary of total nitrogen retention (expressed as % retention per mile) for Klamath River reaches from Iron Gate Dam to Orleans for the June-October and July-September periods, 1998-2002. Table adapted from Asarian and Kann (2006) Table 7. As noted in the text above, reach configuration varied between the current study and Asarian and Kann (2006). The "equivalent reach number" is the reach number from the current study that is most similar.

Equivalent Reach Number	Reach Name	Length (miles)	Year	TN Retention (% of incoming per mile)			
				July to September		June to October	
				By Year	Mean of all Years	By Year	Reach Mean of all Years
4	Iron Gate to Seiad Valley	58.88	1998	0.39	0.41	0.24	0.31
	Iron Gate to Seiad Valley	58.88	1999	0.29		0.21	
	Iron Gate to Seiad Valley	61.15	2000	0.55		0.41	
	Iron Gate to Seiad Valley	61.15	2001	0.20		0.27	
	Iron Gate to Seiad Valley	61.15	2002	0.61		0.44	
5+6A	Seiad Valley to Youngs Bar	93.65	1999	0.28	0.28	0.24	0.24
5	Seiad Valley to Happy Camp	27.92	2001	0.32	-0.12	0.19	-0.19
	Seiad Valley to Happy Camp	27.92	2002	-0.55		-0.58	
	Happy Camp to Orleans	41.54	2001	0.70	0.71	0.53	0.63
	Happy Camp to Orleans	41.54	2002	0.72		0.73	

4.3 MANAGEMENT IMPLICATIONS

4.3.1 Effect of Dam Removal on Nutrient Concentrations Below Iron Gate Dam

To provide a range of estimates for how TP and TN concentrations at Iron Gate Dam might change under a dam removal scenario, the effect of relative retention rates in river reaches were compared to results from a study of the Copco-Iron Gate Reservoir complex by Asarian et al. (2009). Figure 29 is a simplified schematic diagram of the multi-step comparison process.

The Asarian et al. (2009) flow-weighted mean concentration results were calculated for the June-October and July-September seasonal periods (Table 8; note that original Asarian et al. [2009] seasonal summaries did not exactly match those used in the river nutrient budgets). These inflow and outflow concentration results, denoted as "measured data" in Table 8, were used to calculate the percent reduction under the current reservoir scenario (e.g., a 6.1% TP and 32.5% TN reduction was shown for the June-October period).

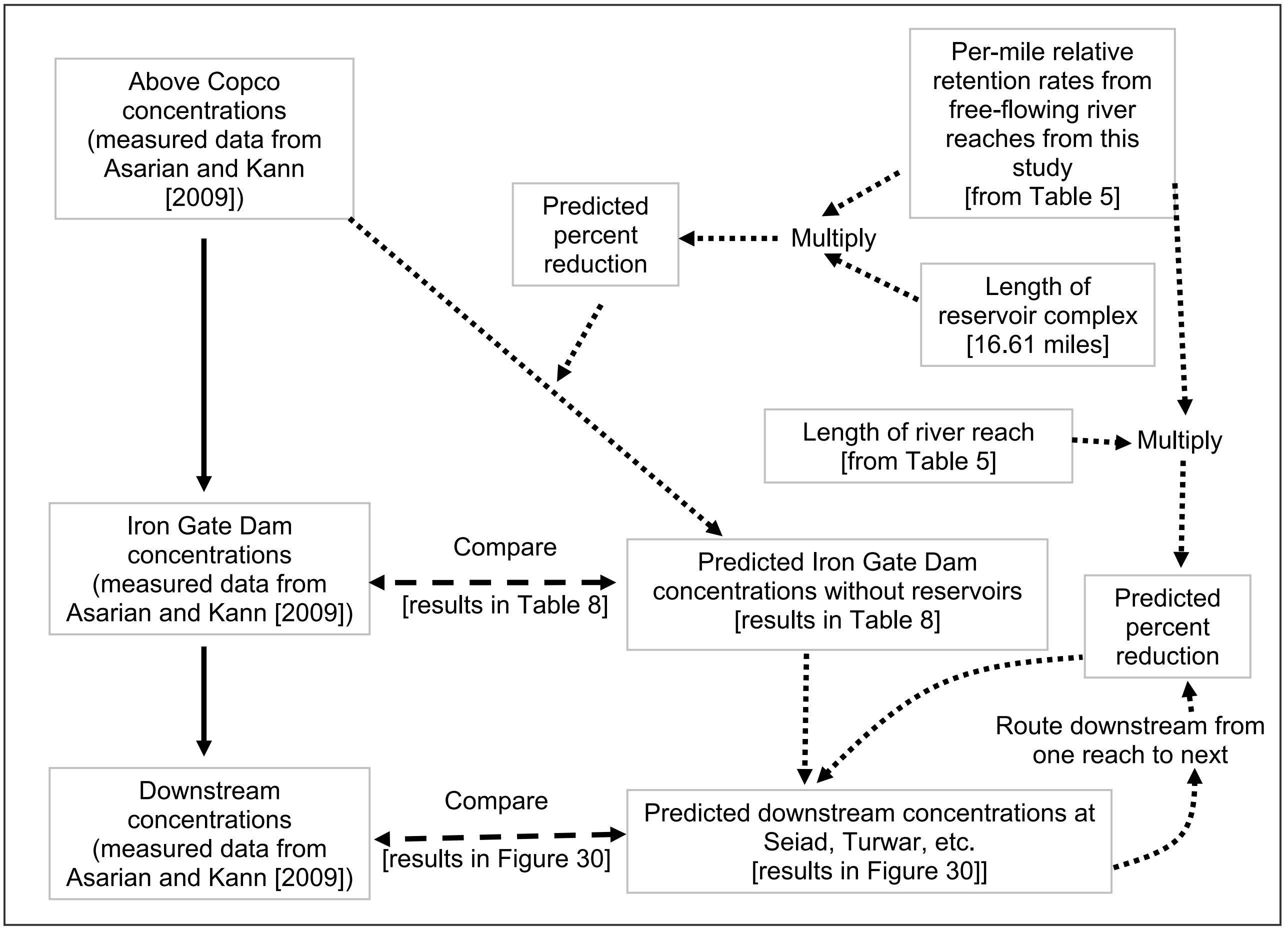

Figure 29. Simplified schematic diagram of method used to estimate the effects of dam removal on nutrient concentrations at Iron Gate Dam and sites downstream.

To evaluate the effect of river retention rates, relative retention rates (%/mile) from Table 5 were multiplied by the length of the Copco-Iron Gate Reservoir complex to estimate percent reductions in concentration that could occur in the reservoir reach absent the reservoirs. The effect of decreased evaporation[13] was also incorporated into the percent reductions. Those percent reductions were then applied to flow-weighted average inflow concentrations to estimate outflow concentration under a free-flowing scenario. The percent change from existing to free-flowing conditions was then computed from estimated and observed flow-weighted reservoir outflow (Iron Gate Dam) concentrations (Table 8). The results indicate that under a dam removal scenario, concentrations of TP and TN would likely rise.

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[13] Due to their large surface area (relative to river reaches), the reservoir complex currently evaporates 1.16% of June-October inflows and 1.49% of July-September inflows (for 2005-2007 as calculated from Asarian et al. 2009 data). This has the effect of increasing nutrient concentration by an equivalent amount. Conversely, in the absence of the reservoirs, reduced evaporation would cause this evaporative effect to largely disappear resulting in a 1.16-1.49% decrease in river nutrient concentrations (due to higher flows at Iron Gate Dam) in addition to the effects of river retention.

For example, TP concentrations are predicted to rise 2-12% (e.g., from 0.144 mg/L to 0.147-0.150 mg/L for the June-October period) under a dam removal scenario. Increases in TN concentrations under dam removal are predicted to be larger than for TP, approximately 37-42% (from 0.910 mg/L to 1.250-1.288 mg/L) for June-October and 48-55% (0.950 mg/L to 1.404-1.469 mg/L) for July-September (Table 8).

Table 8. Comparison of measured inflow/outflow concentrations for the Copco-Iron Gate Reservoir complex and estimated outflow concentrations based on per-mile retention rates in free-flowing river reaches.[14]

			% Conc. Reduction Through Reservoir Reach		**Concentration (mg/L)**		**% Conc. Change at Iron Gate Dam from Existing to Free-Flowing[4]**	
Para-meter	**Location**	**Data/Estimate Source**	**June-Oct**	**July-Sept**	**June-Oct**	**July-Sept**	**June-Oct**	**July-Sept**
TP	Reservoir Inflow	Measured data[1]			0.153	0.182		
	Reservoir Outflow (Iron Gate Dam)	Measured data[2]	6.1%	13.3%	0.144	0.158		
		Estimated from Reach 1 (Keno-Copco)[3]	4.3%	4.8%	0.147	0.173	1.9%	9.8%
		Estimated from Reach 4 (IG-Seiad)[3]	2.7%	4.3%	0.149	0.174	3.7%	10.3%
		Estimated from Reach 5 (Seiad-Orleans)[3]	2.2%	3.3%	0.150	0.176	4.2%	11.5%
TN	Reservoir Inflow	Measured data[1]			1.348	1.548		
	Reservoir Outflow (Iron Gate Dam)	Measured data[2]	32.5%	38.6%	0.910	0.950		
		Estimated from Reach 1 (Keno-Copco)[3]	7.3%	9.3%	1.250	1.404	37.4%	47.8%
		Estimated from Reach 4 (IG-Seiad)[3]	5.1%	8.0%	1.279	1.425	40.6%	50.0%
		Estimated from Reach 5 (Seiad-Orleans)[3]	4.5%	5.1%	1.288	1.469	41.6%	54.6%

Table notes:

1. Flow-weighted average inflow concentration (includes all mainstem and tributary reservoir inflows; computed from 2005-2007 measured data from Asarian et al. [2009]).
2. Flow-weighted average outflow concentrations (computed from 2005-2007 measured data from below Iron Gate Dam; data from Asarian et al. [2009]).
3. "% Conc. Reduction Through Reservoir Reach" was calculated by multiplying per-mile retention rates (Table 5) by 16.61 miles and then adding an additional 1.16% for June-Oct or 1.49% for July-Sept to account for the effect of decreased evaporation (see footnote 13); "Concentration (mg/L)" calculated by applying % reduction rate to measured inflow data.
4. "% Conc. Change at Iron Gate Dam from Existing to Free-Flowing" was calculated based on a comparison of concentrations for existing reservoir outflow (superscript 2, above) and those estimated using river retention rates (superscript 3, above).

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[14] A caveat here is that this method of comparison does not take into account other changes that would likely accompany the removal of Iron Gate and Copco Reservoirs, and which should have a beneficial (i.e. reducing) effect on river concentrations. For example, the effects of the elimination of hydropower peaking and the return of full flows to the J.C. Boyle Bypass Reach have not been quantified. Bypass operations likely reduce organic matter decomposition by routing the river around a turbulent reach, altering nutrient form. High flows from peaking operations decrease travel time and increase water level fluctuation, likely retarding the establishment of periphyton and leading to decreased nutrient retention rates.

The potential effect of increased Iron Gate Dam concentrations on downstream reaches was explored by routing the load downstream in a stepwise fashion. Concentrations were estimated both from reach-specific retention rates calculated above (Table 5) and from the relationship between inflow concentration and percent retention shown in Figure 28 and Appendix A4. These estimated concentrations were then compared to those from the existing with-dam condition (Figure 30) for the years 2007-2008 (the years with complete data for all primary reaches). First, estimated percent increase resulting from dam removal (mean of the Reach 1- and Reach 4-based values from Table 8) was multiplied by existing mainstem load to estimate without-dam concentration at Iron Gate. Second, total inflow load for the Iron Gate to Seiad reach was calculated as the sum of estimated mainstem inflow load and tributary load. Third, outflow concentration for the Iron Gate to Seiad Reach was estimated by applying retention rates (using two rates as described above) to total inflow load for the reach (see caption of Figure 30 for details on the retention values used in the two scenarios). In a stepwise fashion, this was repeated for all downstream reaches, with the estimated outflow load from one reach becoming the mainstem inflow load for the next reach. Although there are clearly uncertainties associated with the above exercise, and actual retention rates following dam removal are not known, the two scenarios presented in Figure 30 provide a reasonable preliminary exploration of downstream concentration.

The resulting analysis predicts that dam removal will result in only a very small change in TP concentration in the Klamath River between Iron Gate and Turwar (Figure 30). TN concentrations will increase more than for TP, although the magnitude of the increase diminishes with increasing distance downstream of Iron Gate. The effect is substantially diminished by Orleans and quite small at Turwar.

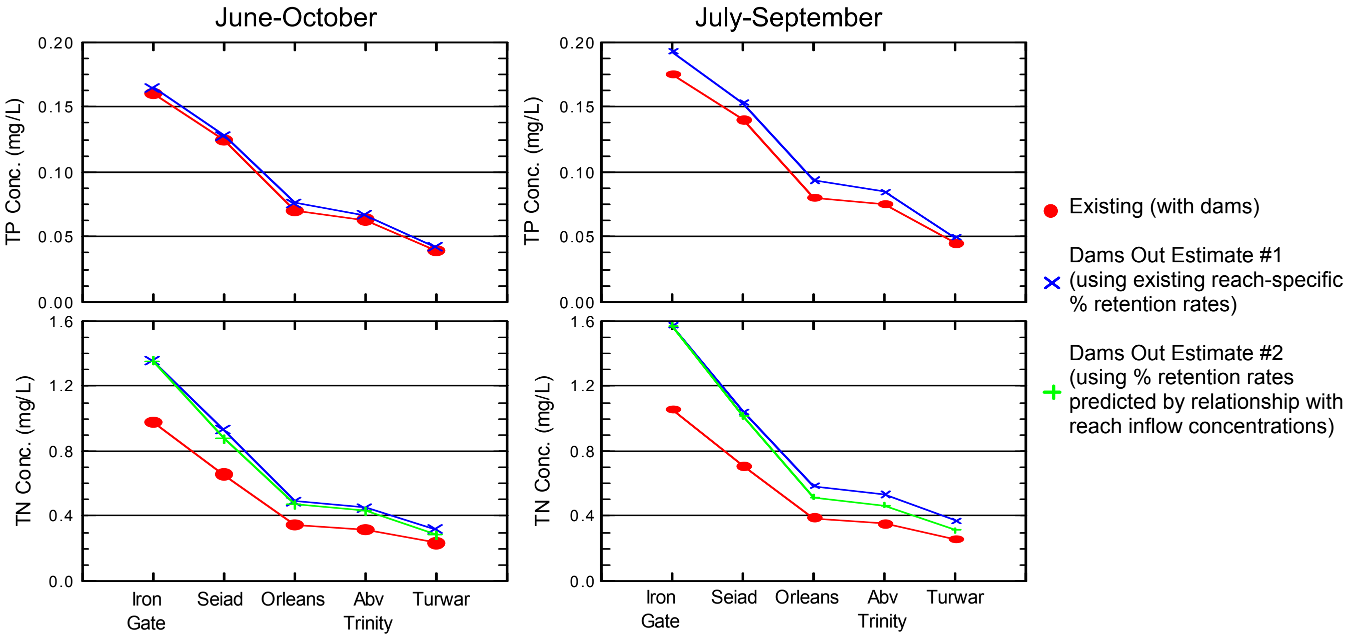

Figure 30. Comparison of TP and TN concentrations from Iron Gate Dam to Turwar for June-October (left panel) and July-September (right panel) of 2007-2008 under three scenarios: a) measured existing conditions, b) Dams-out scenario #1 estimated using the existing percent retention rates for each reach (Table 5), and c) Dams-out scenario #2 estimated by using the percent retention rates predicted by the relationship between reach inflow concentration and percent retention rates (estimated from trend lines in Figure 28 and Appendix A4). Dams-out scenario #2 was only applied to TN because TP had a weak relationship between inflow concentration and percent retention.

4.3.2 Implications of Changes to Nutrient Concentrations Following Dam Removal

Although estimated nutrient concentrations are predicted to increase in the mainstem Klamath River downstream of the dams following dam removal, the resulting effects on downstream algal and macrophyte growth are complex and may vary by reach. If, as indicated above, periphyton in the Klamath River between Iron Gate to Seiad are not nitrogen (or phosphorus) limited (i.e., see discussion in Section 4.1.3 above regarding lack of N-fixing periphyton species), the increases in nitrogen concentrations may not necessarily result in increased periphyton biomass but the effect on periphyton species composition is unknown. For example, filamentous green algae such as *Cladophora* have been identified as playing a key role in the life cycle of the salmonid parasite *Ceratomyxa shasta* (NCRWQCB 2010). The distribution, habitat, and nutrient requirements of *Cladophora* in the Klamath River are poorly understood[15]. Given the current lack of knowledge regarding *Cladophora* in the Klamath River, it is difficult to predict how the species will respond to dam removal or other management changes.

Increased N concentrations expected with dam removal would likely shift N-fixing algae farther downstream (from their current upstream limit of approximately Seiad Valley), and upstream flora could be replaced by non N-fixers. These observations provide an important point to consider when evaluating the effect of dam removal. For example, the current periphytic flora may enable N-fixation, thereby off-setting the effect of decreased N concentrations (due to both reservoir and natural retention) on plant biomass, and it is not clear that biomass of the non-fixers would be greater than that of the current flora. This is especially true because P is not expected to increase appreciably with dam removal, and in fact may even decrease at times (see Figure 7 above and Asarian et al. 2009). Whether or not a shift to P limitation would occur under such a scenario is unclear; however such factors as increased N, stable or decreasing P, N:P ratios, and N-fixation must be considered when evaluating the effect of dam removal on projected plant biomass and water quality in the river below Iron Gate dam. For example, it also appears that N is currently decreased at a proportionally greater rate than P between above Copco and below Iron Gate, leading to lower N:P ratios below Iron Gate (Figure 7). Overall, ratios currently decrease downstream and are generally below the 7.2 Redfield ratio also indicating N limitation and consistent with the presence of N-fixing organisms in the river.

Moreover, other reach-specific factors such as substrate, flow velocity, shading, light, and water temperature also affect biomass trends independent of nutrient dynamics. Such factors must be evaluated when attempting to determine algal or macrophyte biomass following dam removal. Additionally, upstream nutrient reductions (i.e., from treatment wetlands and/or reduced agricultural runoff) could offset the increases in nutrient concentration caused by dam removal.

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[15] There have been no systematic efforts to map the distribution of filamentous green algae (e.g., *Cladophora*) in the mainstem Klamath River. Anecdotal evidence indicates that it grows in dense patches. Within a short reach of river, it can be both highly abundant in some areas and completely absent in others (Richard Stocking, pers. comm.). Due to this patchy distribution, the limited periphyton surveys that have been conducted in the Klamath River have not yet detected *Cladophora*, but the species has been noted during other surveys (*i.e.*, fish disease research).

Finally, in determining the effect of dam removal on algal and plant biomass, the direct effect of dam presence or removal on sediment transport (and substrate), hydrology, light limitation, and days of biomass accrual should be evaluated.

5 CONCLUSIONS

The study described here examined nutrient loading and retention dynamics in the Klamath River from Keno Dam to Turwar, just upstream of the Klamath Estuary, for the June-October and July-September periods of the years 2005-2008, with a focus on the free-flowing river reaches. Nutrient parameters examined included total phosphorus (TP), soluble reactive phosphorus (SRP), particulate phosphorus (PP), total nitrogen (TN), total inorganic nitrogen (TIN), and organic nitrogen (ON).

Due to a combination of factors including tributary dilution and retention in reservoir and river reaches, flow-weighted average June-October concentrations of phosphorus parameters all exhibited large (~10x) decreases from Keno Dam to Turwar. Flow-weighted average June-October concentrations of nitrogen parameters also exhibited large (~10x for total nitrogen and organic nitrogen, ~40x for total inorganic nitrogen) decreases from Keno Dam to Turwar.

Mass-balance nutrient budgets for individual reaches indicated that mainstem inflows were the dominant budget term, generally accounting for >90% of inflow load in 2008. Across the entire Iron Gate to Turwar aggregated reach (Reach 4+5+6+7) for June-October 2008, the mainstem Klamath at Iron Gate accounted for ~65-85% (varied by parameter) of total inflow load, gaged tributaries accounted for ~5-20%, and ungaged tributaries contributing the remaining ~5-10%.

Net retention for the various reaches/parameters was computed as the difference between inflow load [mainstem + gaged and un-gaged tributaries] and outflow load. Negative retention values denote a source from within the system (e.g., sediment or algal regeneration and nitrogen fixation), and positive values denote a sink (e.g., storage in plant or bacterial biomass, denitrification, and ammonia volatilization). Phosphorus retention varied by year and parameter. Across the entire study period (i.e., mean of all years that had adequate data for each site), TP and SRP retention during the June-October and July-September periods was positive for the five primary river reaches. Overall, there appeared to be a longitudinal trend of increasing TP and SRP retention with increasing distance downstream of Iron Gate, and decreasing (or more negative) PP retention. On both a relative and absolute basis, the furthest downstream reach (Reach 7: Above Trinity to Turwar) had the most positive SRP retention and most negative PP retention, suggesting a shift in form from dissolved to particulate as well as an overall retention of phosphorus (TP retention was positive) in Reach 7. TP retention appeared to be positive overall for Reach 1 (Keno to Copco); however, uncertainty was high (possibly due to highly variable Keno TP concentrations) indicating that calculated TP retention in that reach was likely not significantly different from zero.

Nitrogen retention parameters showed clearer longitudinal patterns with less year-to-year variability. For example, a strong declining downstream retention trend was observed on both a relative and absolute basis, with TN retention highest in Reach 1 (Keno to Copco; 24.69 kg/day per mile and 0.47 percent/mile) and lowest (negative) in Reach 7 (Above Trinity to Turwar) for the July-September period. With the exception of Reach 7 (Above Trinity to Turwar) for 2007-2008 (the only years of adequate data for that reach) and Reach 4 (Iron Gate to Seiad) in 2005, TN retention was positive for both the June-October and July-September periods for all other reaches and years. On a relative basis TN retention was higher in the July-September period than in the June-October period at all five reaches; on an absolute basis it was higher at four of five reaches. TIN also showed a strong longitudinal trend, with higher absolute retention rates at the first two reaches below Iron Gate Dam (Reaches 4 [Iron Gate to Seiad] and 5 [Seiad to Orleans] where TIN was generally present at concentrations >0.05 mg/L), lower rates at Reach 6 (Orleans to Above Trinity), and negative rates at Reach 7 (Above Trinity to Turwar). Relative TIN retention rates within Reaches 4 and 5 were similar to each other (0.86±0.12 and 0.95±0.17 for July-September, respectively), with remarkably low year-to-year variation. Both relative and absolute ON retention values were generally lower than for TIN and TN in Reaches 4 and 5, but were higher in Reach 7. The results of this study largely confirm the trends of a previous analysis (Asarian and Kann 2006) of TN dynamics in free-flowing reaches of the Klamath River for the years 1998-2002. The current results are based on more a robust dataset and analysis, but nonetheless, values are in a similar range and show similar longitudinal trends in retention.

The observed negative retention rates for TN and TIN in Reach 7 (Above Trinity to Turwar) are likely due in part to very low incoming concentrations of TIN (the form of nitrogen most easily assimilated by periphyton) leaving nearly zero TIN available for algal uptake in the reach. The lack of TIN in the water column likely provides a competitive advantage to nitrogen-fixing species (particularly the diatom *Epithemia sorex* that associates with endosymbiotic blue-green algae), which dominate the periphyton communities in the mainstem Klamath River from Orleans (and perhaps farther upstream, there are only very limited samples between Seiad and Orleans) to Turwar in the low-flow season.

For nitrogen parameters, reach inflow concentrations appeared to be a major driver of retention rates. On both an absolute and relative basis, TN retention showed a clear pattern of higher retention in reaches with higher inflow TN concentrations. ON retention exhibited a similar pattern, but with more scatter. A similar trend was evident for TIN on an absolute basis, not only between reaches (as with TN) but also within reaches. These results have important implications for potential management changes. For example, if dam removal results in an increase in nitrogen concentrations at Iron Gate Dam, downstream retention rates are likely to rise in response to the increased concentrations. These increased retention rates downstream would then partially offset the effects of increased Iron Gate load on nitrogen concentrations in reaches farther downstream. The influence of concentration on retention rates would also need to be factored in when determining the effect of upstream management efforts (i.e., treatment wetlands and/or reduced agricultural runoff) on downstream concentrations.

The effect of retention across longer river distances was evaluated by aggregating adjacent primary reaches. These analyses indicate that large quantities of nitrogen and phosphorus are retained when longer river lengths were considered. For example, the Iron Gate nutrient load was reduced by 24% for TP, 25% for SRP, 21% for PP, 41% for TN, 93% for TIN, and 21% for ON during July-September 2007-2008 in the 130 miles from Iron Gate to Orleans. Load reductions for the June-October period were lower: 16% of TP, 24% of SRP, -9% of PP, 34% of TN, 82% of TIN, and 15% ON. Both nutrient retention and tributary dilution contribute to reducing nutrient concentrations in the Klamath River as water flows downstream from Iron Date Dam. An

evaluation of the relative effect of dilution/retention indicates that although tributary dilution generally has a proportionately greater effect on concentration reduction, retention is also an important factor.
For example, in the July-September periods of 2007-2008 flow-weighted average TN concentrations decreased from 1.055 mg/L at Iron Gate to 0.388 mg/L at Orleans, a decline of 63%. Of that 63% decline, 65% was due to dilution and 35% due to retention. The percent reductions in concentration due to retention were lower for phosphorus parameters and ON than for TN, but higher for TIN. These results have important implications for Klamath River water quality computer models, because under-representation of natural retention processes in a model could substantially over-estimate nutrient concentrations in the lower Klamath River. For example, in the Iron Gate to Seiad TN example cited above, a dilution-only (no retention) model would predict an Orleans concentration of 0.620 mg/L, 60% higher than the measured value of 0.388 mg/L.

To provide a range of estimates for how TP and TN concentrations at Iron Gate Dam might change under a dam removal scenario, relative retention rates in river reaches were compared with results from a study of the Copco-Iron Gate Reservoir complex by Asarian et al. (2009). TP concentrations are predicted to rise 2-12% (e.g., from 0.144 mg/L to 0.147-0.150 mg/L for the June-October period) under a dam removal scenario. Increases in TN concentrations under dam removal are predicted to be larger than for TP, 37-42% (from 0.910 mg/L to 1.250-1.288 mg/L) for June-October and 48-55% (0.950 mg/L to 1.404-1.469 mg/L) for July-September. The method used to make these comparisons does not take into account other changes that would likely accompany the removal of Iron Gate and Copco Reservoirs, such as the elimination of hydropower peaking and the return of full flows to the J.C. Boyle Bypass Reach, which are expected to have a beneficial (i.e., reducing) effect on river nutrient concentrations.

The potential effect of increased Iron Gate Dam concentrations on downstream reaches was explored by routing the load downstream in a stepwise fashion under two scenarios (with differing retention rates) and comparing with existing conditions for the years 2007-2008. The resulting analysis predicts that dam removal will result in only a very small change in TP concentration in the Klamath River between Iron Gate and Turwar. TN concentrations will increase more than for TP, although the magnitude of the increase diminishes with increasing distance downstream of Iron Gate. The effect is substantially diminished by the time river reaches Orleans and quite small at Turwar.

Although estimated nutrient concentrations are predicted to increase in the mainstem Klamath River downstream of the dams following dam removal, the resulting effects on downstream algal and macrophyte growth are complex and may vary by reach. If, as indicated above, periphyton in the Klamath River between Iron Gate to Seiad are not nitrogen (or phosphorus) limited (i.e., see discussion in Section 4.1.3 above regarding lack of N-fixing periphyton species), the increases in nitrogen concentrations may not necessarily result in increased periphyton biomass but the effect on periphyton and macrophyte species composition is unknown. Increased N concentrations expected with dam removal would likely shift N-fixing algae farther downstream (from their current upstream limit of approximately Seiad Valley), and upstream flora could be replaced by non N-fixers. These observations provide an important point to consider when evaluating the effect of dam removal. For example, the current periphytic flora may enable N-fixation, thereby off-setting the effect of decreased N concentrations (due to both reservoir and natural retention) on plant biomass, and it is not clear that biomass of the non-fixers would be greater than that of the current flora. This is especially true because P is not expected to increase appreciably with dam removal, and in fact may even decrease at times. Whether or not a shift to P limitation would occur under such a scenario is unclear; however such factors as increased N, stable or decreasing P, N:P ratios, and N-fixation must be considered when evaluating the effect of dam removal on projected plant biomass and water quality in the river below Iron Gate dam.

Moreover, other reach-specific factors such as substrate, flow velocity, shading, light, and water temperature also affect biomass trends independent of nutrient dynamics. Such factors must be evaluated when attempting to determine algal or macrophyte biomass following dam removal. Additionally, upstream nutrient reductions (i.e., from treatment wetlands and/or reduced agricultural runoff) could offset the increases in nutrient concentration caused by dam removal.

Finally, in determining the effect of dam removal on algal and plant biomass, the direct effect of dam presence or removal on sediment transport (and substrate), hydrology, light limitation, and days of biomass accrual should be evaluated.

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