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Water Quality Dynamics of the Klamath River Below Iron Gate Dam: A Summary

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Water Quality Dynamics of the Klamath River Below Iron Gate Dam: A Summary

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EXECUTIVE SUMMARY

This study addresses the water quality of the Klamath River downstream from Iron Gate Reservoir (the "lower Klamath") during 2001-2005 with data collected by the Arcata Fish and Wildlife Office (AFWO) in cooperation with the Karuk and Yurok tribes. Discrete, or "grab," samples were collected at stations in the river's mainstem and primary tributaries at 2- to 4-week intervals from May through October of each year and analyzed for a wide suite of constituents. Over 10,000 grab samples were collected in this 5-year period. Additionally, automatic sondes were deployed that recorded measurements of water temperature, dissolved oxygen (DO), pH, and specific conductance at short time intervals, typically every 30 minutes. These are two distinct strategies to data collection. The grab samples cover more stations in the river and permit a much wider range of constituent analysis than is possible with electrometric probes, but these data are relatively sparse in time. Data from the automatic sondes are intense in time, displaying the variation of the above four parameters at many instants within each day of deployment, but sparse in space, and limited in the variety of parameters measured. Detailed quality assurance and quality control (QA/QC) protocols were applied to each data set prior to its use in analyses.

The dominant external control on water quality is river hydrology. The annual cycle of river flow is displayed in Figure ES-1. High flows and high variability in flows occur in winter and early spring. Flows stabilize at low magnitudes and minimal variability in summer and early fall. It is

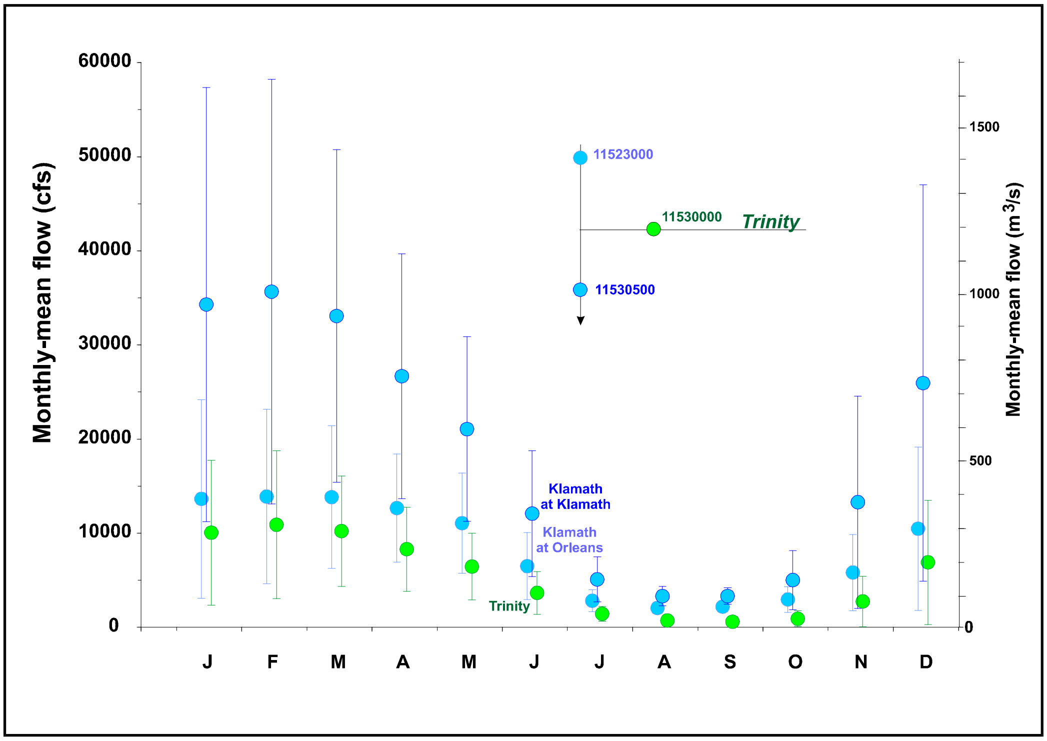

Figure ES-1. Period-of-record means and standard deviations of monthly flows at indicated gauges. Relative location of gauges shown on inset stem diagram.

the summer low-flow condition that is the primary focus of this report. Hydrology was evaluated from four mainstem and four tributary gauges operated by the U.S. Geological Survey (USGS). While the Klamath River downstream from Iron Gate is dominated by releases from the dam, the flow substantially increases downriver due to tributary inputs, by roughly a factor of four under summer low-flow conditions. During 2001-2005, data collection was characterized by generally below-average flows, of which 2001 and 2002 were the lowest. Flows in 2001 approximated the period-of-record lower-decile flows (i.e., these flows were exceeded by more than 90% of the flows in the record) for all gauges except Iron Gate. For late summer (August and September), the 2002 monthly flows were less than the decile.

Nutrients in the river, notably nitrogen and phosphorus, were found to be dominated by the summer low-flow releases from Iron Gate Reservoir, raising concerns on the stimulation of algae growth and the attendant effects on DO. The nutrient concentrations in the river were therefore of primary concern in the analysis of the grab-sample data. A mass-balance computation of total nitrogen (TN) and total phosphorus (TP) was carried out based on measured concentrations in the river supplemented by data on loads from point and nonpoint sources. Mass budgets of total dissolved solids (TDS) were also performed to inform the nutrient budgets, since TDS is conservative, and its concentration varies mainly due to dilution. The relation between in-stream concentrations of nutrients and related parameters, and the identified point and nonpoint loads of nutrients were developed in the form of simplified plug-flow water-quality models for TN and TP. In this simplified model, nutrient kinetics were represented by a first-order decay, and the decay rates estimated by fitting the concentration data to model predictions. An example for TN during July 2001 is shown in Figure ES-2. Under summer low-flow conditions, the overall

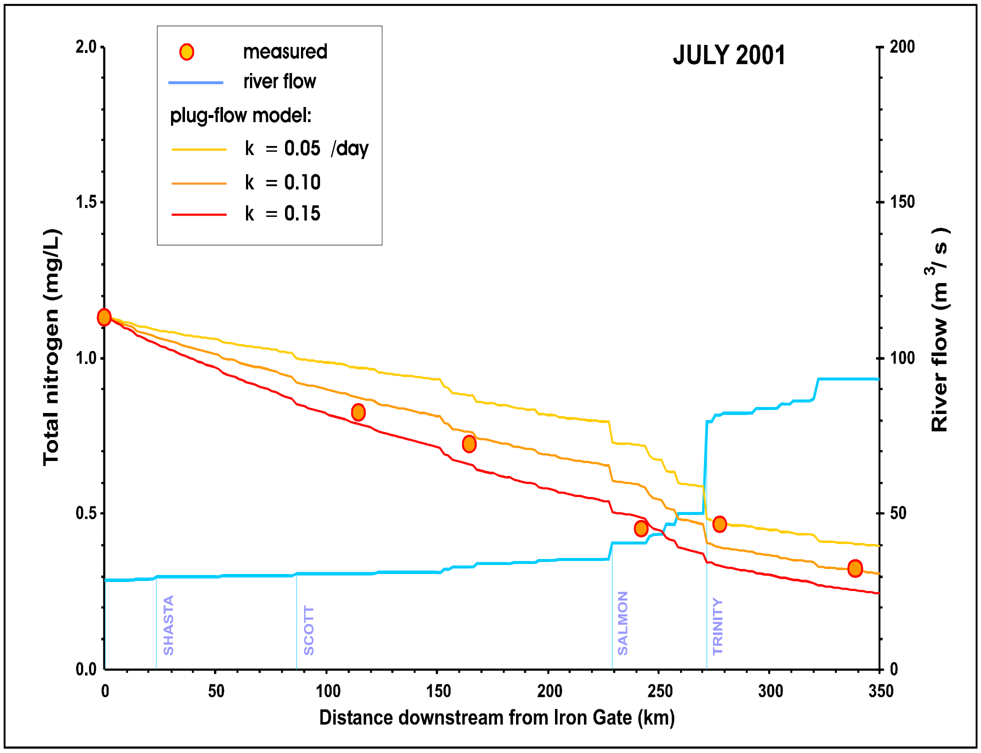

Figure ES-2. River flow, monthly-averaged total nitrogen concentrations, and plug-flow model simulations for three values of first-order decay coefficients k (day $^{-1}$) in the Klamath River.

concentrations of TP and TN in the lower Klamath River are driven by the releases from Iron Gate Dam and decline downstream due to a combination of dilution by tributary inflows and first-order decay.

Measurements of the four electrometric parameters from the sonde deployments were evaluated on both spatial and temporal scales, investigating both inter- and intra-annual differences. A more comprehensive analysis of temperature and DO was carried out based on their diurnal cycles. The daily cycle of solar radiation, which on clear days approximately follows a half-wave sinusoid function of time with maximum value at solar noon, drives a diurnal variation in both temperature and DO. While temperature varies through heating and cooling of the water by solar radiation, the magnitude of this temperature variation is small due to the high heat capacity of water. Temperature is also the primary variable affecting solubility of DO, so solubility varies diurnally as well. Solubility, as measured by the saturation concentration of DO, increases with decreasing temperature. Because the daily temperature variation is small, so also is the daily variation in solubility. The seasonal variation in temperature and solubility is much more important in the oxygen balance of the river. Solubility affects the concentration of DO, because DO is transferred from the atmosphere into the water at a rate proportional to the magnitude of the difference between its concentration and saturation. This process, called reaeration, is a purely physical transfer, governed by turbulence, in turn affected by current speed, water depth, bottom roughness, wind speed, and wave action, which is quantified by a rate coefficient for reaeration. If the DO concentration exceeds saturation, then the same reaeration process transfers oxygen from river water to the atmosphere.

Most riverine organisms, both plants and animals, break down sugars to liberate energy that is then used to fuel various biological processes. The series of biochemical reactions in this breakdown is called respiration and uses oxygen in the reaction, with water and carbon dioxide being the byproducts. The aggregated respiration from this community of organisms results in a continual consumption of oxygen from the water, usually enough to lower the DO concentration below saturation. However, a subset of this community, primarily phytoplankton, benthic algae, and submerged aquatic vegetation, can use the chlorophyll molecule to produce sugars from sunlight, a process called photosynthesis, which consumes carbon dioxide and releases oxygen into the water. Photosynthesis and the associated oxygen liberation track the intensity of sunlight during the day and cease at night. Photosynthesis, also referred to as primary production, and community respiration therefore induce a diurnal variation in DO concentration, which can be substantial. Nutrients in the water, notably phosphorus and nitrogen, fertilize aquatic vegetation stimulating growth increasing the diurnal variation of DO. Excessively fertilized rivers exhibit high supersaturation during the day and greatly depressed DO at night. When this nighttime minimum drops below their lethal threshold, aquatic animals, which require oxygen for their metabolism, succumb to asphyxia.

The diurnal cycles of DO measured by the sondes during the June – September “summer” period of each year were used to quantify rates of gross primary production and community respiration. Community respiration includes bacterial oxygen demand, respiration of algae, both planktonic and benthic, as well as rooted vegetation, and respiration of zooplankton, benthos, and higher heterotrophs in both sediments and the water column. After the various data rejection procedures in the QA/QC protocols and further screening for aberrant behavior, there remained over 3,100 complete diurnal cycles for analysis, from nine mainstem and four tributary stations.

An example of variation of DO and related parameters at the station at Weitchpec in 2005 is shown in Figure ES-3. Beginning around mid-May (day 136), DO data were collected every half hour and all other data were collected once daily at this site. Vertical lines indicate dates of sonde deployment and/or retrieval (Figure ES-3). Throughout June (until about day 180), the river is subject to spring storms carried by the westerlies into the Pacific Northwest, during which time flow in the river is declining but variable. The saturation concentration, controlled by water temperature, exhibits excursions of about 1 mg/L over several days due to these storm systems. Even more dramatic is the variation in daily solar radiation (Figure ES-3) due to clouds associated with the Pacific synoptic systems. Not until July does the flow stabilize below 5,000 cfs. Water temperatures and solubility also stabilize, and throughout August, the steadily declining insolation signals the clear skies of summer, until 1 September (day 244) when the Pacific storms return with autumn. After mid-June (around day 160), but especially during July and August, the diurnal photosynthesis excursions in DO are apparent in the daily range of variation about the mean, on the order of ±1 mg/L, resulting in increasing supersaturation as the summer progresses. The daily photosynthetic production is directly computed from the 24-hr variation in DO converted to units of carbon. This was subjected to a five-day running mean to smooth the time series and better exhibit the longer-term trends (Figure ES-3). Production increases from mid-May through June as algae become established, to

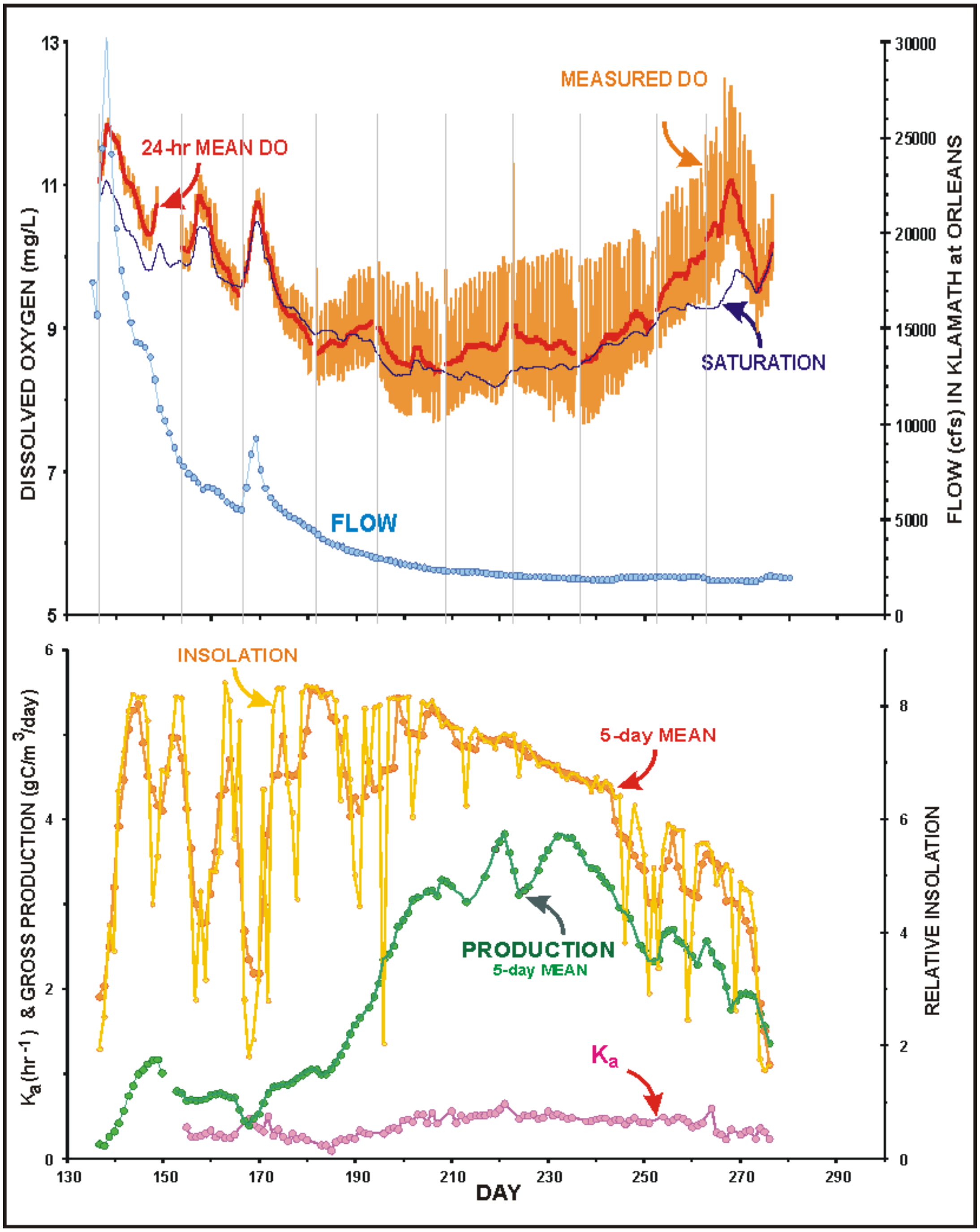

Figure ES-3. Measured DO time series and daily computed production at the Weitchpec Station in 2005, with observed daily streamflow, observed daily relative isolation, and computed reaeration coefficient K_a.

maximum values in July and August. Most methods to determine production from a time series of DO require a separate estimate of reaeration. The method employed here does not, but instead yields the value of the reaeration coefficient K_a as a byproduct of the calculation (Figure ES-3).

The data in Figure ES-3 were distilled to exhibit the general behavior of the DO budget of the Klamath River during 2001-2005 (i.e., to present a DO "climatology" of the river under summer low-flow conditions). As noted above, along the mainstem, in every summer of 2001-2005, the average concentrations of nitrogen and phosphorus generally decline along the length of the river from their high values in the Iron Gate Dam release to the mouth of the river (Figure ES-2). There is a rapid increase of gross primary production and community respiration (i.e., "Prod" and "Resp" in Figure ES-4) from Iron Gate to the Seiad Valley, consistent with establishment of an algal community in the nutrient-rich water. Typically, the highest mainstem value of gross production in the river occurs in this reach. There is a significant depression of production farther downstream around river mile (rm) 100 at Happy Camp, below which production again increases. These features of the averaged data are also exhibited in the individual years. Production and respiration in the principal tributaries (i.e., Shasta, Scott, Salmon and Trinity rivers; not shown in Figure ES-4) differ from each other and from the mainstem, and are consistent from year to year, suggesting very different kinetic processes and drivers in each tributary. Gross production in the Shasta and Scott rivers is generally much higher than the Klamath mainstem value, and typically the highest to be found in the lower Klamath system. In the Trinity, both production and respiration are much lower than the Klamath mainstem values, with only slight year-to-year variation. An additional parameter of ecological interest is the ratio of gross production to community respiration, called the relative autotrophy, also plotted in Figure ES-4 ("Rel Auto"). Values less than 1 are regarded as normal, while values greater than about 2 as eutrophied. On average, the Klamath is typical of large rivers, with values ranging 0.3 to 0.8. The influence of high nutrients from Iron Gate is evident in the higher values in the inland section of the lower Klamath. After declining to Happy Camp, relative autotrophy increases with distance downstream to the mouth, while values in the ocean surface layer are typically around unity.

While these results indicate the Klamath to be net heterotrophic under summer low-flow conditions, the only major allochthonous source of carbon, the discharge from Iron Gate, appears to be insufficient to fuel respiration in the lower Klamath.

There is a correlation between gross primary production and the nutrient decay rates inferred from the plug-flow mass-budget model. This displays a consistency between the mass-budget nutrient analysis based on grab samples and the primary production inferred from the DO sondes, and further suggests that uptake of nutrients by plants is responsible for much (in the case of nitrogen, nearly all) of the observed decay of concentration. Interestingly, the correlation between chlorophyll-*a* – a standard indicator of algal biomass – and gross production inferred from the sonde data is poor.

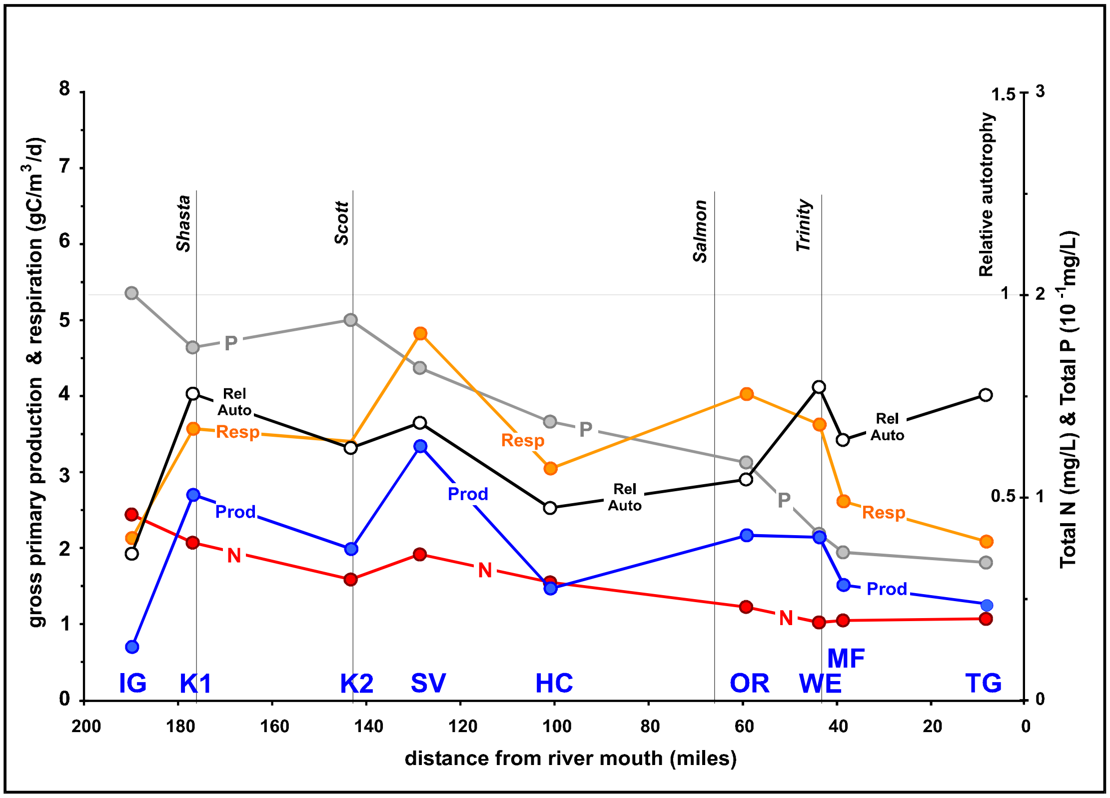

Figure ES-4. Klamath mainstem profiles of 2001-2005 average summer (June-September) nutrients and metabolic parameters. Horizontal line indicates relative autotrophy = 1.

1. INTRODUCTION

Over the past one-and-a-half centuries, the Klamath River has been subjected to extensive modifications resulting from human activities, including logging, mining, and agriculture. During the twentieth century, dams were constructed for purposes of agricultural water supply and power generation, on both the mainstem river and its tributaries. These actions have had a direct effect on the seasonal patterns of runoff and river flow, on short-term variability of river flows, and on flow magnitudes, as well as distribution within the geographical network of channels. In addition, human activities have influenced the quantity and quality of water in the river. Associated with these alterations in hydrology and water quality are impacts on the riparian zone of the river, notably channel morphology, sediments, and concentrations of water-quality parameters. In turn, these alterations have resulted in impacts to the overall riverine ecosystem, including populations of anadromous fish.

Growing concern with the condition of the Klamath River over the last couple of decades has resulted in numerous scientific and engineering studies, ranging in their focus, geographic scope, and scientific approach. The report of the National Research Council (NRC 2008), and more recently, the Klamath Dam Removal Overview Report (DOI, DOC, and NMFS 2012) provide succinct summaries of much of this work, especially as it relates to hydrology of the system and impacts on the anadromous fisheries.

The Arcata Fish and Wildlife Office (AFWO) of the U.S. Fish and Wildlife Service (USFWS) expanded its past collection of water quality data in the Klamath River and its tributaries in 2001, with an extensive effort occurring in partnership with the Karuk and Yurok tribes in 2001-2005. The study presented in this report addresses the 2001-2005 time period for the portion of the Klamath River below Iron Gate Reservoir, shown in Figure 1-1 (referred to as the "lower Klamath" for the purposes of this report, differing slightly from the Hydrologic Unit Code of the same name). While most of the human activities and physical modifications to the river and its watershed have occurred in the Klamath basin upstream of Iron Gate Dam, major impacts have also been observed in the lower Klamath River.

This report focuses on two types of water-quality data collections that were conducted by AFWO and its tribal partners. The first is conventional discrete (i.e., "grab") water sampling. Principal mainstem sampling stations are shown in Figure 1-1. Listed in Table 1-1 are the primary sampling stations for the mainstem river and its major tributaries. The complete listing of all 51 sampling stations where grab samples have been collected is provided in Appendix A-1, both in alphabetical order and by river mile. On occasion, additional grab samples were collected for special studies, to include: diurnal evaluations of nutrients, effects of a pulse flow on resuspension of nutrient matter in the water column, and an evaluation of fall turnover of Iron Gate Reservoir on down-stream river water quality. In 2004, some fecal/total coliform information was also collected at various sites. All totaled, over 10,000 water samples have been collected and analyzed as part of this study and the results stored in a Microsoft Access™ (Access) database.

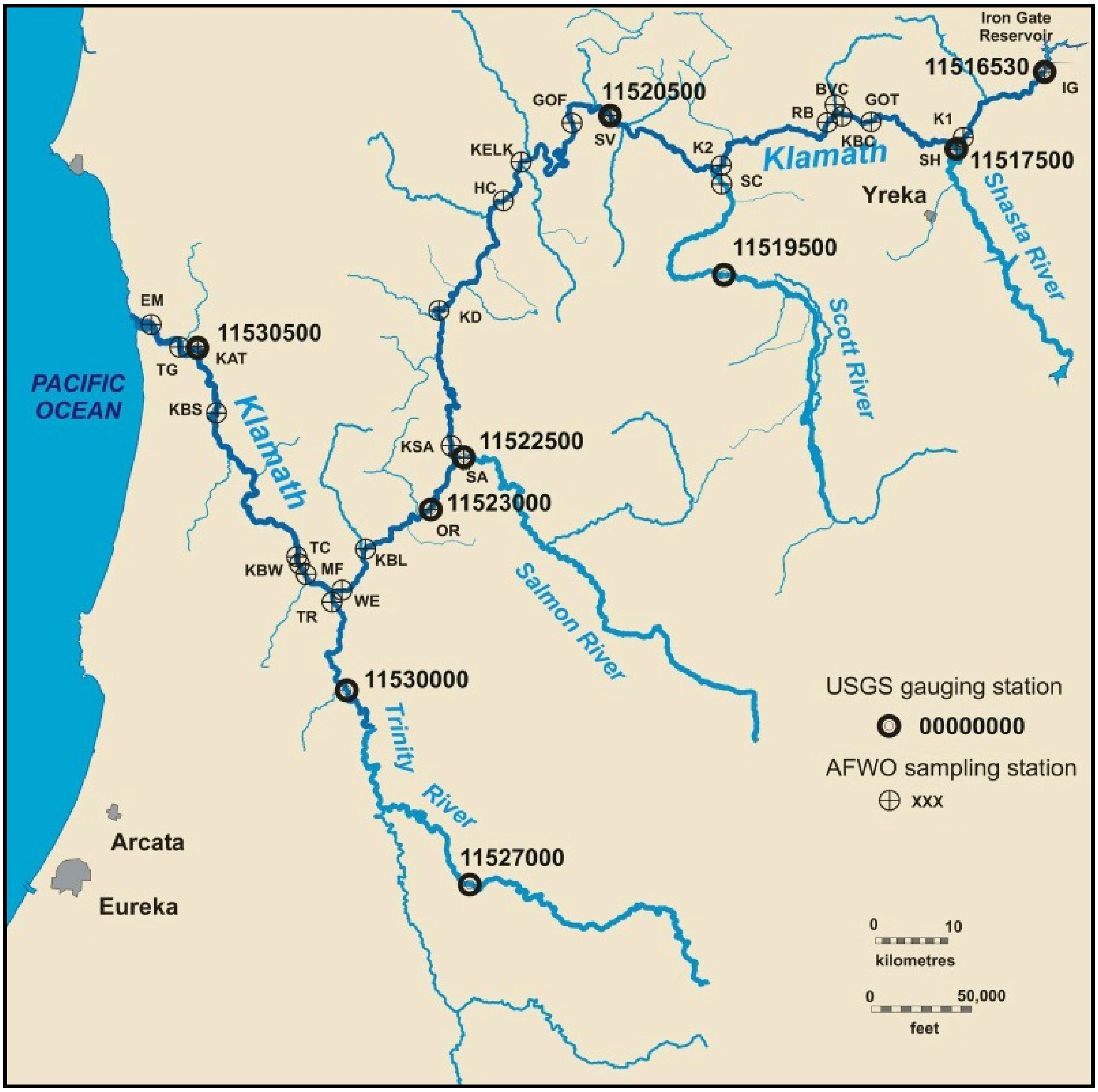

Figure 1-1. Study area on the lower Klamath River and its major tributaries, showing principal USGS streamflow gauges and AFWO/Tribal sampling stations. See Appendix A-1 for the river mile, elevation, and geographic coordinates for each station.

Table 1-1. Sampling stations on the Klamath River and its tributaries for grab samples and sonde deployment. Location information includes river mile (rm; distance from mouth of the river) and elevation for each station.

Station[1]		*Location*	*Dist (rm) from mouth*			*Elev*
			River	*Trib*[2]	*Trib*[3]	*(ft)*
IG	sonde	Klamath River at Iron Gate Hatchery Bridge	189.8			2178
BC		Bogus Creek	189.2	0.2		
K1	sonde	Klamath River above Shasta	176.8			2031
S1		Shasta River at Louie Rd Crossing	176.6	32.0		2300
S2		Shasta River at A12 Bridge	176.6	22.6		2250
L1		Little Shasta River CDFG wildlife area	176.6	15.7	11.8	2400
L2		Little Shasta River	176.6	15.7	6.5	2100
S3		Shasta River at Montague Grenada	176.6	15.1		2160
SRWC		Shasta River above Willow Creek (near Rt 3)	176.6	9.0		
S4		Shasta River above Yreka Creek	176.6	7.9		2100
YR		Yreka Creek	176.6	7.6	0.6	2000
Y2		Yreka Creek above Waste Water Plant	176.6	7.6		
SH	sonde	Shasta River near mouth	176.6	0.5		2031
GOT		Klamath River below Gottville	164.9			
KBC	sonde	Klamath River above Beaver Creek	161.1			1752
BVC		Beaver Creek	161.1	0.1		1755
RB		Klamath River at Round Bar pool	158.5			
K2	sonde	Klamath River above the Scott River	143.2			1520
SC	sonde	Scott River near mouth	143.0	1.5		1520
HAM		Klamath River below Hamburg, Rodney Pt.	140.0			
SV	sonde	Klamath River at Seiad Valley	128.5			1320
GOF		Klamath River below Fort Goff, at Seattle Creek	121.4			
ELK		Elk Creek	105.5	0.1		1040
KELK		Klamath River below Elk Creek above WWTP	105.4			
HC	sonde	Klamath River below Happy Camp	100.8			960
CLR		Clear Creek	98.6	0.1		960
KD		Klamath River above Dillon Creek	84.3			780
DLN		Dillon Creek	84.2	0.1		780
KSA		Klamath River above Salmon River	66.1			455
SA	sonde	Salmon River near mouth	66.0	1.0		480
OR	sonde	Klamath River at Orleans	59.1			400
UL		Ullathorne Creek (below Orleans)	56.1	0.1		
RCC		Red Cap Creek, 150 ft upstream of Allen Bridge	52.7	0.3		
BL		Bluff Creek @ mouth	49.5	0.1		320
WE	sonde	Klamath River at Weitchpec	43.6			240
TR	sonde	Trinity River near mouth	43.5	0.5		240
MF	sonde	Klamath River at Martins Ferry	40.4			160
KBW	sonde	Klamath River below Weitchpec	40.3			
TC	sonde	Klamath River above Tully Cr (below MF)	38.5			155
KBS		Klamath River above Blue Creek	16.5			40
KAT	sonde	Klamath River near Klamath, new USGS site	8.1			8
TG	sonde	Klamath River at Terwer	6.7			8
EM		Klamath River Estuary mainstem	0.1			5

[1] Grab samples at all stations, sonde deployment indicated; [2] Second-order tributaries; [3] Third-order tributaries

The second type of water-quality data collection is the operation of automatically recording monitors moored in the river. These robotic "sondes" measure and record water temperature, dissolved oxygen (DO), pH, and specific conductance of the water flowing past the sensor. Sondes have been deployed at over a dozen sites below Iron Gate Dam in the mainstem of the Klamath River and in its major tributaries. These sites are co-located with some of the grab-sample stations, where data on nutrients and chlorophyll-*a* are obtained, generally at 2- to 4-week intervals from May through October.

The purpose of this report is to present an overview of the study through summaries of its principal results, addressing the following objectives:

i. Assess the grab sample and sonde data quality prior to its release to other agencies engaged in the study of the Klamath River basin.
ii. Characterize the hydrology in the Klamath River basin from 2001 to 2005, as reflected in the USGS gauging records, compared to the period of record.
iii. Estimate nutrient (primarily total nitrogen [TN] and total phosphorus [TP]) loads in the river, their variation in space and time, and the fate of those nutrients in the river mainstem using a simplified mass-balance model.
iv. Determine the spatial and temporal variations in sonde measurements of temperature and DO and derive metabolism parameters from those measurements.
v. Develop an integrated summary of the relationship of flow, insolation, nutrients, productivity, reaeration, community respiration, and chlorophyll-*a* in the lower Klamath.
vi. Develop conclusions about the present state of the Klamath, from both the standpoint of identifying present impairments and of establishing a baseline for evaluating the effect of future alterations to the river.

The data analysis used in this study focuses on making direct inferences from field measurements, as opposed to extensive modeling. The study has four main tasks, represented in the following respective chapters. Further details of the methodologies and results have been documented in a series of reports and technical memoranda, listed in the Literature Cited section.

2. HYDROLOGICAL SETTING

This study is confined to the lower Klamath River, extending from Iron Gate Dam to the estuary at the river's confluence with the Pacific Ocean. The main source of hydrological data is the streamflow gauging program of the U.S. Geological Survey (USGS). The four mainstem gauges and gauges on the four principal tributaries that were employed to characterize the flows in the Klamath River are listed in Table 2-1, along with the average and range of the period-of-record mean annual flows. While a geographic map like Figure 1-1 gives a reasonably accurate display of a river and its tributaries, a stem diagram abstracts the relative locations of its features and is often more useful as a simple depiction of the essential configuration of a stream network. A stem diagram of the Lower Klamath River that shows the relative locations of these gauges is presented in Figure 2-1.

2.1. Hydroclimatology

To a first approximation, the major determinants of northern California hydroclimate, and of the Klamath Basin in particular, are the position of the mid-latitude westerlies and the physiography of the land surface. Precipitation is induced or enhanced when the moisture-laden westerlies are forced up by the elevation of the land. In the lee of the coastal ranges, the airstreams have lost much of their moisture in the ascent, and precipitation is diminished. The main seasonal signal in precipitation, hence streamflow, is due to the annual strengthening and latitudinal descent of the westerlies during winter, in which cyclones are steered into the Pacific Northwest region. The resulting runoff is due to rainfall that results in an immediate response or to snowfall that is stored as snowpack and runs off with the spring melt. The seasonality in river flow is evidenced in the annual variation of monthly streamflow statistics shown in Figures 2-2 – 2-4. In these figures, the period of record for each gauge extends from the year given in Table 2-1 through 2005. Note the change of ordinate scale in Figure 2-4. The consistency of the annual signal is perhaps better displayed by normalizing the monthly mean values to the long-term annual mean, as calculated as $Q_i / \overline{Q}$, where Q_i is the long-term mean flow of month i, ranging $1 \leq i \leq 12$, and $\overline{Q}$ denotes the long-term annual mean, displayed graphically in Figure 2-5. Figure 2-5 uses the same averaging period for all gauges, *viz*. 1961-2004, which begins with the Iron Gate impoundment.

Several observations may be made from the Figures 2-1 thru 2-5:

(1) In the upper portion of the study reach (Figure 2-1), mainstem flow is dominated by the releases from Iron Gate Dam.
(2) From Iron Gate Dam to the USGS gauge at Klamath, the flow in the Klamath River increases by about a factor of four in low flows and by an order of magnitude in high flows.
(3) The typical annual variation is increasing flows through the fall, high flows in winter (January through March), declining flows in spring, and low flows in summer (July through October).
(4) There is considerable inter-annual and intra-annual variation in this pattern.

Table 2-1. Principal USGS gauges on the Klamath River and tributaries, with period-of-record annual flows.

Gauge number	Location	Useable record begins:	Years in record	Mean flow (cfs) Average	Minimum	Year	Maximum	Year
Klamath mainstem								
11516530	Iron Gate	1960	45	2076	647	1992	3760	1983
11520500	Seiad Valley	1951	54	3935	1170	1992	7478	1983
11523000	Orleans	1927	78	8178	3094	1994	16976	1983
11530500	Klamath	1950[1]	53	17899	7447	1991	40054	1983
Tributaries								
11517500	Shasta near Yreka	1944	61	188	84	1992	375	1983
11519500	Scott near Fort Jones	1941	64	638	150	1994	1387	1983
11522500	Salmon at Somes Bar	1927	78	1775	664	2001	3573	1983
11530000	Trinity at Hoopa	1931	74	5248	1707	1977	12735	1983

[1] Data missing for 30 October 1995 - 30 September 1997

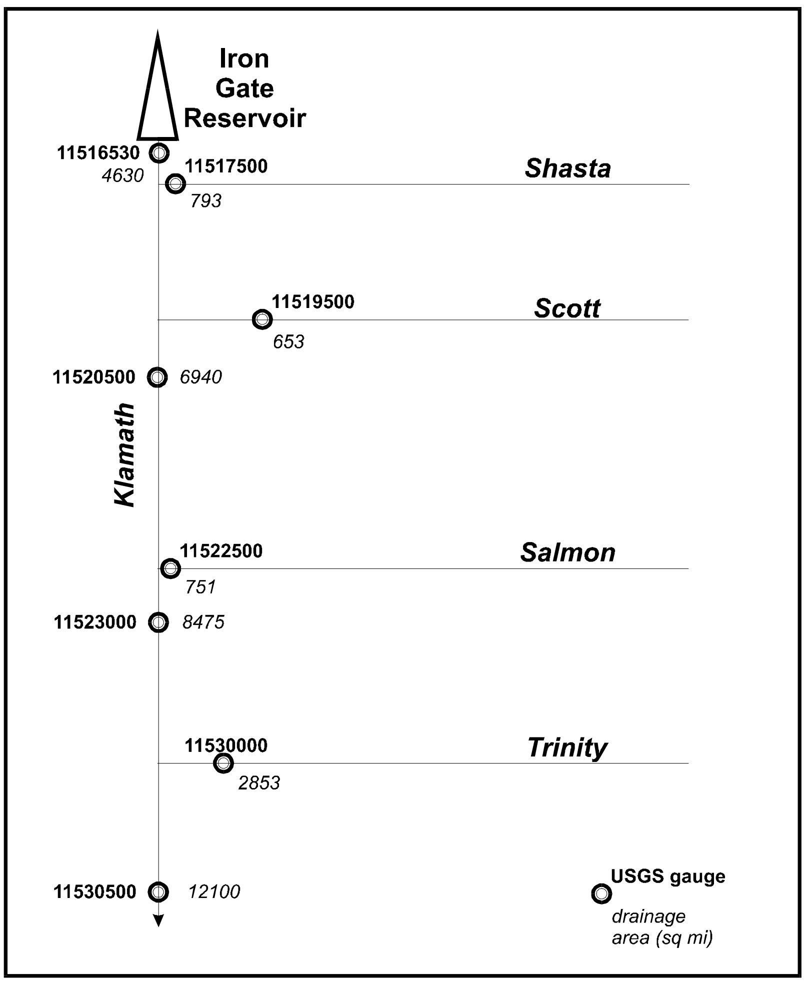

Figure 2-1. Stem diagram of study reach of Klamath River (cf. Figure 1-1).

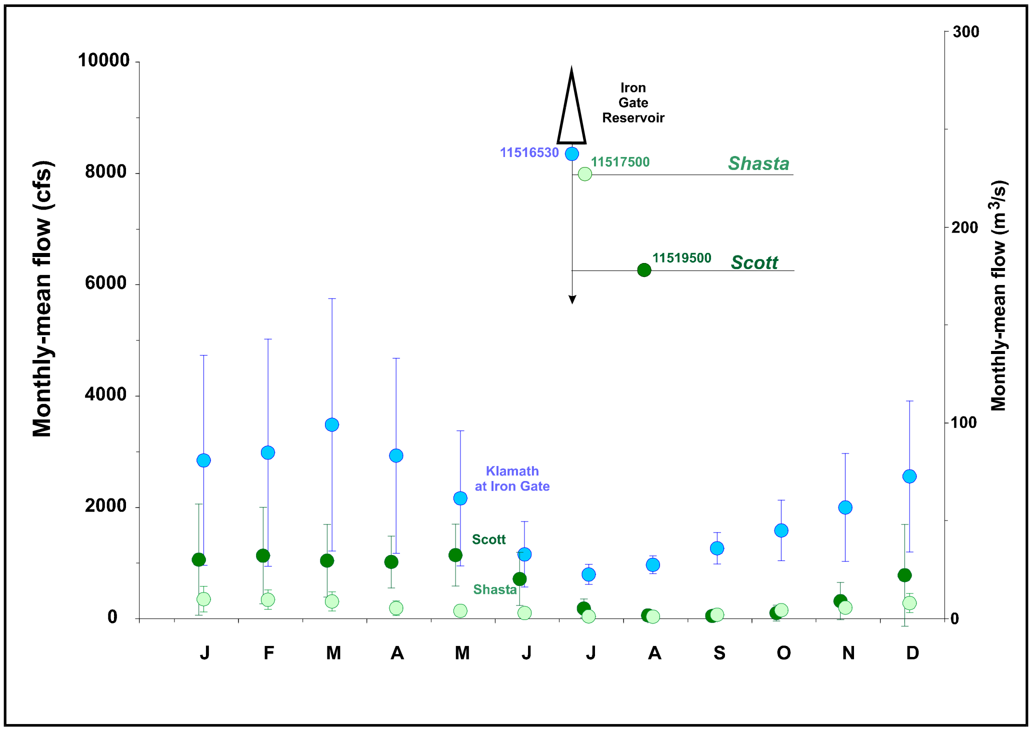

Figure 2-2. Period-of-record means and standard deviations of monthly flows at indicated gauges (cf. Figure 2-1).

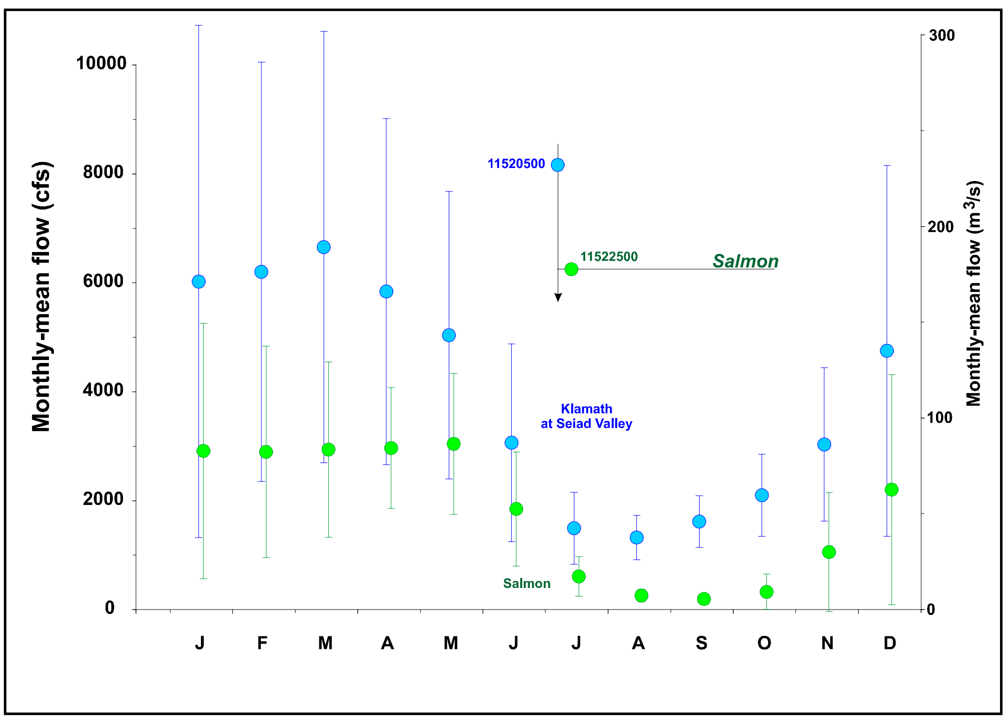

Figure 2-3. Period-of-record means and standard deviations of monthly flows at indicated gauges, continued (cf. Figure 2-1).

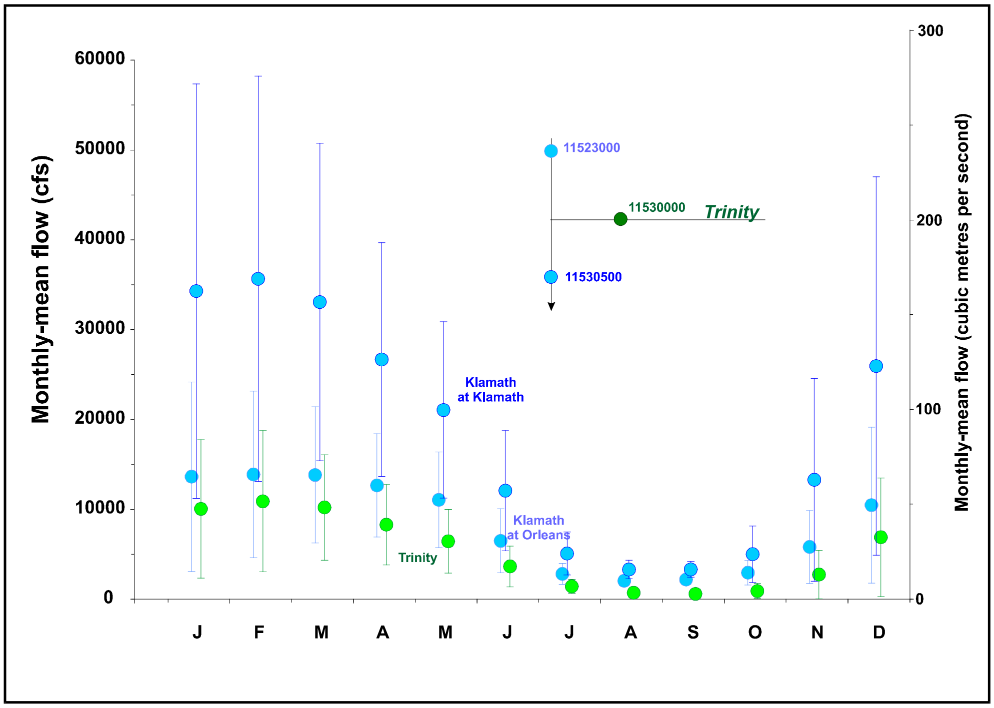

Figure 2-4. Period-of-record means and standard deviations of monthly flows at indicated gauges, continued (cf. Figure 2-1).

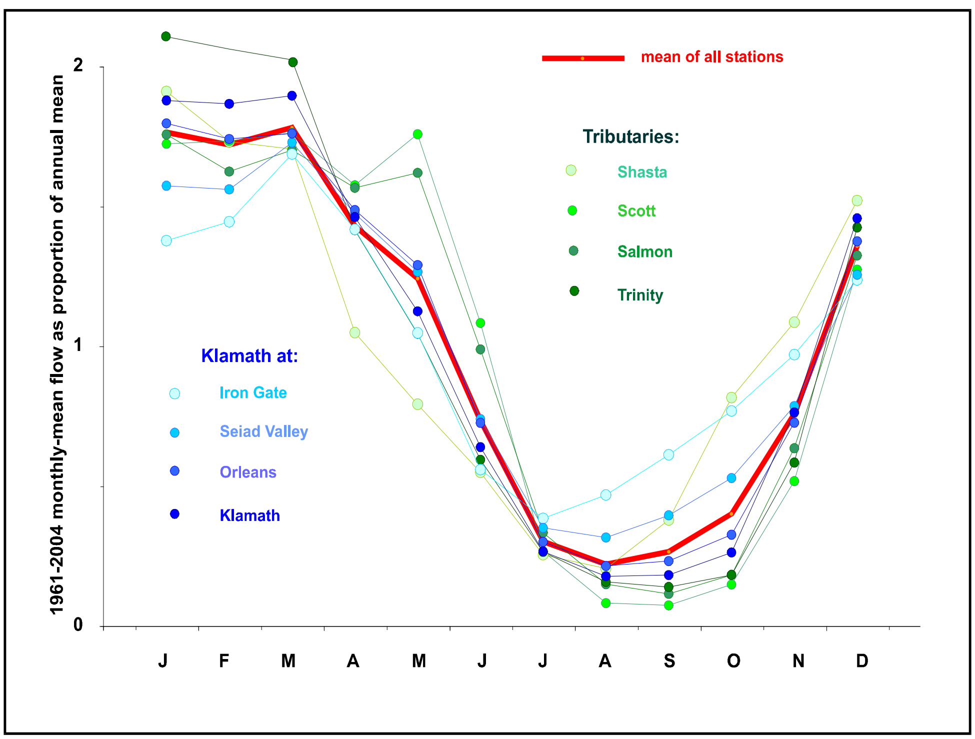

Figure 2-5. Annual variation of 1961-2004 monthly-mean streamflow at the gauges (Figures 2-2 – 2-4 normalized to annual flow).

In general, an "average" year, in which the monthly means approximate their long-term average values, is rare. Most importantly, there tend to be runs of below-average and above-average flows, which are evidenced in chronological time series of annual flows but better diagnosed by examination of the monthly flows. Figure 2-6 shows the cumulative departure of the monthly flow from the period-of-record mean

$$(Q_1 - \overline{Q}) + (Q_2 - \overline{Q}) + (Q_3 - \overline{Q}) + \ldots + (Q_N - \overline{Q}) \qquad (2\text{-}1)$$

for the Nth month in the chronological time series, in which $\overline{Q}$ denotes the period-of-record mean monthly flow. Such a diagram facilitates the identification and comparison of drought periods, as well as fluvials (i.e., periods of inflow surfeit). For present purposes, a drought is a period of at least 7 years of below-average flow, exhibited in a cumulative-flow diagram as a period of decline in the cumulative. Historical droughts so diagnosed are indicated by the straight-line fits in Figure 2-6. The duration of a drought is the time base of the line (i.e., the period over which the average decline in cumulative flow is sustained, and the intensity of the drought is measured by the negative slope of the line). At this gauge, the frequency of major droughts has been roughly one every 13 years. We note that the period of water-quality data collection reported here (2001-2005) has been one of below-average flows, but the drought of 1986-1995 is the most intense in the period of record analyzed, which extended through 2005. Historically, one must go back to the decade of the 1930's to find a drought of similar intensity.

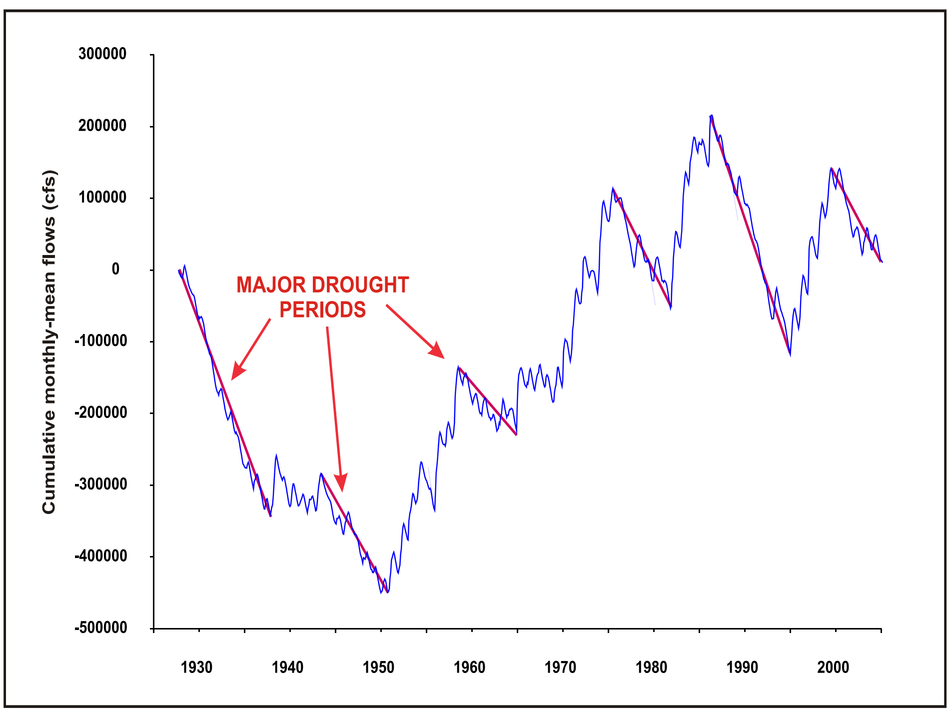

Figure 2-6. Cumulative monthly flow diagram, Klamath at Orleans.

To compare the historical time series at each of the gauges in Table 2-1, the cumulative flow diagrams have been normalized to the high-flow events of 1983 and are shown together in Figure 2-7. The consistency among the gauges is remarkable. For most of the period of record (i.e., prior to about 1985) there are three distinct clusters of graphs: (1) the upper reaches and tributaries, *viz*. Iron Gate, Seiad Valley, the Scott and the Shasta; (2) the mid-reach gauges of the Klamath at Orleans and the Salmon (despite their different watershed areas); and (3) the lower gauges at Klamath and the Trinity. The cumulative-flow graph of the last differs substantially from the others in that the intensity of droughts is considerably less, due no doubt to the increased rainfall on the coastal ranges. After about 1975, these clusters are no longer distinct (Figure 2-7) and all agree in the intensity and duration of the drought of 1986-95.

2.2. Summary of 2001-2005 hydrology

As noted above, flows during 2001-2005 were generally characterized as below-average. Furthermore, the Klamath has been in a state of relative drought for the past two decades, apart from the 1995-2000 period of above-average flow (*cf*. Figs. 2-6 and 2-7). An alternative measure of the relative magnitude of river flow is the cumulative frequency (i.e., the fraction of the data that a given flow value exceeds). Figure 2-8 exhibits the cumulative frequencies for flow at the mainstem stations on the Klamath during 2001-2005. For all except two gauges in two years, the annual-mean flows are less than the period-of-record median (i.e., flows with an exceedance frequency of 0.5, which is typically lower than the mean). The lowest measure was in 2001, approximating the period-of-record lower-decile flows for all gauges except Iron Gate. On an annual-flow basis, the sampling period of this study was atypical, which is advantageous since the lower flows are considered to represent conditions of higher biological stress.

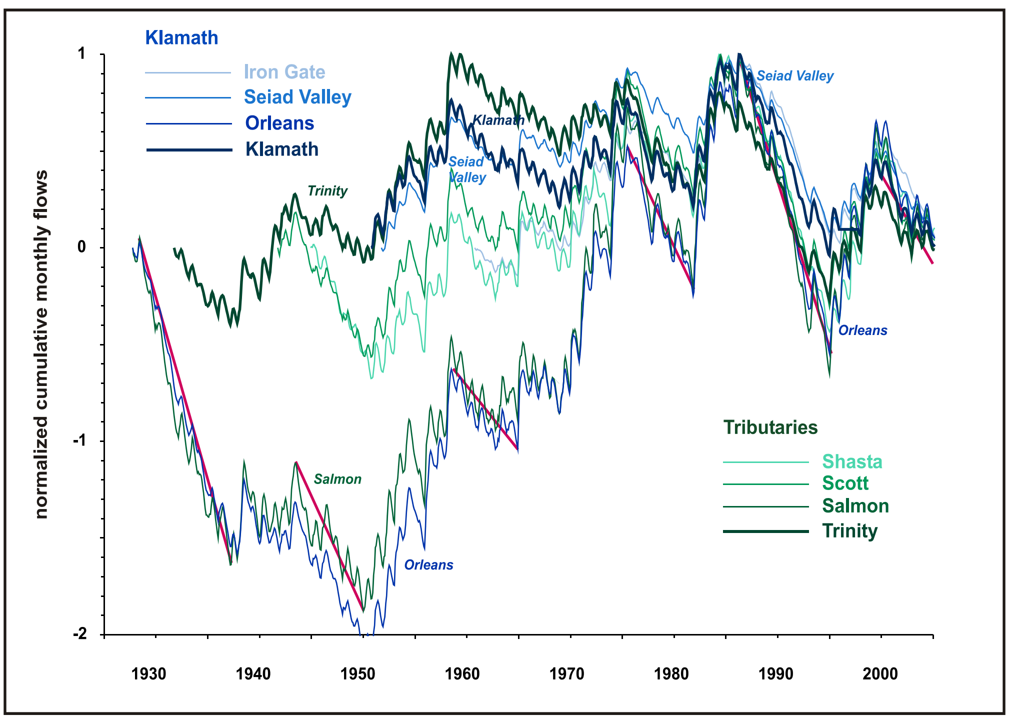

Figure 2-7. Normalized cumulative monthly flow diagrams, all gauges.

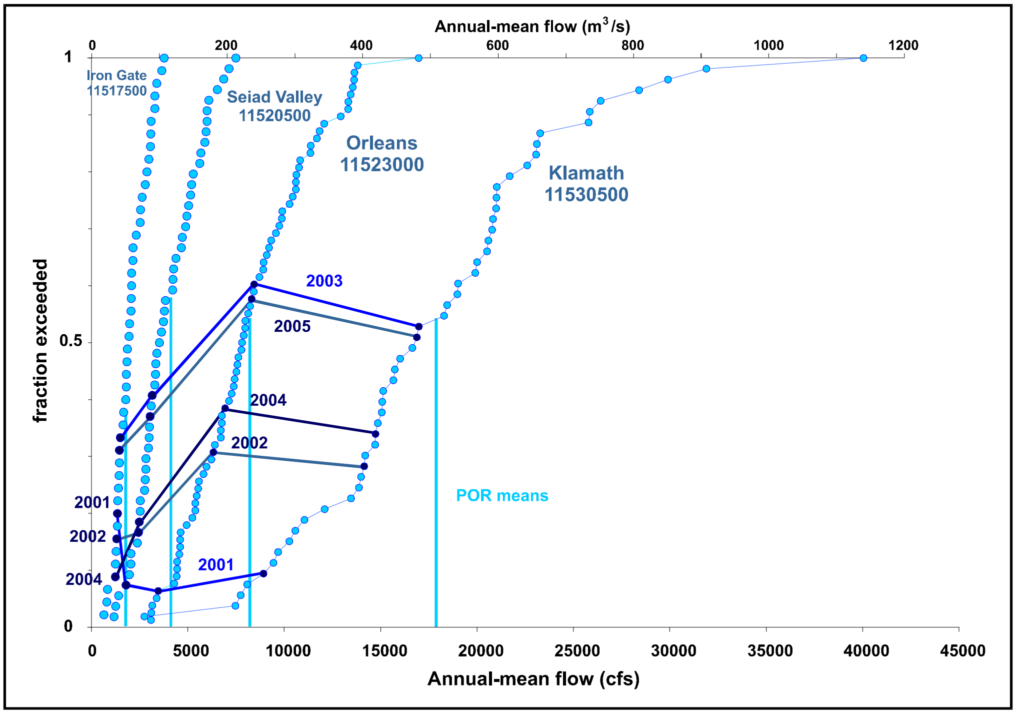

Figure 2-8. Annual-mean-flow cumulative frequency diagrams for Klamath mainstem stations, 2001-2005.

Table 2-2. Monthly mean flows for sampling periods, June – October 2001-2005, at mainstem gauges on the Klamath.

	Iron Gate 11516530		Seiad Valley 11520500		Orleans 11523000		Klamath 11530500	
Month	Flow (cfs)	Exceeding (%)	Flow (cfs)	Exceeding (%)	Flow (cfs)	Exceeding (%)	Flow (cfs)	Exceeding (%)
2001								
June	1897	87	2094	41	2756	10	6006	17
July	1012	89	1095	35	1429	6	3271	21
August	1023	56	1046	17	1209	8	2713	28
September	1026	20	1070	15	1224	5	2601	19
October	1308	20	1463	15	1603	6	3447	29
2002								
June	993	58	1853	24	3593	22	6528	21
July	837	78	1080	30	1647	12	3187	15
August	666	9	787	7	1263	10	2327	11
September	813	9	902	6	1305	8	1993	8
October	1047	15	1229	11	1638	9	2405	7
2003								
June	1304	73	3261	69	7248	69	12902	66
July	827	76	1253	50	2666	58	5201	66
August	996	29	1218	43	2088	56	3463	66
September	1254	33	1444	31	2049	41	3383	58
October	1366	43	1630	27	2172	22	3057	15
2004								
June	953	56	1946	35	4727	41	9473	47
July	674	11	941	15	2095	29	4382	55
August	752	18	840	13	1525	17	2964	47
September	913	13	1025	13	1641	15	3049	49
October	926	9	1217	9	2219	25	3087	16
2005								
June	1222	69	2569	57	6684	64	14443	72
July	925	84	1288	56	3140	73	6487	79
August	999	31	1100	26	2161	62	3647	74
September	1179	31	1290	26	2051	44	3123	51
October	1357	41	1620	24	2124	19	3584	33

Given the considerable intra-annual variation and the relatively short travel times in the Klamath River (discussed below), the annual mean flows do not provide a complete assessment of how representative the hydrology was during the field sampling runs (Figure 2-8). For this purpose, the monthly mean flows, and their associated exceedance frequencies are summarized in Table 2-2 for the primary water-sampling months of June - October. From this table, the following conclusions can be drawn:

(1) The lowest-flow periods were in 2002, with most of the summer monthly flows being less than the lower decile, while 2001 was nearly as low, with some of the flows only being between the decile and quartile.
(2) 2004 would have been characterized as low as 2001 and 2002, except for the enhanced runoff from the lower watershed.
(3) 2003 is the closest approximation to a "normal" year, with most of the monthly flows vacillating about median. The flows in 2005, like 2004, were skewed toward higher runoff contributions in the lower watershed.
(4) The above generalizations do not apply so much to the Iron Gate gauge, because of the artificial distortion due to controlled releases through the dam.
(5) In all five years, the onset of the fall freshet was delayed into November.
(6) One consequence of (5) is that every October during 2001-2005, flow was below the median, and in most cases substantially so.

The distribution of total yearly flows in the Klamath as measured at the lowest gauging station (Klamath River near Klamath) are provided in Table 2-3 and compared to the percentage distribution during 1961-2005, the longest complete period in which data from all the principal gauges are available (Table 2-1). The category “other” is the total of flows not represented in the gauges listed. For practical purposes, this is the total ungauged flows that enter the Klamath between the gauging stations, primarily through tributary inflows. Based on volume of flow, the contribution of the Scott and Shasta is comparatively minor, while flows entering the reach below Iron Gate Dam and from the Trinity River tend to dominate the June – October sampling period, ungauged runoff typically being secondary. Over the year, however, ungauged runoff comprises nearly half the total flow at the Klamath gauge.

Table 2-3. Proportion (%) of flows at the mouth of the Klamath River by source.

Location	Jun	Jul	Aug	Sep	Oct	Year
2001						
Iron Gate	31.6	31.0	37.7	39.4	38.0	15.1
Shasta	0.4	0.7	0.7	1.8	3.7	1.2
Scott	0.8	0.2	0.2	0.2	0.1	1.7
Salmon	6.8	5.7	3.4	3.1	3.0	7.5
Trinity	26.1	25.4	26.4	24.3	17.7	29.2
Other	34.2	37.0	31.5	31.2	37.5	45.3
2002						
Iron Gate	15.2	26.3	28.6	40.8	43.5	9.2
Shasta	0.7	0.8	1.0	1.6	5.5	0.9
Scott	6.0	2.0	0.6	0.6	0.7	3.4
Salmon	17.3	11.3	7.3	6.3	5.1	10.8
Trinity	30.2	29.0	29.9	31.7	23.8	31.9
Other	30.6	30.7	32.5	19.1	21.4	43.7
2003						
Iron Gate	10.1	15.9	28.8	37.1	44.7	8.8
Shasta	0.7	1.2	2.0	2.4	4.9	1.1
Scott	8.1	3.5	2.5	1.5	2.2	4.4
Salmon	17.4	11.7	8.7	5.8	5.3	12.0
Trinity	34.7	39.8	33.2	34.3	21.6	32.0
Other	29.0	27.9	24.8	19.0	21.2	41.7
2004						
Iron Gate	10.1	15.4	25.4	29.9	30.0	8.4
Shasta	0.7	0.9	1.4	2.2	5.4	1.1
Scott	4.5	1.8	0.5	0.4	1.5	3.4
Salmon	15.6	12.9	8.7	5.5	10.2	11.5
Trinity	40.3	40.7	33.1	33.8	31.6	32.6
Other	28.8	28.4	30.9	28.1	21.3	43.0
2005						
Iron Gate	8.5	14.3	27.4	37.7	37.9	8.6
Shasta	0.7	0.5	1.0	2.0	4.0	1.2
Scott	4.5	2.1	0.6	0.5	1.0	3.8
Salmon	13.4	11.8	8.1	6.2	6.0	11.2
Trinity	39.5	41.0	28.9	27.1	22.4	35.2
Other	33.4	30.4	34.0	26.4	28.8	39.9
1961-2005						
Iron Gate	10.8	17.8	32.3	41.3	35.0	11.8
Shasta	1.0	1.1	1.3	2.3	3.4	1.1
Scott	6.4	3.8	1.7	1.5	2.0	3.6
Salmon	17.0	13.7	9.1	6.9	7.4	10.5
Trinity	26.9	28.7	25.5	22.0	19.5	27.8
Other	38.0	35.0	30.1	26.0	32.7	45.2

The range of flow conditions encountered at gauges on the mainstem Klamath River (i.e., Iron Gate [IG]; Seiad Valley [SV]; Orleans [OR]; Terwer [TG]; Table 1-1) during the five year study period is shown in Figures 2-9 through 2-13. These figures display the observed daily flow at each of the four USGS mainstem gauges below Iron Gate (Figure 2-1), for May - September. Though the chief focus of this analysis is on the summer period from June – September, May is included in these figures to display the magnitude of the spring runoff event. A split ordinate is used to better resolve the flows during the July – September low-flow season. Each of these figures show the flows corresponding to daily non-exceedance values of 10%, 50% (median) and 90% for the low-flow season, to characterize the statistical variation of flows at Orleans over the 1961-2005 period (beginning with post-construction filling of Iron Gate Dam). Flows at Orleans in both 2001 (Figure 2-9) and 2002 (Figure 2-10) were uncharacteristically low, generally exceeding only about 10% of the 1961- 2005 flow data. It should be noted, however, that a major fish kill occurred on the mainstem Klamath River in 2002 below the Trinity River confluence. Though estimates vary, the USFWS reported that a minimum of 34,000 adult fish, primarily fall-run Chinook salmon, died during the event (Guillen 2003). In 2003 (Figure 2-11) and 2004 (Figure 2-12), flows were slightly above and below the median, respectively, but in both years the lower river (below the Trinity confluence) experienced higher flows in late August through early September due to additional releases of water from Trinity Dam (and Iron Gate in 2003) to reduce the likelihood of another major fish kill. In 2004, this late-August event was manifested throughout the river below Iron Gate but was most prominent in the coastal region due to increased contributions from the Trinity (Figure 2-12). The year 2005, exhibited the highest flows of the study period but declined to nearly the median toward the end of the summer, with no major inflow events or managed releases to disturb the steady flows during the August-September period (Figure 2-13).

These flows are also summarized as travel times from Iron Gate Dam to each of the three mainstem gauges (Figure 2-14), based upon the routine measurements of stream velocity performed by the USGS (Armstrong and Ward, 2008a). Two immediate inferences can be drawn that are crucial to interpretation of the water-quality and kinetic processes operating within the Klamath, and especially the interpretation of the sonde data (see Chapter 4). First, despite the wide range in flows during the May-September period and from year-to-year, the travel times are much more stable, especially during the low-flow period. During this period, travel times from Iron Gate are about 2 days to Seiad Valley (which agrees well with the RMA-2 model values presented by Deas and Orlob, 1999), 4-5 days to Orleans, and 6-8 days to Terwer. This is because an increase in flow results primarily in an increase in water surface elevation (and associated increase in cross section), rather than an increase in current speed, consistent with hydraulic principles. Second, the entire reach of the Klamath from Iron Gate to the mouth is replaced by new water in about three days under high spring runoff conditions, and in about seven days under summer low-flow conditions.

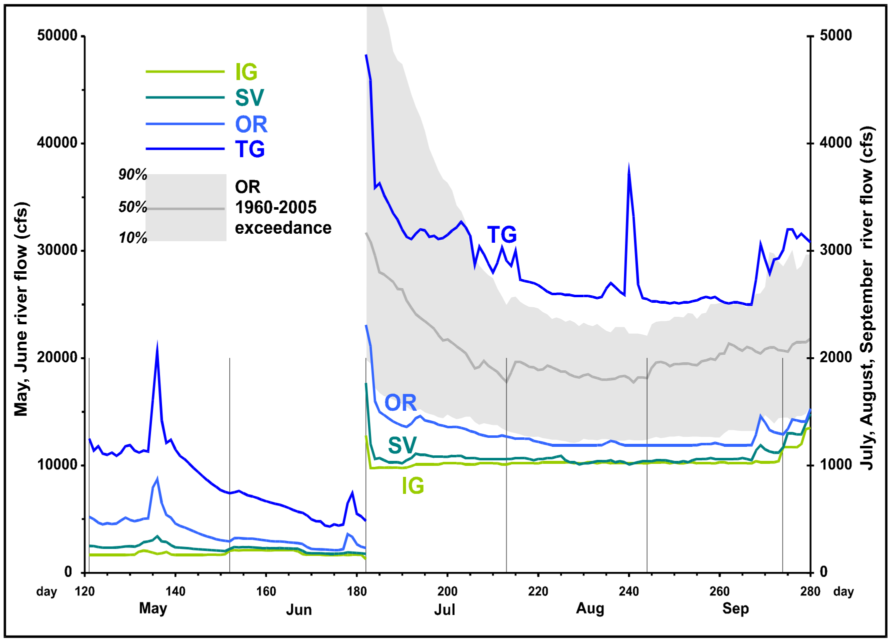

Figure 2-9. Gauged flows in the mainstem of Klamath River, 2001 at Iron Gate (IG), Seiad Valley (SV), Orleans (OR), Terwer (TG).

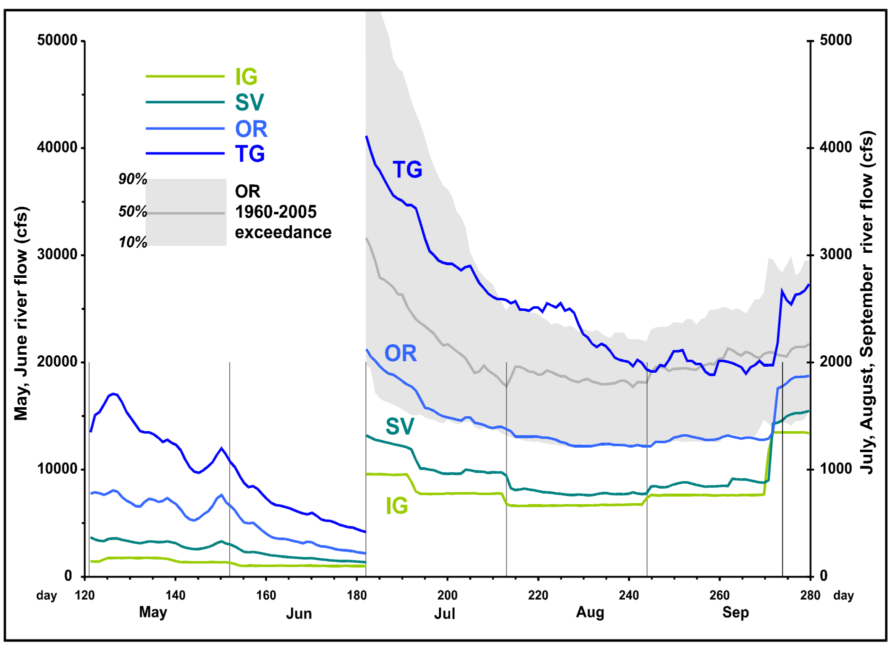

Figure 2-10. Gauged flows in mainstem of Klamath, 2002 at Iron Gate (IG), Seiad Valley (SV), Orleans (OR), and Terwer (TG).

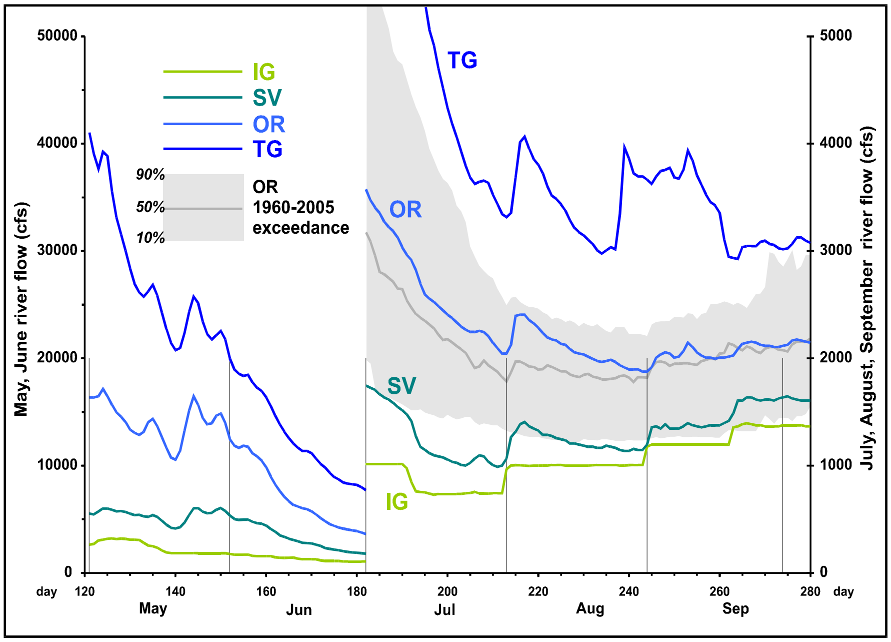

Figure 2-11. Gauged flows in mainstem of Klamath, 2003 at Iron Gate (IG), Seiad Valley (SV), Orleans (OR), and Terwer (TG).

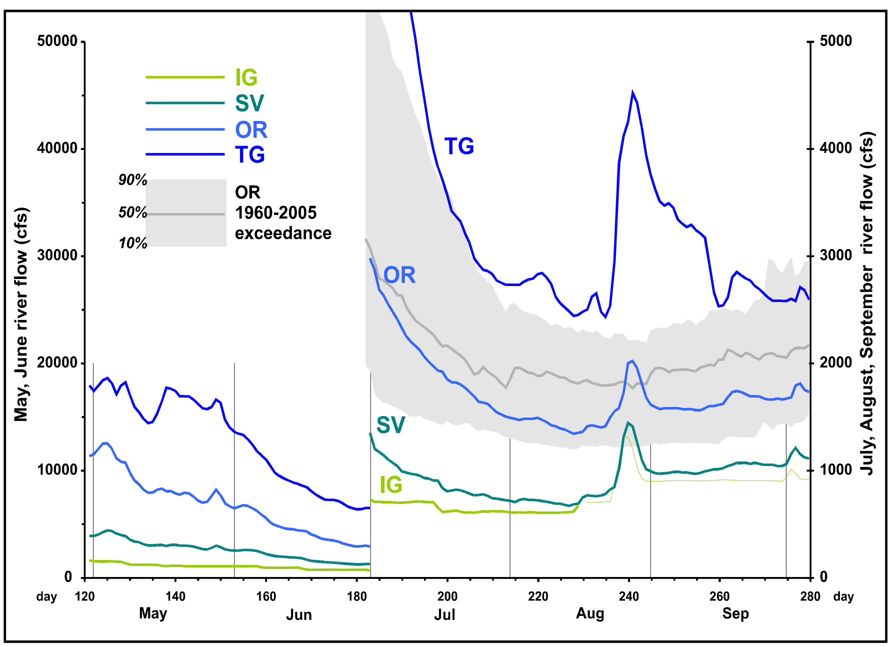

Figure 2-12. Gauged flows in mainstem of Klamath, 2004 at Iron Gate (IG), Seiad Valley (SV), Orleans (OR), and Terwer (TG).

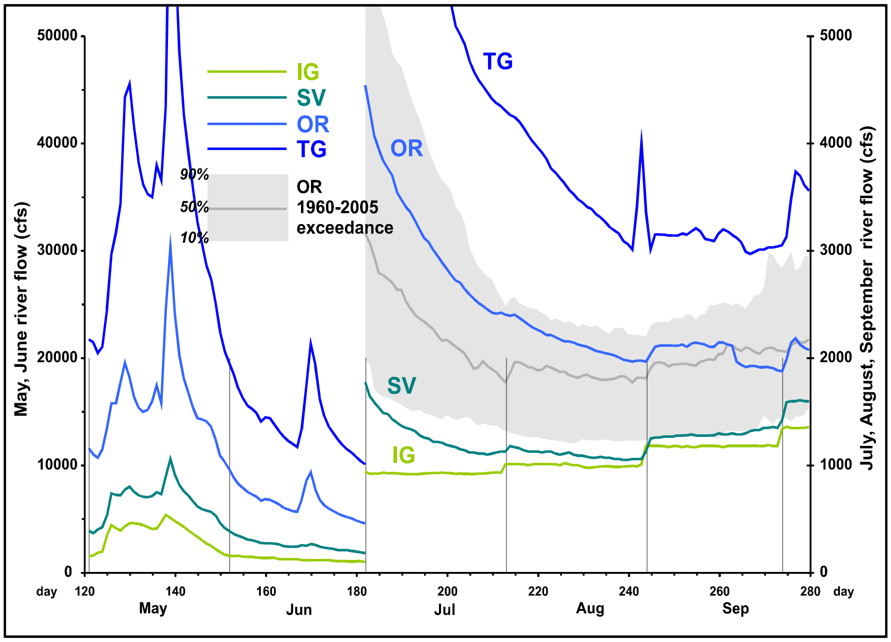

Figure 2-13. Gauged flows in mainstem of Klamath, 2005 at Iron Gate (IG), Seiad Valley (SV), Orleans (OR), and Terwer (TG).

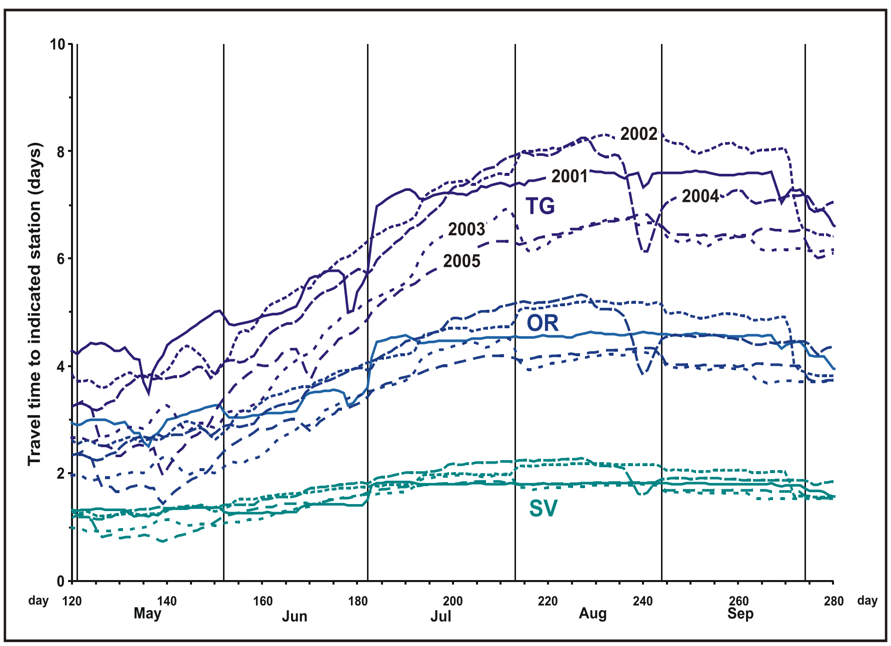

Figure 2-14. Mainstem Klamath River travel times from Iron Gate to Seiad Valley (SV), Orleans (OR), and Terwer (TG), 2001-2005.

3. SPACE-TIME VARIATIONS IN NUTRIENT LOADS

In collaboration with the Karuk and Yurok Tribes, the AFWO collected an extensive suite of water-quality data in the Klamath River during 2001-2005. Two strategies were employed to collect these data. First, a series of Hydrolab DataSondes® were deployed that automatically collected measurements of water temperature, DO, pH, and specific conductance at short time intervals (see Chapter 4 for further details). Second, AFWO and tribal partners collected grab samples at 2- to 4-week intervals from May through October. Though the grab samples are sparse in time, they cover more stations in the river and permit a much wider range of constituent analysis than is possible with electrometric probes.

Of concern in the Klamath are the concentrations of nutrients, notably nitrogen and phosphorus, and related parameters, such as chlorophyll-*a*, biochemical oxygen demand (BOD) and total suspended solids (TSS). On occasion, additional grab samples were collected for special studies that included diurnal evaluations of nutrients, effects of a pulse flow on re-suspension of nutrient matter in the water column, and an evaluation of the effect of fall turnover of Iron Gate Reservoir on downstream river water quality. During the 5-year period of study, approximately 10,000 water samples were collected and analyzed as part of this study and the results stored in an Access database. This report is focused on the Klamath downstream from Iron Gate, and therefore does not present analyses for these special studies nor for data collected upstream from Iron Gate.

3.1. Overview of database and assessment of data quality

The 51 sampling stations from which grab samples were taken are listed in Table 1-1 (see Appendices A-2 and A-3 for further information about the sampling stations). The number of grab samples taken at each station is provided in Table 3-1. Most grab samples were taken in the Klamath River mainstem below Iron Gate Dam with fewer samples taken in the mainstem Klamath River above Iron Gate Dam (not considered in the present report) and in the tributaries such as the Salmon, Scott, Shasta, and Trinity rivers (Table 3-1).

The grab-sample database includes the following constituents:

(1) Inorganics (i.e., alkalinity, calcium, magnesium, TSS, and total dissolved solids [TDS]);
(2) Carbonaceous organic material (i.e., biochemical oxygen demand and total organic carbon [TOC]);
(3) Nutrient forms (i.e., nitrogen [total Kjeldahl nitrogen or TKN, ammonia-N, nitrite-N, nitrate-N, plus derived parameters nitrite + nitrate-N, TN, total organic nitrogen] and phosphorus [TP and ortho-P]);
(4) Bacteria (i.e., total coliform and fecal coliform groups);
(5) Algal forms (i.e., chlorophyll *a* and pheophytin).

These are the key constituents needed to understand the basic limnology of the river and the impacts of waste discharges, runoff, impoundment, and other anthropogenic factors on water quality.

Table 3-1. Number of grab samples taken at stations in the Klamath River Basin during 2001-2005. River mile represents the distance upstream from the mouth of the river.

Station	*Location*	*River mile (rm)*	*Number of grab samples*
LR	Link River below dam	253.2	200
KS	Klamath Straights Drain	240.5	134
KN	Klamath River below Keno Dam	223.2	167
JB	Klamath River before JC Boyle Powerhouse (Bypass)	220.5	132
JP	Klamath River at JC Boyle Powerhouse	220.4	136
JC	Klamath River below JC Boyle return	217.0	160
KRSL	Klamath River at Stateline	209.2	16
C1	Klamath River above Copco 1	205.5	137
C2	Klamath River below Copco 2	196.5	205
IGRB	Iron Gate Reservoir Bottom	190.1	36
IGRS	Iron Gate Reservoir Surface	190.1	37
IG	Klamath River at Iron Gate Hatchery Bridge	189.8	1245
BC	Bogus Creek	189.2	15
K1	Klamath River above Shasta	176.8	170
L1	Little Shasta River CDFG wildlife area	176.6	30
L2	Little Shasta River	176.6	28
S1	Shasta River at Louie Rd Crossing	176.6	96
S2	Shasta River at A12 Bridge	176.6	73
S3	Shasta River at Montague Grenada	176.6	79
S4	Shasta River above Yreka Creek	176.6	81
SH	Shasta River near mouth	176.6	920
SRWC	Shasta River above Willow Creek (near rt 3)	176.6	15
Y2	Yreka Creek above Waste Water Plant	176.6	14
YR	Yreka Creek	176.6	81
GOT	Klamath River below Gottville	164.9	15
BVC	Beaver Creek	161.1	15
RB	Klamath River at Round Bar pool, near town of Klamath River	158.5	44
K2	Klamath River above the Scott River (small pullout across from green highway sign- Horse Creek 4 miles)	143.2	205
SC	Scott River near mouth	143.0	612
HAM	Klamath River below Hamburg river access point 56 Rodney Pt.	140.0	15
SV	Klamath River at Seiad Valley	128.5	656
GOF	Klamath River below Fort Goff, river access point 66, Seattle Creek	121.4	15
ELK	Elk Creek	105.5	15
KELK	Klamath River 200 yards below Elk Creek, above WWTP	105.4	15
HC	Klamath River below Happy Camp	100.8	544
CLR	Clear Creek	98.6	15
KD	Klamath River above Dillon Creek	84.3	14
DLN	Dillon Creek	84.2	15
KSA	Klamath River above Salmon River	66.1	39
SA	Salmon River near mouth	66.0	504
OR	Klamath River at Orleans	59.1	701
UL	Ullathorne Creek (Below Orleans)	56.1	15
RCC	Red Cap Creek, 150 ft upstream of Allen Bridge	52.7	15
BL	Bluff Creek @ mouth	49.5	12
WE	Klamath River at Weitchpec	43.6	420
TR	Trinity River near mouth	43.5	628
MF	Klamath River at Martins Ferry	40.4	446
TC	Klamath River above Tully Cr. (below MF)	38.5	155
KBC	Klamath River above Blue Creek	16.5	26
TG	Klamath River at Terwer	6.7	699
EM	Klamath River Estuary mainstem	0.1	102

The *Protocol for Collection of Nutrients Grab Samples* (AFWO 2005) describes the procedures used for collection of water samples from the Klamath River and its tributaries, how the samples were handled after collection, and how they were stored from the time of collection to delivery at the laboratory. The methods described in this *Protocol* indicate that standard field procedures were used that would protect the samples from contamination, deterioration, and mishandling.

For QA/QC purposes, it is desirable to estimate the precision, accuracy, completeness, representativeness, and comparability of the data. *Precision* measures the reproducibility of the sampling (field) and analytical (laboratory) methodology, and is quantified as the relative percent difference between duplicate (i.e., replicate) sample analyses:

$$\text{Relative Percent Difference} = \frac{(M_1 - M_2)x100}{(M_1 + M_2)/2} \qquad (3\text{-}1)$$

where the two duplicate measurements are M_1 and M_2. The precision goals as identified by CSWRCB (2000) were met for all analytes used in our study (Armstrong and Ward 2005).

Accuracy is defined as the degree to which the analytical measurement reflects the true concentration of the constituent of interest in the sample and may be determined by the percent recovery of a known spike from the sample. The result is expressed as a percent of the spike recovered from the sample:

$$\text{Percent Recovery} = \frac{(SSR - SR)x100}{SA} \qquad (3\text{-}2)$$

where SSR= spiked sample result, SR = sample result, and SA = spike added. The accuracy requirement is at least 90% for nutrients and 70% for organics (CSWRCB 2000), which were also met in our study.

Data *completeness* is defined as the percentage of usable data (i.e., usable data divided by the total possible data). While the data needed to estimate completeness for the entire program are not available, the completeness of the grab-sample database can be estimated, and it is quite high at well over 90%, meeting the completeness goals of CSWRCB (2000).

Based on evaluation of the AFWO grab-sample database, Armstrong and Ward (2005) reach the following conclusions:

(1) Water-quality sampling has taken place from 2001 through 2005 at several locations in the Klamath River basin both in the river mainstem and the major tributaries and analyzed for inorganic, organic, nutrient, bacterial, and algal constituents, and the results from that sampling effort have been stored in the grab-sample database along with associated laboratory and QA/QC information.

(2) The AFWO grab-sample database is easily usable in its Access format, the database structure is satisfactorily described in a document authored by AFWO personnel (Turner 2004), and the experienced Access user can easily construct queries to extract water-quality data from the database.

(3) An analysis was made of the field sampling and sample handling protocols, and it was ascertained that standard practices were being used to gather and store samples prior to their delivery to a laboratory for analysis.
(4) The water-quality data in the grab-sample database were analyzed to determine how well sample integrity was preserved through the sampling and analytical process, and for accuracy, precision, completeness, representativeness, and comparability. The results indicated that overall the database equals or exceeds the QA/QC expectations of the CSWRCB (2000).
(5) Where problems were noticed in the database, it was clear that AFWO had discerned the problem early on and had taken corrective actions, and it is also clear that AFWO is continuing to improve the database by adding more QA/QC information as it becomes available.
(6) AFWO's Klamath River grab-sample database is ready for use in other studies of water quality.

In summary, the data in the AFWO grab-sample database have been acquired through field sampling and sample handling methods that are in accordance with standard practice. Laboratory analysis of the samples collected have been carried out by laboratories practicing acceptable QA/QC procedures. While intra-laboratory comparisons would have been highly desirable for those analytes being tested by more than one laboratory, the lack of these comparisons does not negate the excellent quality of these data as reported in Armstrong and Ward (2005).

In the analysis of this water-quality data, it became evident that analytical detection limits had changed over the years for constituents of interest in this study, notably nutrients. Some of these detection limits were high enough that many of the values for constituents were below those detection limits. A compilation of these detection limits by analyte, station, and year made it clear that the method detection limits (MDLs) have varied over time and among stations for most of the analytes listed.

It is common in water-quality sampling to encounter samples whose concentrations of chemical constituents are below the limit of detection of the techniques being used (Chapman 1992, Berthouex and Brown 1994). These results may be reported as "not detected" (ND) or less-than values (< or LT), and if used in water-quality analysis, these designations must be replaced by a numerical value. The most common substitutions being the limit of detection (LOD), one-half the limit-of-detection (0.5 LOD), or zero. The resulting data sets are thus artificially curtailed at the low-value end of the distribution and are termed *censored*. Because numerous non-detects occur in the AFWO database, a decision had to be made about how to handle these, (i.e., whether to substitute a value for below detection entries and if so what should that value be). As detailed in Armstrong and Ward (2008a), it was decided that substitution for ND values should be the MDL/2, because this is a conventional approach that is commonly used in scientific literature (e.g., EPA, 2000a; EPA, 2000b; Kayhanian et al., 2002).. This also provides a midpoint of concentration, and hence load, between the other two assumptions of ND = 0 and ND = MDL. Moreover, Armstrong and Ward (2008a) concluded that:

(1) High confidence can be placed in the TN data collected since about 2004 as long as a low MDL is used, but low confidence must be assumed for most of the nitrogen load estimates for most of the years and months because of the high percentage of ND's.
(2) Highest confidence can be placed in the total P data because of the very small percentage of ND's.

3.2. Constituent loads in time and space

To manage water quality in the Klamath River, it is essential to know the sources and magnitudes of those constituents that potentially could have significant impacts on the DO, nutrients, and transparency of the river in space and time, which in turn affect vegetation (notably phytoplankton, periphyton and submerged aquatics) and fish populations. For those constituents whose dominant source in the river is mass transport through runoff, tributary inflows, or direct point injection (notably, wastewater discharges), their respective rate of mass transfer, or *load*, is fundamental. The focus of this section is the loading of nitrogen and phosphorus to the lower Klamath River during 2001-2005, specifically the June through October sampling period in each year. Other constituents are also of interest, namely dissolved inorganics, dissolved organics, suspended substances, and phytoplankton. Concentrations of organic materials may indicate the load that oxygen demanding materials are exerting on DO resources of the Klamath River. These concentrations may be estimated in several ways, but the constituent used in this study is TOC, whose measurement technique is limited to dissolved or colloidal-sized forms of organics. Materials suspended in the water column may decrease water transparency and thereby limit light penetration and photosynthesis. These are made up of inorganic and organic materials and may be measured as TSS. The primary nutrients supporting the growth of phytoplankton and other vegetative forms are measured by TN and TP, although the bioavailable forms of these nutrients make up only a portion of the total concentrations. TN is determined as the sum of organic nitrogen (total Kjeldahl nitrogen - ammonia nitrogen) and inorganic nitrogen (the bioavailable forms: ammonia nitrogen + nitrite nitrogen + nitrate nitrogen). TP is measured directly (with bioavailable phosphorus estimated as orthophosphorus). Finally, measures of living phytoplankton, dead phytoplankton, and other vegetative forms that have become suspended are estimated from chlorophyll and pheophytin concentrations, respectively.

Mass loads of water-quality constituents entering the lower Klamath River translate into concentrations of these constituents which in turn can be judged to impact the uses of the river. The approach of this study is to use constituent concentrations in the AFWO water-quality database coupled with flows to estimate constituent loads to the Lower Klamath River from the Iron Gate Reservoir release and the major and minor tributaries, and to track these loads downstream in the mainstem Klamath River.

To estimate constituent loads, two key pieces of information are required – flows and constituent concentrations. Flow information was obtained from the USGS for gauged stations within the study area, as described in Chapter 2. Constituent concentrations are available in the AFWO grab-sample database, described in the preceding section. The product of flow (volume per time) and concentration (mass per volume) is load (mass per time). Sources of loads fall into four major categories:

- the upstream load into the study area (in this case the release from Iron Gate Reservoir);
- major tributaries that are typically gauged for flows and monitored for constituent concentrations and for which constituent loads may be estimated;
- point-source wastewater loads that discharge directly to the river or that discharge to a tributary, in which case the point-source load can be separated from the tributary load as appropriate; and
- minor tributary loads again to the river directly or to a major tributary.

Loads attributed to releases from Iron Gate Reservoir and those that could be estimated for the four major tributaries (i.e., the Shasta, Scott, Salmon, and Trinity rivers) and the minor tributaries (see KA and AES 2006 for full list) are addressed here. Point-source wastewater loads, which are not addressed here, may be estimated from self-reporting data available from the U.S. Environmental Protection Agency or the appropriate California agency, either directly or through Typical Pollutant Concentrations (i.e., typical concentrations of nitrogen and phosphorus in wastewater discharges based on levels of treatment provided and the nature of the raw wastewater being treated).

The dissolved inorganics, measured by TDS, can provide information about the water-quality environment and its suitability for intended uses. In this work, its primary purpose is as a conservative tracer material in the lower Klamath River, thereby providing a means to determine how well mass balances are being achieved. If mass balances for conservative materials are not closed within acceptable accuracy, then inferences from mass balances for non-conservative materials, such as nutrients, would be suspect. More importantly, the error in closing a mass balance for a conservative tracer provides an estimate of the uncertainty latent in mass budgeting non-conservative constituents.

In water-quality management, the most immediate way to assess relationships between in-stream concentrations of a constituent and its point and non-point loads is through mass budgets of loads, which is completely data-based. Another approach to assess these relationships is through mass-balance-based water-quality modeling (see Section 3.3 for further details). Based on the principle of conservation of mass and continuity of flow, a mass balance for a conservative constituent dictates that the mass flux downstream from the confluence of two or more inputs is the sum of the individual mass fluxes from those inputs. The departure from such a balance in fluxes is diagnostic that the constituent is non-conservative (i.e., its concentration is further increased or decreased by kinetic decay processes).

The practical application of this concept for the Klamath River is in calculations of mass-budget concentrations of a constituent in the river below the confluence of a tributary and the mainstem, or a waste discharge to a tributary. For substances like phosphorus, that are known to interact with living and nonliving components of a riverine environment, there may be a net loss of mass from the water column as it is taken up (e.g., for phosphorus by vegetation, adsorbed to sediments and other surfaces, and perhaps lost in other ways from the water column). This mass loss must be accounted for in a mass-balance-based model, where it is generally represented as a first-order reaction, unless the kinetics of the phenomena causing the losses are known to be more complex.

To estimate constituent loads in the mainstem of the Klamath River, average monthly flows for June through October during 2001-2005 were used at the mainstem and tributary USGS gauging stations listed in Table 2-1. For the ungauged portions of the Klamath River watershed, flows in each watershed were estimated by converting the average monthly runoff yields (in inches/month) determined by Ward and Armstrong (2006a) into flow per unit area (cfs/mi^2), then multiplying by the watershed area to get the monthly average flow (in cfs). From Figure 2-1 and data provided in Appendix A-1, the ungauged watershed areas on the Klamath mainstem were determined to be approximately 854 mi^2 between Iron Gate and the Scott River confluence, 650 mi^2 between the Scott River confluence and the Salmon River confluence, and 1,772 mi^2 between the Salmon River confluence and the Klamath River gauge near Klamath, mainly comprised of ungauged tributaries.

The equation used to calculate monthly constituent loads for a generic constituent is:

$$\begin{aligned} W(\text{kg/mo}) &= Q\left[\frac{\text{ft}^3}{\text{sec}} \bullet \frac{28.32\text{L}}{\text{ft}^3} \bullet \frac{86{,}400\text{sec}}{\text{d}}\right] \bullet S\left[\frac{\text{mg}}{\text{L}} \bullet \frac{\text{kg}}{10^6\,\text{mg}}\right] \bullet n\left[\frac{\text{d}}{\text{mo}}\right] \\ &= 2.446848 \bullet Q(\text{cfs}) \bullet S(\text{mg/L}) \bullet n(\text{d/mo}) \end{aligned} \qquad (3\text{-}3)$$

where Q denotes monthly average flow value, S the monthly average constituent concentration in units of mg/L, and n is the number of days in each of the months from June through October. For example, for an average daily flow of 235 cfs and a monthly average TP concentration of 0.12 mg/L during the month of July, the load is calculated to be:

2,139 kg/mo (2.446848 x 235 cfs x 0.12 mg/L x 31 d/mo).

To estimate constituent loads from the ungauged drainage areas, constituent yields from adjacent gauged areas were used as estimates of the yields from the ungauged areas:

$$\begin{aligned} W(\text{kg/mo}) &= Y\left(\frac{\text{in}}{\text{mo}}\right) \bullet A_{ug}(\text{mi}^2) \bullet S\left(\frac{\text{mg}}{\text{L}}\right) \bullet \left(\frac{\text{kg}}{10^6\,\text{mg}}\right) \bullet n\left(\frac{\text{d}}{\text{mo}}\right) \\ &= Y\left(\frac{\text{cfs}}{\text{mi}^2}\right) \bullet A_{ug}(\text{mi}^2) \bullet S\left(\frac{\text{mg}}{\text{L}}\right) \bullet \left(\frac{\text{kg}}{10^6\,\text{mg}}\right) \bullet n\left(\frac{\text{d}}{\text{mo}}\right) \\ &= 2.446468 \bullet Q(\text{cfs}) \bullet S\left(\frac{\text{mg}}{\text{L}}\right) \bullet n\left(\frac{\text{d}}{\text{mo}}\right) \end{aligned} \qquad (3\text{-}4)$$

where the values for constituent concentration were the average values over the five calendar years for the AFWO station co-located at a USGS gauging station draining a watershed considered to represent the relatively undeveloped characteristics of the ungauged watershed throughout the lower Klamath River. For this study, that watershed was the Salmon River and the average concentration was determined at AFWO Salmon station co-located with the gauging station near its mouth. This river was selected because of its relatively undeveloped nature and the assumption that constituent concentrations would represent background levels.

Constituent data were available at the stations sampled by AFWO (Table 3-1) and contained in the Access database described in Section 3.1. These stations were mostly at or close to the USGS gauging stations. In the few instances when they were not, they were considered to approximate nutrient loads and estimated as if they were co-located. Monthly average values were computed for all constituents in the AFWO database at all stations and at all months in which samples were taken. The monthly loads were then arranged for each calendar year so that they reflected the geographic positions of mainstem stations or the locations of the confluences of the major tributaries. The schematic arrangement of the values for each month of each calendar year is shown in Table 3-2.

Constituent loads were determined for TN, TP, TDS, TSS, TOC, and chlorophyll-*a*. This section focuses on the nutrients TN and TP. The calculation procedure is the same for all the constituents, as laid out in Table 3-2 (see Armstrong and Ward, 2008a for all calculated loads and other analytical details). To estimate nitrogen and phosphorus loads in the lower Klamath River, estimates of TN and TP concentrations were needed, as opposed to component species of these two nutrients. It was necessary to estimate TN from component forms of nitrogen first before loads could be calculated. TP on the other hand was directly determined analytically.

Table 3-2. Arrangement and calculation of terms in flow and load mass budget (Eqn= equation referenced in text).

	Location	*Gauge Number*	*Flow*	*Load*
(1)	Klamath at Iron Gate	11516530	measured	Eqn (3-3)
	Tributaries:			
(2)	Shasta near Yreka	11517500	measured	Eqn (3-3)
(3)	Scott near Ft Jones	11519500	measured	Eqn (3-3)
(4)	Total		(2) + (3)	(2) + (3)
(5)	Ungauged		(7) – (1) – (4)	Eqn (3-4)
(6)	Total intervening		(4) + (5)	(4) + (5)
(7)	Klamath near Seiad Valley	11520500	measured	Eqn (3-3)
	Tributaries:			
(8)	Salmon at Somes Bar	11522500	measured	Eqn (3-3)
(9)	Ungauged		(11) – (7) – (8)	Eqn (3-4)
(10)	Total intervening		(8) + (9)	(8) + (9)
(11)	Klamath at Orleans	11523000	measured	Eqn (3-3)
	Tributaries:			
(12)	Trinity at Hoopa	11530000	measured	Eqn (3-3)
(13)	Ungauged		(15) – (11) – (12)	Eqn (3-4)
(14)	Total intervening		(12) + (13)	(12) + (13)
(15)	Klamath at Klamath	11530500	measured	Eqn (3-3)

The final step of this analysis was to examine the constituent mass balance between the main gauging stations on the Klamath River (i.e., between the Iron Gate and Seiad Valley gauges, the Seiad Valley and Orleans gauges, and the Orleans and Klamath gauges, as schematized in Table 3-2. The computed monthly loads during 2001-2005 are presented in Table 3-3. The existence of a flow balance follows from two key assumptions of the hydrology: that the net interflow (i.e., exchange between the water in the river channel and that in the hyporheic zone) is negligible, and there is no net storage (positive or negative) of surface water in the reach between gauges. As noted above, the constituent loads were determined independently based on measured concentrations at the Klamath and major tributary stations and estimated minor tributary concentrations, so an exact mass balance may or may not exist. By calculating the difference between the downstream Klamath River constituent load and the upstream Klamath River constituent load from the major tributaries and ungauged areas, a mass balance was considered achieved if this difference was near zero. These aggregated loads are given for each year in Table 3-3. If the difference was negative, then there was a loss of mass in the river which would be typical for non-conservative substances subject to decay, settling, or other mechanisms of loss from the water column. If the difference was positive, then there was a gain of mass, presumably due to an instream source or volumetric growth, for example, vegetation as represented by chlorophyll-*a*. Given the errors associated with substitution of values for NDs and the normal sampling and analytical errors, one must view these differences with caution, for unusual concentration variations can produce erratic mass-balance results. This issue is addressed further in Armstrong and Ward (2008b).

From Table 3-3, constituent loadings are seen to vary considerably in space and time, depending on flows and concentrations. There were relatively few patterns discernible among the loads for any one constituent, although mass balances revealed constituent mass losses as expected for non-conservative materials like TN and TP (Table 3-3), as well as TOC and chlorophyll-*a*.

Table 3-3. Nutrient loads by month in 2001-2005, computed from measurements of flow and concentration as schematized in Table 3-2.

	Total nitrogen load (kg/mo)					*Total phosphorus load (kg/mo)*				
Location	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
2001										
Klamath at Iron Gate	112,116	86,975	133,441	100,700	189,226	17,827	13,824	30,824	19,199	18,526
Tributaries:										
Shasta near Yreka	1,636	1,605	1,238	2,330	7,050	772	778	939	1,122	2,738
Scott near Ft Jones	606	142	136	106	113	145	33	31	8	9
Total	2,242	1,747	1,374	2,436	7,163	917	811	970	1,130	2,747
Ungauged	1,572	868	-45	-98	379	115	96	-6	-14	82
Total intervening	3,815	2,615	1,329	2,339	7,542	1,032	907	964	1,115	2,829
Klamath near Seiad Valley	96,669	68,721	100,578	123,668	176,473	23,002	11,959	23,012	18,452	26,637
Tributaries:										
Salmon at Somes Bar	3,744	3,993	1,914	1,546	2,142	609	431	484	135	233
Ungauged	3,304	2,521	1,575	965	644	242	277	201	141	139
Total intervening	7,048	6,513	3,489	2,511	2,786	851	709	684	277	372
Klamath at Orleans	92,386	49,038	71,074	81,964	143,541	14,566	8,128	17,883	14,372	21,475
Tributaries:										
Trinity at Hoopa	14,399	21,026	17,672	17,428	18,641	21,311	2,900	2,746	1,394	1,374
Ungauged	21,842	17,272	17,412	9,731	21,488	1,599	1,901	2,220	1,427	4,649
Total intervening	36,241	38,298	35,084	27,159	40,130	22,910	4,802	4,966	2,821	6,023
Klamath at Klamath	88,180	80,636	293,202	114,557	172,788	44,090	17,244	26,748	19,284	30,505
					Aggregate load (kg/mo)					
Klamath at Iron Gate	112,116	86,975	133,441	100,700	189,226	17,827	13,824	30,824	19,199	18,526
Major tributaries	20,385	26,766	20,960	21,410	27,946	22,837	4,143	4,199	2,659	4,354
Ungauged	26,719	20,660	18,942	10,598	22,511	1,956	2,274	2,415	1,554	4,870
Difference at Klamath	-71,040	-53,766	119,858	-18,151	-66,895	1,470	-2,997	-10,690	-4,129	2,755

(continued)

Table 3-3 (continued). Nutrient loads by month.

	Total nitrogen load (kg/mo)					*Total phosphorus load (kg/mo)*				
Location	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
2002										
Klamath at Iron Gate	40,085	72,173	55,534	59,972	72,106	9,475	12,064	9,845	15,515	22,227
Tributaries:										
Shasta near Yreka	2,031	1,739	1,589	1,112	5,753	1,251	728	735	876	3,679
Scott near Ft Jones	15,933	1,900	227	169	251	985	125	40	24	109
Total	17,963	3,639	1,815	1,281	6,004	2,236	853	775	900	3,789
Ungauged	5,473	2,643	1,830	597	592	401	291	233	88	128
Total intervening	23,436	6,282	3,645	1,878	6,596	2,637	1,144	1,008	987	3,916
Klamath near Seiad Valley	65,018	45,067	35,823	41,576	59,835	13,262	12,837	10,448	13,572	24,245
Tributaries:										
Salmon at Somes Bar	14,476	6,357	1,622	1,145	1,701	1,324	835	512	344	643
Ungauged	22,607	9,678	10,524	5,271	7,117	1,655	1,065	1,342	773	1,540
Total intervening	37,084	16,034	12,145	6,416	8,818	2,979	1,901	1,854	1,117	2,183
Klamath at Orleans	65,936	43,719	43,096	36,721	66,474	14,902	9,618	10,583	13,411	27,749
Tributaries:										
Trinity at Hoopa	18,094	14,013	9,244	13,124	4,347	3,474	1,471	1,056	1,529	1,435
Ungauged	12,512	10,539	8,155	750	3,367	916	1,160	1,040	110	728
Total intervening	30,606	24,552	17,399	13,873	7,714	4,390	2,632	2,096	1,638	2,163
Klamath at Klamath	83,858	68,502	70,616	43,896	54,716	16,772	11,283	10,504	15,510	17,874
					Aggregate load (kg/mo)					
Klamath at Iron Gate	40,085	72,173	55,534	59,972	72,106	9,475	12,064	9,845	15,515	22,227
Major tributaries	50,534	24,008	12,681	15,550	12,052	7,034	3,160	2,344	2,772	5,866
Ungauged	40,592	22,860	20,509	6,617	11,076	2,972	2,517	2,615	970	2,396
Difference at Klamath	-47,353	-50,540	-18,108	-38,243	-40,518	-2,708	-6,458	-4,299	-3,748	-12,616

(continued)

Table 3-3 (continued). Nutrient loads by month.

	Total nitrogen load (kg/mo)					Total phosphorus load (kg/mo)				
Location	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
2003										
Klamath at Iron Gate	62,697	42,331	56,288	90,694		18,187	19,441	15,111	22,098	
Tributaries:										
Shasta near Yreka	3,595	2,591	3,277	3,316		1,634	2,120	1,806	1,447	
Scott near Ft Jones			4,822					313		
Total	3,595	2,591	8,098	3,316	0	1,634	2,120	2,119	1,447	0
Ungauged	10,668	3,126	1,460	766	795	781	344	186	112	172
Total intervening	14,262	5,717	9,559	4,082	795	2,415	2,464	2,305	1,559	172
Klamath near Seiad Valley			66,967					15,703		
Tributaries:										
Salmon at Somes Bar			12,518					1,366		
Ungauged	22,599	13,744	12,615	5,367	6,601	1,654	1,513	1,608	787	1,428
Total intervening	22,599	13,744	25,133	5,367	6,601	1,654	1,513	2,974	787	1,428
Klamath at Orleans			87,098	92,817				14,411	30,086	
Tributaries:										
Trinity at Hoopa		86,358	48,022	51,056			8,793	1,281	3,999	
Ungauged	15,292	7,930	4,959	2,281	3,917	1,120	873	632	335	847
Total intervening	15,292	94,287	52,982	53,337	3,917	1,120	9,666	1,913	4,334	847
Klamath at Klamath	520,892	216,964	144,468	148,998		54,930	28,008	15,235	37,250	
				Aggregate load (kg/mo)						
Klamath at Iron Gate			56,288					15,111		
Major tributaries			68,639					4,765		
Ungauged			19,034					2,427		
Difference at Klamath			507					-7,067		

(continued)

Table 3-3 (continued). Nutrient Loads by month.

Location	Total nitrogen load (kg/mo)					Total phosphorus load (kg/mo)				
	Jun	*Jul*	*Aug*	*Sep*	*Oct*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
2004										
Klamath at Iron Gate	45,840	43,485	52,336	32,159	57,612	8,398	9,209	14,126	18,089	10,890
Tributaries:										
Shasta near Yreka	3,927	1,616	873	1,371		832	801	952		
Scott near Ft Jones	14,043	2,665	290	274		757	59	116	120	
Total	17,970	4,281	1,163	1,646	0	1,589	860	1,068	120	0
Ungauged	6,498	2,547	704	397	1,338	476	280	90	58	289
Total intervening	24,467	6,828	1,867	2,042	1,338	2,065	1,140	1,158	178	289
Klamath near Seiad Valley	52,720	19,623	17,521	20,682		10,715	9,276	11,468	22,563	
Tributaries:										
Salmon at Somes Bar	32,630	11,793	5,360	3,366		1,088	1,372	195	465	
Ungauged	16,877	10,052	9,478	5,880	11,985	1,236	1,107	1,208	862	2,593
Total intervening	49,507	21,845	14,838	9,246	11,985	2,323	2,479	1,403	1,327	2,593
Klamath at Orleans	121,446	43,690	40,259	65,409		21,166	13,981	35,082	21,080	
Tributaries:										
Trinity at Hoopa	84,042	37,174	20,483	20,826		2,801	1,352	1,713	6,096	
Ungauged	12,079	8,626	10,103	4,920	-1,868	884	950	1,288	722	-404
Total intervening	96,121	45,800	30,586	25,747	-1,868	3,686	2,301	3,001	6,818	-404
Klamath at Klamath	208,611	91,398	61,818	86,840		18,775	8,641	10,565	32,453	
Aggregate load (kg/mo)										
Klamath at Iron Gate	45,840	43,485	52,336	32,159		8,398	9,209	14,126		
Major tributaries	134,642	53,248	27,005	25,838		5,478	3,584	2,976		
Ungauged	35,453	21,225	20,285	11,197		2,596	2,337	2,586		
Difference at Klamath	-7,324	-26,560	-37,809	17,646		2,303	-6,488	-9,122		

(continued)

Table 3-3 (continued). Nutrient loads by month.

Location	*Total nitrogen load (kg/mo)* Jun	*Jul*	*Aug*	*Sep*	*Oct*	*Total phosphorus load (kg/mo)* Jun	*Jul*	*Aug*	*Sep*	*Oct*
2005										
Klamath at Iron Gate	62,031	46,918	81,494	100,407	137,133	7,918	7,609	11,788	15,098	16,260
Tributaries:										
Shasta near Yreka	4,319	1,419	2,016	2,669	3,963	1,358	641	633	787	1,866
Scott near Ft Jones	13,870	2,555	185	127	264	722	61	10	7	29
Total	18,188	3,974	2,201	2,796	4,227	2,080	702	643	794	1,895
Ungauged	7,745	3,344	958	412	1,452	567	368	122	60	314
Total intervening	25,934	7,318	3,159	3,208	5,678	2,647	1,070	765	855	2,209
Klamath near Seiad Valley	80,418	106,594	106,581	90,976		10,748	8,793	13,270	14,863	
Tributaries:										
Salmon at Somes Bar	15,393	6,371	5,260	708		784	348	157	85	
Ungauged	28,246	18,591	16,909	7,439	5,044	2,068	2,047	2,156	1,091	1,091
Total intervening	43,639	24,963	22,170	8,146	5,044	2,852	2,394	2,313	1,176	1,091
Klamath at Orleans	62,560	25,008	93,089	80,259		14,720	9,765	13,931	14,606	
Tributaries:										
Trinity at Hoopa	47,327	147,331	9,127	3,106		5,026	1,209	400	373	
Ungauged	26,678	11,792	9,545	2,942	11,460	1,953	1,298	1,217	432	2,479
Total intervening	74,006	159,123	18,672	6,049	11,460	6,979	2,507	1,617	804	2,479
Klamath at Klamath	263,464	63,479	34,306	81,832		25,445	8,858	9,683	12,378	
Aggregate load (kg/mo)										
Klamath at Iron Gate	62,031	46,918	81,494	100,407		7,918	7,609	11,788	15,098	
Major tributaries	80,909	157,676	16,588	6,610		7,890	2,258	1,201	1,252	
Ungauged	62,670	33,728	27,412	10,793		4,588	3,713	3,495	1,583	
Difference at Klamath	57,855	-174,842	-91,188	-35,978		5,049	-4,723	-6,800	-5,555	

These constituent loads may be used in other efforts such as water-quality modeling to estimate constituent concentrations in the lower Klamath River to compare to existing concentrations and to forecast constituent concentrations under future flow and loading conditions (see Section 3.3). From these mass budgets, several conclusions may be drawn:

(1) TN and TP loads from Iron Gate Reservoir tend to dominate the loadings to the lower Klamath River.
(2) The difference between TN and TP loads at Klamath and the inflows upstream are almost always negative confirming that these nutrients are lost from the river water column between Iron Gate and the downstream station at Klamath above the estuary during the months June through October. Similar behavior of the TOC loads was found in Armstrong and Ward (2008a).
(3) For the conservative parameter TDS, loadings to the lower Klamath River were evenly divided among Iron Gate Reservoir, the major tributaries, and the ungauged areas. Surprising mass losses were determined for TDS, and it is not clear whether this arose from inaccuracy in the measured concentrations or from other factors (Armstrong and Ward 2008a).
(4) For TSS, Iron Gate, the major tributaries, and ungauged areas all contribute loads in significant amounts although the proportions change considerably from month to month and year to year. Of significance are the differences between the downstream load at Klamath and the sum of loads from Iron Gate, the intervening tributaries and ungauged areas, which were found to be positive in some months suggesting internal sources of TSS (e.g., scour) and negative in others suggesting loss from the water column (e.g., settling).
(5) Except for June of each year, Iron Gate Reservoir dominated the loads of chlorophyll-*a* with contributions frequently exceeding 80 and 90 percent (Armstrong and Ward 2008a). According to the mass budgets, generally there were net losses of chlorophyll-*a* in the river except for a few months, such as June and October of 2001 and August 2005, in which there was a gain, sometimes considerable.

3.3. Nutrient loads and their fate: use of a plug-flow model

The load-budget approach presented in the previous section has several benefits, including being based on data and being integrated over large segments of the river. It also integrates over all biochemical processes operating in the watercourse, however, so that the difference in loads between two stations in the river is the *net* effect of all physical and chemical sources and sinks. To differentiate these processes, a more sophisticated mass budget is necessary. In this section, we address the relation between in-stream concentrations of nutrients (and related parameters) and the identified point and nonpoint loads of nutrients using a plug-flow mass-balance-based model. Concentrations of any waterborne parameter more than those estimated by river dilution of known loads can be indicative of either underestimate (or incomplete identification) of loads, or the operation of an additional source of the parameter, such as resuspension or fluxes from bed sediments. Concentrations substantially lower than those estimated from known loads can be diagnostic of high rates of loss or assimilation. Either provides insights into the behavior of that parameter in the river.

Water-quality models based on mass balances vary in complexity, from steady-state simplified models to steady-state segmented models to dynamic segmented and networked models. A thorough review of these models and their applications may be found in Thomann and Mueller (1987), Chapra and Reckow (1983) and Chapra (1997). Steady-state simplified models incorporate mass-balance and flow-balance principles and provide a reasonable representation of natural systems, commonly used for first approximations of constituent concentrations in natural systems. Such simplified models include Continuously Stirred Tank Reactor (CSTR) models, plug-flow models, and dispersive-flow models. CSTR models have been used most often to represent lakes and embayment estuaries, while plug-flow and dispersive-flow models have been used to represent both slow- and fast-moving rivers, as well as linear estuaries. It is the steady-state plug-flow model that is selected here to represent constituents in the lower Klamath River, based on the domination of transport by longitudinal currents (*cf*. travel times displayed in Figure 2-14).

As detailed in Thomann and Mueller (1987), two assumptions apply in plug-flow models:

(1) Water-quality constituents are homogeneous in the cross section of the river so that there are no lateral or vertical concentration gradients. The consequence of this assumption is that constituents discharged to a river are instantaneously mixed laterally and vertically in the river cross section and no plume exists that varies across the section, an assumption that obviously only approximates what occurs.
(2) There is no mixing of water in the longitudinal direction downstream (i.e., each element or "plug" of water with its associated water quality flows downstream in a unique, discrete fashion). The consequence of this assumption is that there is no longitudinal spread of water or constituents due to dispersion or velocity gradients, so that a pulse discharge of some constituent is mixed throughout the river cross section at the point of discharge (per the first assumption) and the water receiving the constituent stays intact as a plug carrying the constituent downstream.

While these assumptions may appear to constrain the use of the plug-flow model for riverine systems like the lower Klamath River, that is not the case. The first assumption is significantly violated only in the portion of the river immediately below the confluence of a discharge or tributary and the mainstem. The second assumption well represents riverine systems in which advective transport is significantly greater than dispersive transport, as is the case for the lower Klamath River.

For plug-flow models, constituent concentrations are calculated based on mass balances at the point of discharge and at distances downstream, as a plug of water and its associated constituents passes through those points. At a waste-discharge or tributary input point, the mass balance calculation in the river may be stated in the following way:

Mass rate of constituent from just upstream of the discharge point
+ mass rate of constituent added by source at the discharge point
= mass rate of constituent immediately downstream of discharge point

Downstream constituent concentrations may be calculated using a first-order differential equation for a steady-state distribution of a reactive substance in a stream or river. The concentration change downstream from a point source or tributary discharge can be expected to decrease exponentially from a concentration of S_0 at the point of discharge to some concentration S at distance x downstream. The rate of concentration change downstream is dependent on the relative magnitudes of the decay rate and stream velocity. The larger the decay rate, the faster the concentration will decrease. On the other hand, the higher the river velocity, and hence the smaller the exponential change with distance, the slower the downstream concentration will decrease.

This development of the plug-flow model for water-quality constituents in rivers shows that concentrations of those constituents can be easily calculated downstream from a headwater input with known flow and constituent concentration, or from a discharge by first calculating the concentration of the constituent in the river following the discharge (i.e., S_0) and then by calculating concentrations downstream $S(x)$, knowing the average river velocity and the decay rate of the constituent. This also means that estimates of the average river velocity U and the decay rate K must be known or determined in some way, and there are indeed ways to estimate these two values. Also needed are the flows and constituent concentrations upstream and in the discharge itself.

To apply the plug-flow model to the Klamath River, the following steps need to be carried out: (1) segment the river into reaches so that the head of each reach is a discharge point (e.g., a tributary or the inflow from Iron Gate Reservoir); (2) develop estimates of river velocity directly from field measurements or indirectly through flow vs. velocity relationships (Thomann and Mueller 1987), (3) develop estimates of the decay rate *K;* and (4) estimate mass rates of nutrient load from discharge points and in the river itself.

The basic plug-flow model for the lower Klamath River nutrient concentrations consists of a Microsoft Excel™ (Excel) workbook with multiple worksheets. Worksheets for flows and constituent load estimates are linked to the final worksheet, the water-quality worksheet. Of the three worksheets for discharges, the first is for wastewater discharges (i.e., point sources; though none are specified at this point), the second is for the major tributaries (i.e., the Klamath River below Iron Gate – actually a "headwater" inflow, the Shasta River, the Scott River, the Salmon River, and the Trinity River), and the third is for the 30 minor tributaries which are listed in KA and AES (2006). In the water-quality model worksheet, the flows and nutrient loads calculated in the previous three worksheets are combined with calculations of nutrient concentrations in the Klamath River in tabular format at various river mile points downstream from Iron Gate Dam. Graphs of flows and nutrient concentrations vs. distance downstream from Iron Gate Reservoir are included.

Three constituents were modeled, specifically TDS, TP, and TN. Selected model results are presented in this section. The complete suite of model results is given in Armstrong and Ward (2008b). As was the case for the simple load-budget analyses of the preceding section, TDS values were determined directly from laboratory analyses of samples taken at the stations indicated and during the months for which averages were calculated. Likewise, TP values were taken directly from the TP colorimetric test. TN was calculated as the sum of total organic nitrogen and total inorganic nitrogen; total organic nitrogen as total Kjeldahl nitrogen minus ammonia nitrogen, and total inorganic nitrogen as the sum of ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen. Because of the variability in availability of values for these various components of TN, some estimates of TN had to be determined in other ways. Further, the problem of below-detection values was particularly acute in nitrogen determinations, and the assumption was made that a less-than-detection value was approximated by one-half the detection level, as discussed in Section 3.1.

An additional problem encountered in the model application was the lack of availability of constituent concentration data in the inflows, as well as in the Klamath River for certain months modeled. The former required the use of station-average concentrations to approximate inflow concentrations for those months. The latter meant that there were no observed values available downstream for comparison to modeled concentrations.

In any water-quality modeling effort, it is important to determine that the mass-budget model is indeed conserving mass (i.e., the mass balances are working). One way to check this is to enter constant concentrations of a fictional conservative material (i.e., $K = 0$) into each of the sources and to determine if the simplified water-quality model reproduces those concentrations downstream. Using the flows for one of the months to be modeled, concentrations of 100 mg/L were entered for each of the sources and downstream concentrations calculated by the simplified model; the model did indeed calculate concentrations of 100 mg/L at every calculation point confirming that the mass balance calculations in the simplified water-quality model were operating correctly.

To determine how well the simplified model can represent actual water quality in the system to be modeled, a natural conservative material like TDS is modeled, again to check the mass-balance characteristics of the model, as well as, to determine how well observed concentrations of the constituent are represented. Calculated concentrations of the constituent should reflect the effects of flows only through the mass balances calculated, since there is no decay and thus no mass lost due to decay. How well the model represents TDS provides some indication of its ability to represent water quality in general and, more importantly, an estimate of base-level accuracy of representing non-conservative materials, notably the error introduced by imprecision of measurements.

TDS was modeled in the lower Klamath River for June through October during 2001-2005. The typical concentration profile was a steady decrease downstream punctuated by drops in concentrations where major tributaries entered. As expected, the rate of decrease downstream was determined primarily by inflows. The comparisons of modeled to measured TDS values were closely aligned in 2001 and 2004. An example of this comparison is shown in Figure 3-1. For 2002, 2003, and 2005, the comparisons of predicted and observed TDS values were less aligned when observed values for inputs were missing and station averages had to be used. TDS modeling did demonstrate the simplified water-quality model to be very satisfactory for constituent water-quality modeling in the lower Klamath River.

TP was modeled with a first-order decay, since it was expected that it would behave nonconservatively due to biological assimilation and physical removal by sediment settling. The decay rate is estimated by comparing observed concentrations to several model profiles computed using different first-order decay rates, as indicated in Figure 3-2. Several patterns emerged from the simplified water-quality modeling of TP in the lower Klamath River, as exemplified by Figure 3-2. First, TP behaved as a non-conservative material as expected, with temperature having a significant effect on decay rates. During the warmer months of July and August, decay rates were significantly higher than in the cooler months of September and October when the decay rates were so low that TP behaved almost as a conservative material. Second, during the very high flow months of June and sometimes July, TP decay rates were somewhat insensitive to decay rate as hydraulic transport rates overwhelmed decay rates. Third, TP concentrations downstream from Iron Gate Reservoir were driven largely by the concentration leaving Iron Gate, and that concentration tended to increase from June through August and then decline thereafter. The typical pattern for TP concentrations in the lower Klamath River was a decreasing concentration in the river downstream from Iron Gate Reservoir. This is because the TP loading from Iron Gate Reservoir is far more than the loading of any other input downstream.

TN was modeled for June through October during 2001-2005 and calculated TN values were compared to measured values at stations downstream from Iron Gate Reservoir (where data were available). TN behaved like TP in many respects in that it is a non-conservative material, decay rates appeared to be related to temperature, concentrations downstream are driven by the TN concentration leaving Iron Gate Reservoir, and those concentrations increased from June through October of each year. Example modeled profiles of TN are shown in Figure 3-3.

Like TP, there were patterns of TN concentrations at Iron Gate and downstream that proved typical for all years. Concentrations in the Iron Gate release were between 0.5 mg/L and 1.9 mg/L for all five years, and there was often an increase in concentration from June to August, followed by a decrease by October. Concentration profiles downstream also showed a steady decrease due to dilution with the inflows downstream that had lower TN concentrations than the mainstem Klamath River. Like TP, the TN loading from Iron Gate Reservoir was significantly higher than any inflow loads downstream, and hence the TN loads coming from Iron Gate Reservoir drive the concentrations downstream.

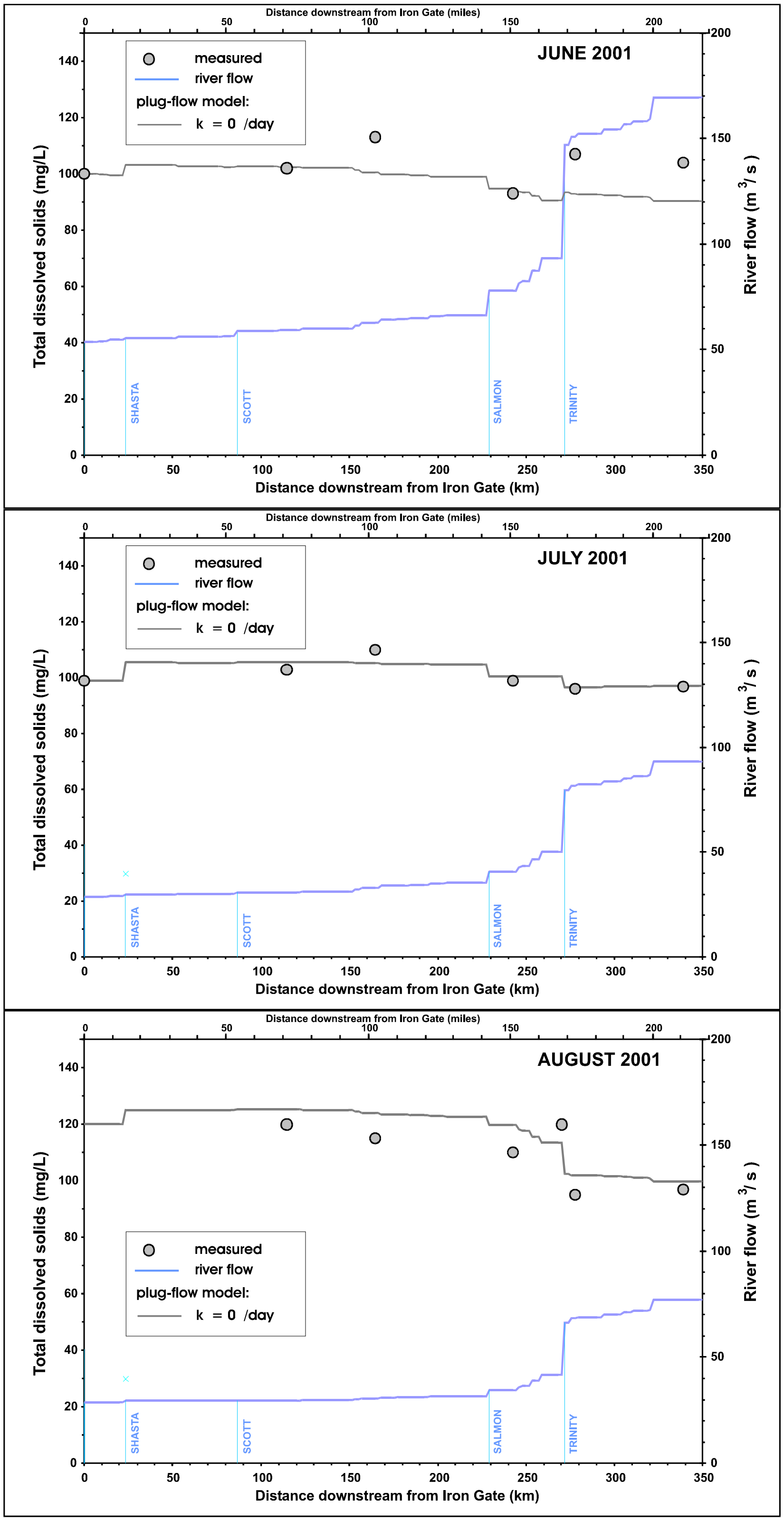

Figure 3-1. Klamath modeled TDS profile and measured concentrations, 2001.

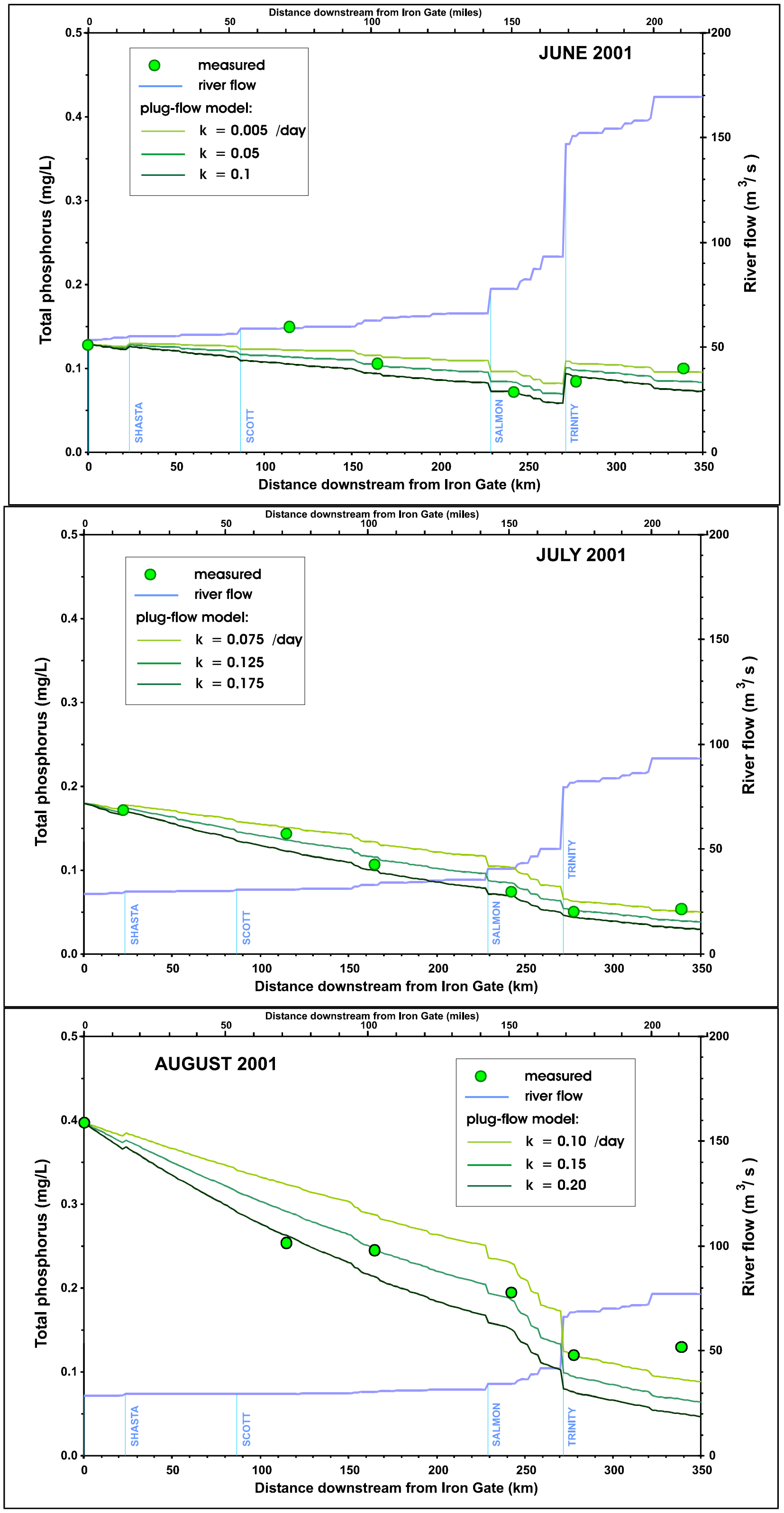

Figure 3-2. Klamath modeled total phosphorus profile and measured concentrations, 2001.

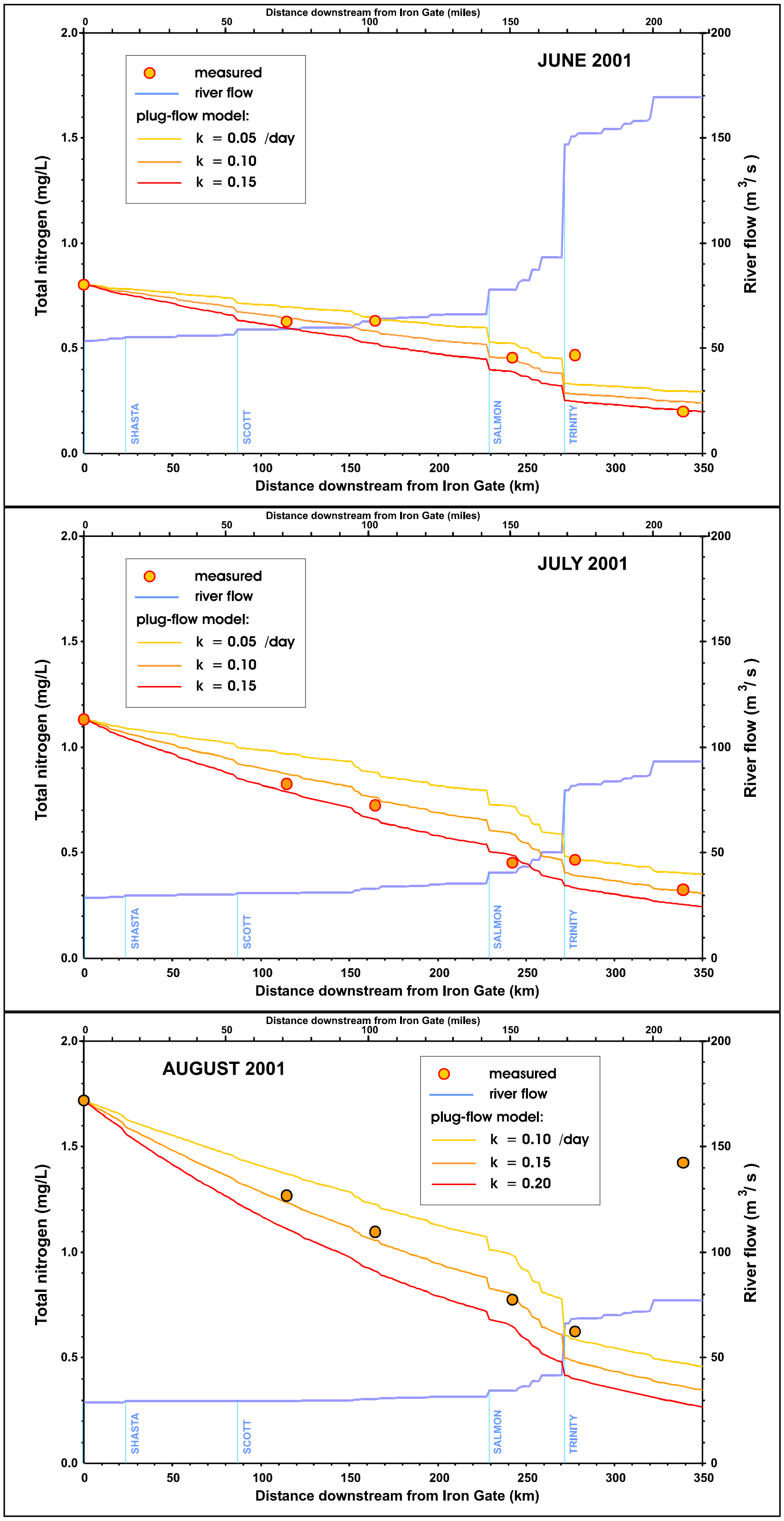

Figure 3-3. Klamath modeled total nitrogen profile and measured concentrations, 2001.

A summary of the monthly decay rates for phosphorus and nitrogen is given in Table 3-4. It is well known that most reactions increase with temperature increases in natural waters, and, to the extent that TN and TP kinetics are comprised of decay mechanisms that are temperature-dependent, those decay rates will be affected by temperature. Further work is needed to clarify the role of temperature on these temperature-dependent decay rates.

Two types of sensitivity analyses were conducted. The first concerned the sensitivity of calculated concentrations to the decay rate *K*. During the colder months (i.e., June, September, and October) the variation in the decay coefficient has little effect on the calculated concentrations. This is due in part to the very low decay rates found to be appropriate for TP and TN in the lower Klamath River during those months, but also due to the dominance of advective transport over decay during the high flow months of June, and to some extent, July. During the warmer months of July and August, the decay rates usually increased significantly due to the increased biological activity that would affect nutrient concentrations. Although other mechanisms may be involved causing the loss of phosphorus and nitrogen from the water column during downstream transport, biological mechanisms are assumed to be dominant.

The other sensitivity analysis we conducted was on the boundary condition at Iron Gate Reservoir, namely the concentration of nutrients leaving the reservoir. As nutrient concentrations in the Iron Gate releases increase or decrease, the downstream concentrations were found to change accordingly. Changes in modeled downstream nutrient concentrations matched almost proportionately the changes at Iron Gate Dam. This would be expected in an advective transport dominated system, and it confirms the analyses noted above that releases from Iron Gate Reservoir drive TP and TN concentrations downstream.

Table 3-4. Decay rates (1/day) inferred from modeled concentration profiles.

Year	*June*	*July*	*August*	*September*	*October*
Total phosphorus					
2001	0.05	0.125	0.15	0.05	0.01
2002	0.005	0.05	0.005	0.075	0.05
2003	0.01	0.01	0.075	0.005	0.01
2004	0.005	0.005	0.125	0.005	0.005
2005	0.01	0.1	0.01	0.05	0.01
Total nitrogen					
2001	0.1	0.1	0.15	0.1	0.075
2002	0.005	0.1	0.125	0.125	0.1
2003	0.005	0.005	0.005	0.05	0.01
2004	0.1	0.1	0.1	0.075	0.005
2005	0.15	0.15	0.05	0.05	0.01

3.4. Summary of results

The coherence of nutrient loads to the lower Klamath River and the nutrient concentrations in the River as contained in the AFWO grab-sample water-quality database has been tested using a mass-balance approach. This relates in-stream concentrations of nutrients in the lower Klamath River to the balance of mass inputs from headwaters (Iron Gate Reservoir), major gauged tributaries (Shasta, Scott, Salmon, and Trinity rivers), and minor ungauged tributaries (see KA and AES 2006 for full list). In-stream concentrations are also the result of nutrient mass-loss mechanisms that cause them to decrease with distance downstream from these mass-input points. This mass-balance approach is embodied in mass-budget-based water-quality models, and one of those models suitable for the lower Klamath River is the plug-flow model, which is useful for general assessment of the impact of nutrient loads in an advection-dominated riverine system. Its assumptions of mass balances at points of discharge, the dominance of advective processes over dispersive in transporting materials downstream in fast-moving rivers, and mass-loss mechanisms being accounted for by an overall first-order decay coefficient are appropriate for the lower Klamath River. A model of this nature can provide useful insights about how a system like the lower Klamath River will respond to flow changes and constituent loads and, compared to more complex water quality models, is convenient and relatively inexpensive.

From the presentation of data and modeling results above, it is evident that there are two dominant influences on water quality in the lower Klamath River under summer conditions. The first is the release from Iron Gate Reservoir. While the flows out of Iron Gate Reservoir in the months and years studied are not particularly large, the concentrations of TP and TN are. These concentrations decrease downstream due primarily to diluting flows from the major and minor tributaries, as well as biological activity during the warmer months. If the TP or TN concentration in the Iron Gate release is high, then their concentrations tend to stay high downstream until they are diluted by lower nutrient content inflows from major and minor tributaries. Conversely, if the TP or TN concentration in the Iron Gate release is low, then concentrations are low throughout the lower Klamath River.

It was also noted that TP and TN concentrations typically increase in the Iron Gate release between June and October, while flows decreased from June to July and then increase through October. Whether this is a consistent pattern from year-to-year extending from 2001-2005, beyond the study period of 2001-2005 has not been determined. If it is a consistent pattern, then water-quality characteristics in the reservoir and operation of the reservoir need to be examined for causative effects on release water quality.

The following conclusions may be drawn from this study:

(1) A simplified plug-flow water-quality model has been applied successfully to the lower Klamath River to represent flows, TDS, TP, and TN concentrations.
(2) The plug-flow model has been applied to monthly TDS, TN, and TP for June through October during 2001-2005.
(3) Through calibration and sensitivity analyses, the apparent decay rate for TP and TN was very low during the cooler months of June, September, and October and significantly higher during the warmer months of July and August.

(4) Through further sensitivity analyses, it was apparent that constituent concentrations in the lower Klamath River overall are driven by the releases from the Iron Gate Reservoir, that the upper reach of the lower Klamath River is heavily influenced by the TP and TN concentration in the release from the Iron Gate Reservoir, and that the lower reach of the river is heavily influenced, primarily via dilution, by the inflows from the major and minor tributaries.
(5) Water-quality characteristics in Iron Gate Reservoir and/or operational patterns may influence the decrease in release flows and increase in TP and TN concentration noted between June and September during 2001-2005.
(6) The TP and TN water-quality models appear to be useful for addressing water resources and water-quality management plans in the lower Klamath River.

4. SPACE-TIME VARIATIONS IN SONDE MEASUREMENTS & DERIVED METABOLISM PARAMETERS

4.1. Sonde data

In addition to the grab samples analyzed in Chapter 3, a separate data set was obtained from the multiprobe sondes deployed during 2001-2005. These robotic instruments automatically measure and record temperature, pH, conductivity, and DO using electrometric probes (Figure 4-1a) and an internal digital data logger. The instruments are housed in a 4-6 inch (10-15 cm) perforated metal cylinder (Figure 4-1b) and are anchored in the stream with a secure tether to some fixed object in the water (e.g., a bridge piling) or onshore (e.g., a tree or boulder, Figure 4-2). Typically, the instrument is deployed for a period of two weeks, which is safely within the battery life, and set to record measurements every 30 minutes, although both the deployment period and the measurement interval were varied depending upon river conditions. For the data evaluated here, DO measurement was effected through membrane-probe technology[1]. A systematic detailed protocol of deployment and extraction measurements was developed, including (1) measurements with a separate calibrated instrument before extraction, (2) post-extraction cleaning and calibration check to assess fouling and drift, and (3) re-calibration of the sonde probes prior to re-deployment (Turner and Zedonis 2004a).

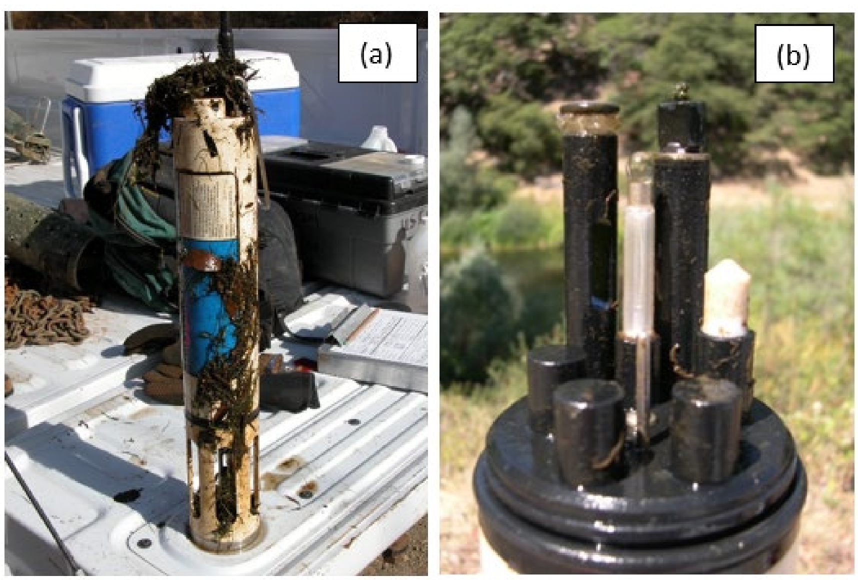

Figure 4-1. View of (a) electrometric sonde at extraction (note algal growth) and (b) close up of probea with housing protective housing removed.

[1] After the 2001-2005 study period, AFWO used sondes employing luminescent DO technology, which avoids much of the biofouling issues of the membrane.

Figure 4-2. AFWO biologist deploying sonde in Klamath River.

The principal sonde stations are summarized in Table 4-1 (see also Table 1-1 and Figure 1-1). The amount of data amassed during the study was quite large, approaching half-a-million independent sets of measurements of the four-parameter suite (i.e., water temperature, pH, DO, and conductivity) totaling nearly 2 million independent data points. Of importance are the measurements of DO, whose detailed time variation, together with that of water temperature, allows the inference of several key parameters characterizing the kinetics and ecology of the Klamath River. Sondes tend to accumulate various errors deriving from their untended operation in a hostile environment, such as loss of calibration, electronic drift, and biofouling. Because of these potential sources of error, all data were subjected to rigorous and intensive QA/QC protocols before use in quantitative analysis. These procedures included an extensive data correction process devised for specific application to the AFWO monitoring in the Klamath River (Ward and Armstrong 2006b, 2006c, 2006d). The temperature data were determined to be quite accurate and therefore require no additional correction procedures (Turner and Zedonis 2004b). The DO data that met QA/QC standards are hereafter referred to as “corrected” and are summarized here (Ward and Armstrong 2010). Although not analyzed here, the pH and conductivity data were collected by the AFWO sondes and are available for future studies.

Table 4-1. Sonde station locations in the Klamath River and its tributaries. River miles (rm) represent the distance from the mouth of the river, with stations located between Iron Gate and Seiad operated by the USFWS, stations between Happy Camp and Orleans by the Karuk Tribe, and stations from Weitchpec downstream to Terwer maintained by the Yurok Tribe.

Station	*Location*	*Mainstem (rm)*	*Trib (rm)*	*Elevation (ft)*	*Depth (ft)*	*Nearest USGS gauging station*
Mainstem stations (Klamath River)						
IG	Below Iron Gate	189.8		2178	3-8	co-located 11516530
K1	Above Shasta	176.8		1860	3-8	
K2	Above Scott	143.2		1520	3-10	
SV	Seiad Valley	128.5		1320	5-12	co-located 11520500
HC	Happy Camp	100.8		960	5-20	
OR	Orleans	59.1		400	5-20	co-located 11523000
WE	Weitchpec	43.6		240	5-20	
MF/TC/KBW	Above Tully Creek	38.5		280	5-20	
TG/KAT	Terwer	6.7		8	5-20	near 11530500
Tributary stations (near mouths)						
SH	Shasta River near Yreka	176.6	0.5	2031	1-2	co-located 11517500
SC	Scott River near Fort Jones	143.0	1.5	1600	1-10	co-located 11519500
SA	Salmon River at Sommes Bar	66.0	1.0	480	5-15	co-located 11522500
TR	Trinity River near mouth	43.5	0.5	240	5-15	d/s from 11530000

4.2. Analysis methodology

The analysis of production and kinetics reported here is based upon the time series of sonde-measured water temperature T and corrected DO concentration C. From water temperature, solubility of DO as saturation concentration C_S can be calculated rather precisely using the equation of Weiss (1970; Ward and Armstrong 2006f). The calculation of primary production and related kinetic parameters is detailed in Ward and Armstrong (2006e) and is summarized here. The concentration of cross-section-mean DO in a stream may be described as:

$$\boxed{\begin{array}{c}\text{time}\\ \text{rate-of-change}\\ \text{in DO}\end{array}} = \boxed{\text{reaeration}} + \boxed{\begin{array}{c}\text{community}\\ \text{respiration}\end{array}} + \boxed{\text{photosynthesis}}$$

$$\frac{\Delta C}{\Delta t} = K_a D + C_r + P \tag{4-1}$$

This equation states that oxygen concentration C will be increased or decreased if the net algebraic sum of the three processes on the right is positive or negative, respectively.

The first of these processes is reaeration (i.e., the transfer of oxygen between air and water across the water surface) governed by the DO deficit $D = (C_S - C)$. This transfer is turbulent and is strongly enhanced by the speed of the current in the river, bed and channel morphometry, wind stress on the surface, and surface waves. These mechanical factors are represented by the magnitude of the reaeration coefficient K_a which multiplies the deficit in equation (4-1). When the oxygen concentration in the water is less than saturation, so that deficit D is positive, then oxygen is transferred from the atmosphere into the water at a rate in proportion to the size of the deficit. When the deficit is negative, oxygen is transferred out of the water into the atmosphere.

Community respiration C_r is the sum of sediment oxygen demand, bacterial respiration, plant respiration, and respiration of zooplankton and macro-heterotrophs (e.g., fish). Bacterial respiration is the consumption of oxygen in the metabolism of bacteria in the water. In streams that receive a high organic load, as measured by biochemical oxygen demand (BOD, see Chapter 3), bacterial respiration (the product of BOD and a deoxygenation coefficient) can become the dominant component of community respiration[2]. Plant respiration is mainly due to floating and attached algae (i.e., phytoplankton and periphyton). Plant respiration operates continuously, throughout the day and night.

Sediment oxygen demand is the removal of oxygen from the water by biochemical consumption on or within the bed sediments of the river. Technically, periphyton respiration could be included in sediment oxygen demand, at least for those algae found on the river bed, but it is better to include these benthal algae with the periphyton populating various surfaces (e.g., rocks, pilings, plant stems, debris) that are immersed in the river. Larger rates of sediment oxygen demand are typically associated with fine-grained sediments with a high concentration of organic compounds.

Finally, P is the influx of oxygen due to photosynthesis by phytoplankton and periphyton. DO is a byproduct of the production of carbohydrates by these plants, which uses carbon dioxide dissolved in the water. These carbohydrates, comprising much of the mass of the plants, then serve as the basic food for the riverine ecosystem. Because the rate of carbohydrate formation is closely related to, and often measured by, the rate of oxygen liberated, this oxygen influx is loosely termed “photosynthesis” and “production.”

The essential ingredient for photosynthesis in the river is sunlight. To a good approximation, the rate of photosynthesis is proportional to the intensity of incident sunlight. Clear-sky solar radiation at a point on the earth’s surface varies during the day as a cosine function of time $cos\{\pi(t-t_n)/t_d\}$, where t_n is time of local noon and $t_d \equiv t_s-t_r$ is the daylight period, t_r and t_s denoting times of sunrise and sunset, respectively (Figure 4-3). “Time” in this relation is measured in any convenient—but consistent—unit and convention (e.g., Universal Coordinated, prevailing civil, or local solar). The amplitude of this cosine varies with position on the earth, and slowly varies with season due to the changing (apparent) elevation of the sun. At night, photosynthesis essentially shuts down. The diurnal variation of the rate of photosynthesis therefore is a flat-line zero at night and a cosine during the day, under clear-sky conditions. The daily total photosynthesis is the accumulation of this function, which is a shifted sine function of twice the amplitude (Figure 4-3). This is also refered to as “gross photosynthesis” or “gross production,” in contrast to “net production,” which includes the oxygen consumed by algal respiration.

[2] Almost all the measured BOD’s from grab samples were below detection limits.

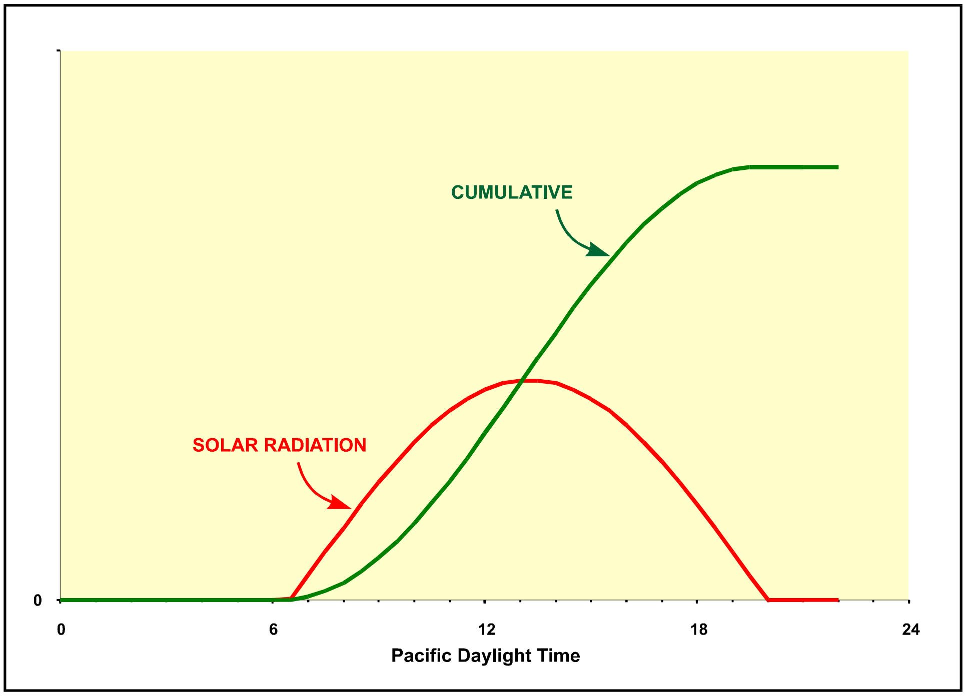

Figure 4-3. Functional form of clear-sky insolation and cumulative insolation at the Weitchpec station (WE) on a typical mid-August day.

Daily gross production, which we denote Γ, is measured in units of mg O_2/L and can be approximately converted to carbon production Γ_c by assuming that the product of photosynthesis is the glucose molecule, whence $\Gamma_c = 0.375\ \Gamma$ gC/m³. In the present context, we regard this simply as a units conversion from mg O_2/L to gC/m³ to facilitate comparison of the production data from the Klamath with literature values from other aquatic systems, and is consistent with the definitions provided in Odum (1956) and Williams (1993).

The relation (4-1) for the rate of change in DO concentration C may be written to separate the daytime period from the nighttime period, as shown below:

$$\Delta C/\Delta t = \begin{cases} K_a D + C_r & \textit{nighttime} \\ K_a D + C_r + S\cos\{\pi(t-t_n)/t_d\} & \textit{daytime} \end{cases} \qquad (4\text{-}2)$$

where S is solar radiation magnitude at solar noon. We need to determine the values of K_a, C_r, and S using the DO and temperature measurements from a sonde. The method of analysis is, first, during the nighttime part of the diurnal record, to determine values of $\Delta C/\Delta t$ from the change in DO between measurement times at the sonde and the corresponding values of deficit D, from the measured DO and saturation computed from measured water temperature. These data are fitted by least squares to a straight line, whose slope is K_a and whose y-intercept is C_r according to the nighttime component of equation (4-2). Second, using a simple rearrangement of the daytime component of equation (4-2), as follows:

$$\Delta C/\Delta t - (K_a D + C_r) = S \cos\{ \pi(t-t_n)/t_d \} \qquad (4\text{-}3)$$

we can use the values of K_a and C_r established from the nighttime data to compute the left side of this equation at each time of measurement, to which the function on the right side may be fitted to determine S. While these data could be fitted by least squares to a cosine function of clock time, Ward and Armstrong (2010) demonstrated numerical improvement by accumulating their values over the daylight period and then fitting to a half-cycle sinusoid (Figure 4-3).

As an example, the results of this analysis for Klamath Station at Weitchpec, 17-18 August 2004 (deployment WE_081104), are displayed in Figures 4-4 and 4-5. The diurnal excursion of DO is moderate, around 2 mg/L, with DO approaching saturation in late afternoon. The nighttime regression yields a correlation of 0.81 (explained variance of 65%), with regression values of:

$$K_a = 0.42 \text{ hr}^{-1} = 10.0 \text{ d}^{-1} \qquad (4\text{-}4)$$

$$C_r = -\ 1.018 \text{ mg/L/hr} = -24.4 \text{ mg/L/d} \qquad (4.5)$$

The least-squares fit of equation (4-3) gives $S = 0.72$ mg/L/hr (explained variance of 98%) from which the daily gross production is $\Gamma = 6.2$ mg O_2/L.

Several assumptions are made associated with equation (4-2) and the sonde measurements of DO:

(1) The stream is sufficiently well-mixed such that DO is substantially constant over the cross section.
(2) The longitudinal gradient in DO is small enough that transport of DO is negligible compared to $\Delta C/\Delta t$.
(3) The community respiration terms proceed at constant rates during the diurnal period.
(4) The rate coefficient for reaeration K_a is constant throughout the diurnal period.
(5) Primary production proceeds at a rate proportional to incident light, which is assumed to be a cosine function of time.

Assumption (1) implies that the sonde measurement is a reliable approximation to the section-mean value of DO used in equation (4-1). Assumption (2) states that the time variation in DO measured by the sonde is due to local variation in DO only, and not to the streamflow moving water of different DO into the sonde location. Assumption (3) posits that the respiring organisms, mainly the microorganisms responsible for sediment oxygen demand and for bacterial stabilization of organics, as well as the phytoplankton and periphyton, are stable and vary on time scales longer than a day. Assumption (4) in effect dictates that the same physical processes controlling mechanical reaeration are maintained throughout the day and night. If the river flow

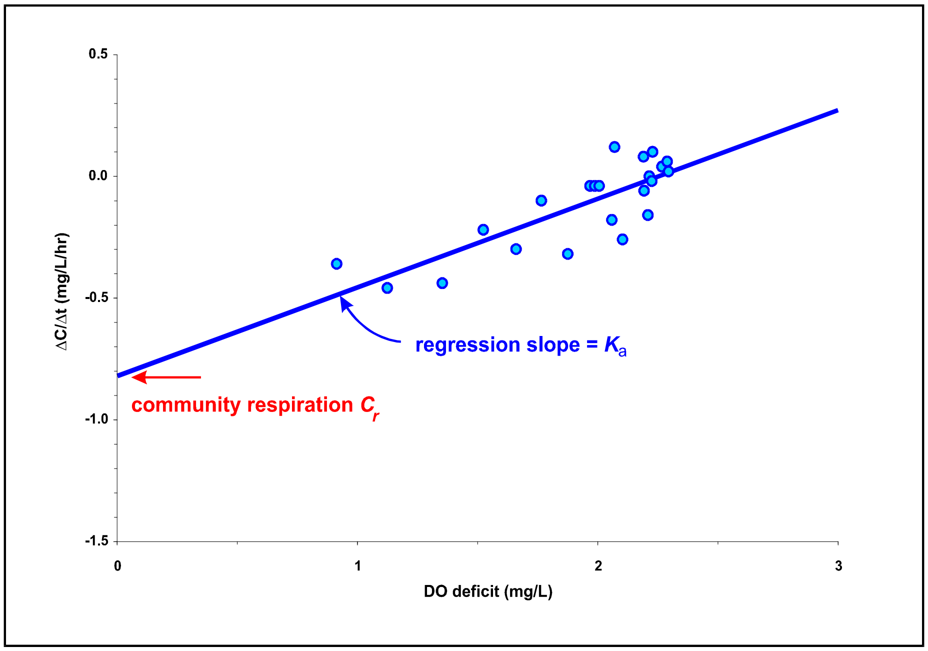

Figure 4-4. Regression of ΔC/Δt on deficit using nighttime data from the Weitchpec station on 17-18 August 2004.

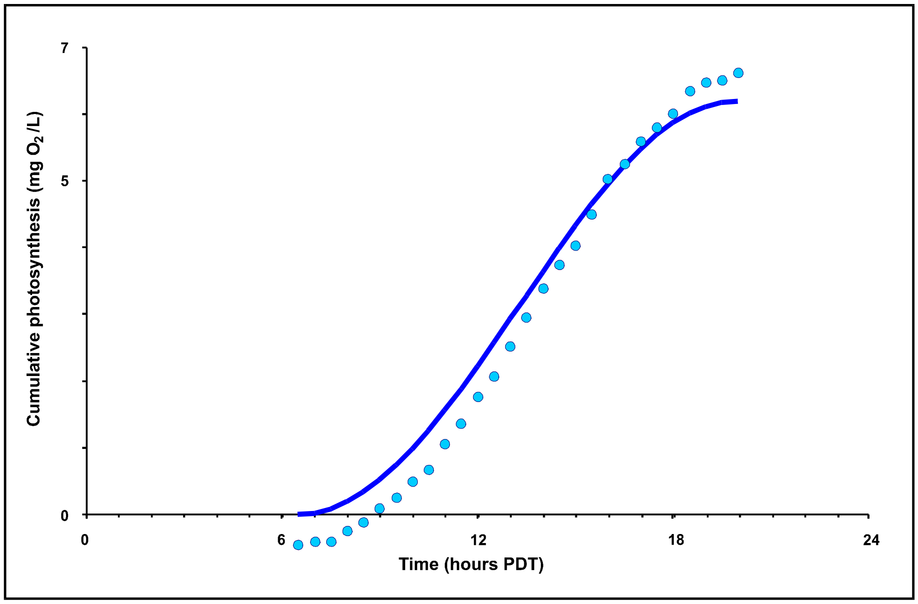

Figure 4-5. Least-squares fit of daytime cumulative residuals from linear regression (Figure 4-4) to half-wave sinusoid using data from the Weitchpec station on 17-18 August 2004.

varies only on time scales longer than a day, this assumption should generally hold true. This is satisfied for the lower flows of summer, the season of primary interest in this work. Assumptions (2) and (4) together imply that any inferences drawn from analysis of nighttime measurements are applicable as well to the associated daytime period. Assumption (5) would be expected to be satisfied under conditions of homogeneous atmospheric transparency, of which a clear sky is a special case. It is further posited that this cosine depiction will also apply as a statistical model for cases in which the clear sky conditions are interrupted randomly by clouds or smoke. Further, this assumption implies that any superposed nonlinearities between photosynthetic oxygen evolution and light intensity, including photosaturation and photoinhibition (e.g. Kirk 1994, Falkowski and Raven 1997), have a negligible effect on oxygen production. Details of the calculations involved in the analysis of the sonde data are given in Ward and Armstrong (2010).

There were over 7,100 complete diurnal cycles captured in the sonde data during 2001-2005, spread over the sampling network of thirteen stations. The correction processes result in some rejection of data (i.e., 16% of the data set or 1,136 complete diurnal cycles), leaving 5,960 complete (corrected) diurnal cycles of DO available to support analyses of primary production and associated kinetic parameters. The deployment periods for the sondes varied during March – November, depending on the station and year. In this analysis, we focus on the June – September period, because this is the period that is generally subject to more stable river flow and the main period for maximum primary production. There were over 4,600 complete corrected diurnal cycles during this period, however, not all of these are usable. For the above methodology to be applied, it is necessary that a viable regression of $\Delta C/\Delta t$ versus deficit D be established (Figure 4-4), which in some cases is not possible. For example, the measured DO may simply track the variation in saturation over the diurnal period, following the variation in water temperature, or the range of diurnal variation in DO may be too small to allow a reasonable estimate of the regression slope. Violation of any of the five assumptions listed above (e.g., due to storm runoff events, high winds, excessive river flow) will prohibit the use of this analysis. Therefore, these data sets were subject to an additional layer of screening in which tests for such anomalies are applied (Ward and Armstrong 2010). In some cases, the data are rendered "noisy" and can still be used with smoothing, such as a running average. In most cases, however, the problematic data were simply eliminated from consideration. This reduced the available data to ca. 3,100 diurnal cycles that can be used in these analyses - still a formidable set of data. .

4.3. Oxygen budgets and ecosystem metabolism

The sonde data sets can be analyzed in many ways. DO variations (and associated kinetics) during specific diurnal periods, along with ancillary information on river flow, meteorology and insolation, can be evaluated. Events, such as flow pulses or apparent organic load injections, can be identified in the record and tracked downstream over time, during which their effects on DO kinetics can be isolated. Here we undertake a larger scale view, to distill the information from these datasets to exhibit the general behavior of the DO budget of the Klamath during 2001-2005 (i.e., to present a DO "climatology" of the river).

Relative locations of the principal sonde stations are indicated on the stem diagram of Figure 4-6. The upstream limit of the study reach, *viz*. the lower Klamath, is Iron Gate Reservoir, releases from which typically dominate the hydrology of the first 100 rm below the dam during the

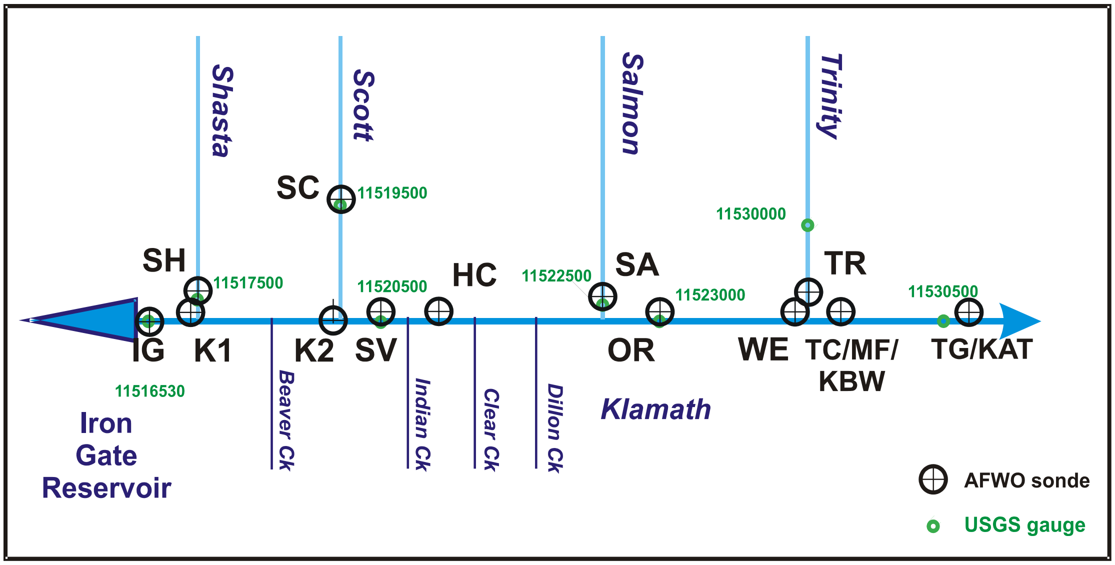

Figure 4-6. Stem diagram of Klamath and major tributaries showing relative locations of sonde stations (cf. Figure 2-1).

low-flow summer season (see Chapter 2, Ward and Armstrong 2006a). The 2005 DO record from the Iron Gate station, located just downstream from Iron Gate Dam, is shown in the upper panel of Figure 4-7. The individual (corrected) sonde measurements are indicated by the fine trace, upon which is superimposed the running 24-hr mean. The variation of instantaneous DO about this running mean is a direct indication of photosynthetic activity. The concentration of DO saturation, computed from the sonde-measured water temperature, is the dark blue line. The vertical lines on this figure denote the sonde deployment periods. The river flow is essentially the release from Iron Gate, and during the summer, is most often constant. Two features of the DO variation are immediately evident: (1) the photosynthetic variation of DO is small; and (2) there is a large DO deficit, which, though highly variable, generally increases toward the end of summer and early fall. These features prove to be characteristic of DO at this station for each year of the study period. The DO deficit of water exiting Iron Gate is due to summer stratification of the reservoir, with the associated decline in DO through the thermocline layer down to the nearly anoxic hypolimnion, so that lower-DO water is entrained into the release, which is drawn from a depth about 10 m. The marked increase in deficit late in the season, typically the early fall, is the effect of the seasonal overturn of the reservoir.

The corresponding time series of insolation (i.e., solar radiation received at the ground surface), reaeration coefficient, and gross daily production are displayed in the lower panel of Figure 4-7. Both the 5-day running mean and screened values of production are shown in the plot[3]. Insolation data were obtained from records of the USGS, from stations established according to NWCG (2005). The nearest radiation station, or an average of several, to each sonde station was used to estimate daily solar radiation over the data-collection period. Unfortunately, these data

[3] Screened data are not subjected to a running average because the screening too frequently interrupts the continuity of the time series.

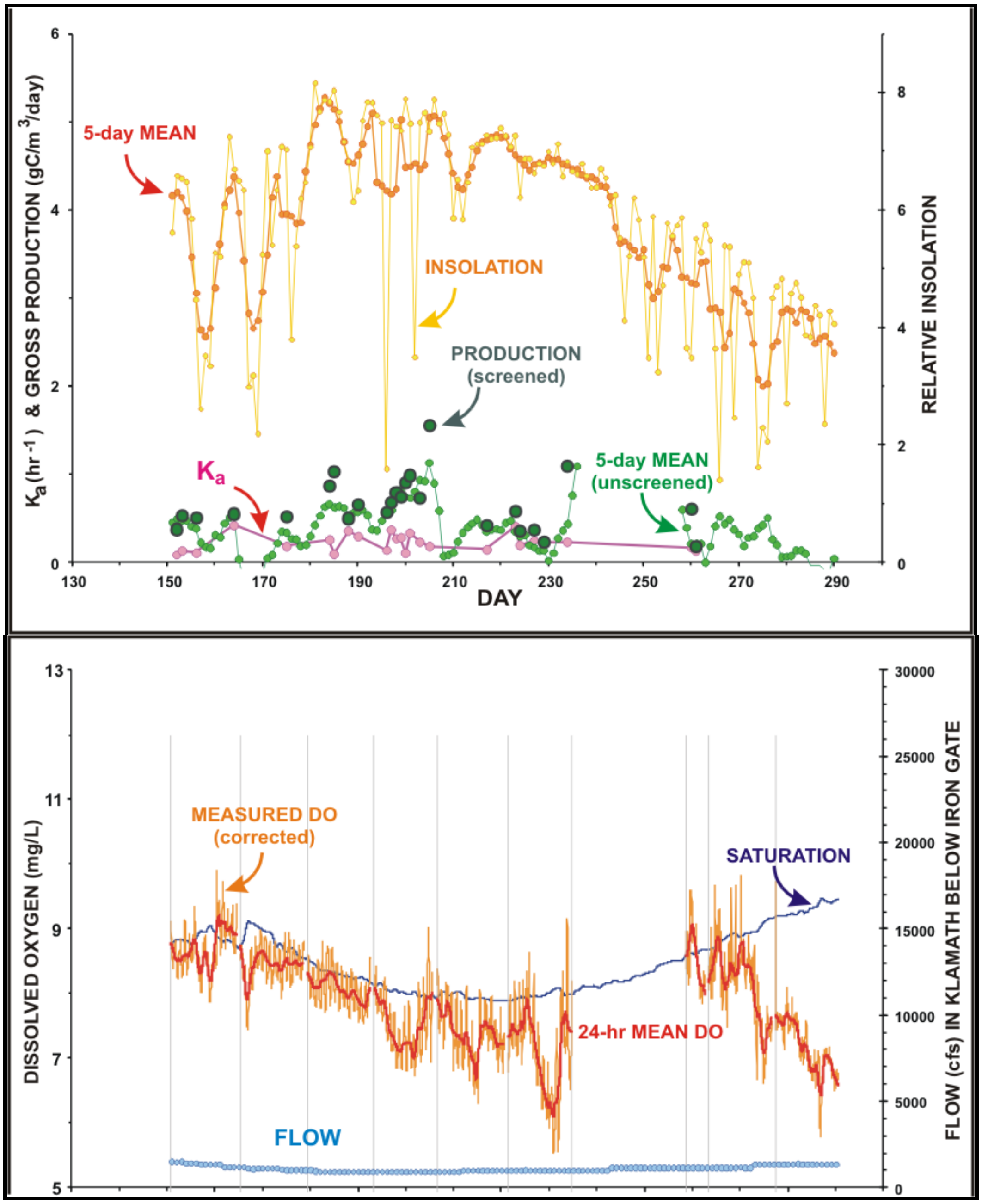

Figure 4-7. Measured DO time series (corrected) at the Iron Gate station, 2005, with streamflow, relative insolation, and computed kinetic variables. Vertical lines indicate dates of sonde deployment and/or retrieval.

sets proved to be problematic (i.e., poorly calibrated due to inconsistency across data files and corruption by errant spikes). With the expectation that daily clear-sky solar radiation should vary as the cosine of the local solar zenith, we were able to empirically adjust or expunge the anomalies to produce a time series of *relative* insolation (i.e., uncalibrated to the actual insolation at a sonde station). This is sufficient to address the correlation of primary production with insolation, which is its sole purpose in this analysis.

With distance down the river, runoff and tributary flows dilute the reservoir water to include loads of organics and nutrients, so that the features of the Iron Gate station (reflected in the release from the reservoir exemplified in Figure 4-7, become transformed into those more typical of a flowing river. This is illustrated by data for the same year at the Weitchpec station (Figure 4-8)[4]. Over the summer, the DO concentration generally tracks its solubility, first decreasing as temperature rises in early summer then increasing as temperature declines in late summer. The daily range of variation about the mean, on the order of ±1 mg/L, even before the effects of respiration are removed, evidences algal production (Figure 4-9), resulting in increasing supersaturation as the summer progresses. Reaeration coefficient K_a is stable over the course of the summer, which is consistent with the stability of river flow and the generally quiescent meteorology of the summer. The pattern of a modest increase in K_a in July (days 180-210) and decline in September (days 245-275) is consistent with its dependency upon water temperature. Most prominent, of course, is the substantial increase in estimated gross production during June and its maintenance through the remainder of the summer into early fall.

There is year-to-year consistency in the magnitude and longitudinal distribution of the reaeration coefficients, as shown by the error bars about the 2001-2005 station means (Figure 4-10). Generally, there is an increase in K_a with distance downstream from Iron Gate to about Orleans, then a decline to the mouth of the river, with an exception to this pattern being the depressed value at Happy Camp. The two upper tributaries, the Scott and Shasta, are systematically about a factor of three higher than the corresponding values on the mainstem.

[4] Figures 4-7 and 4-8 have the same time and variable axes to facilitate their comparison.

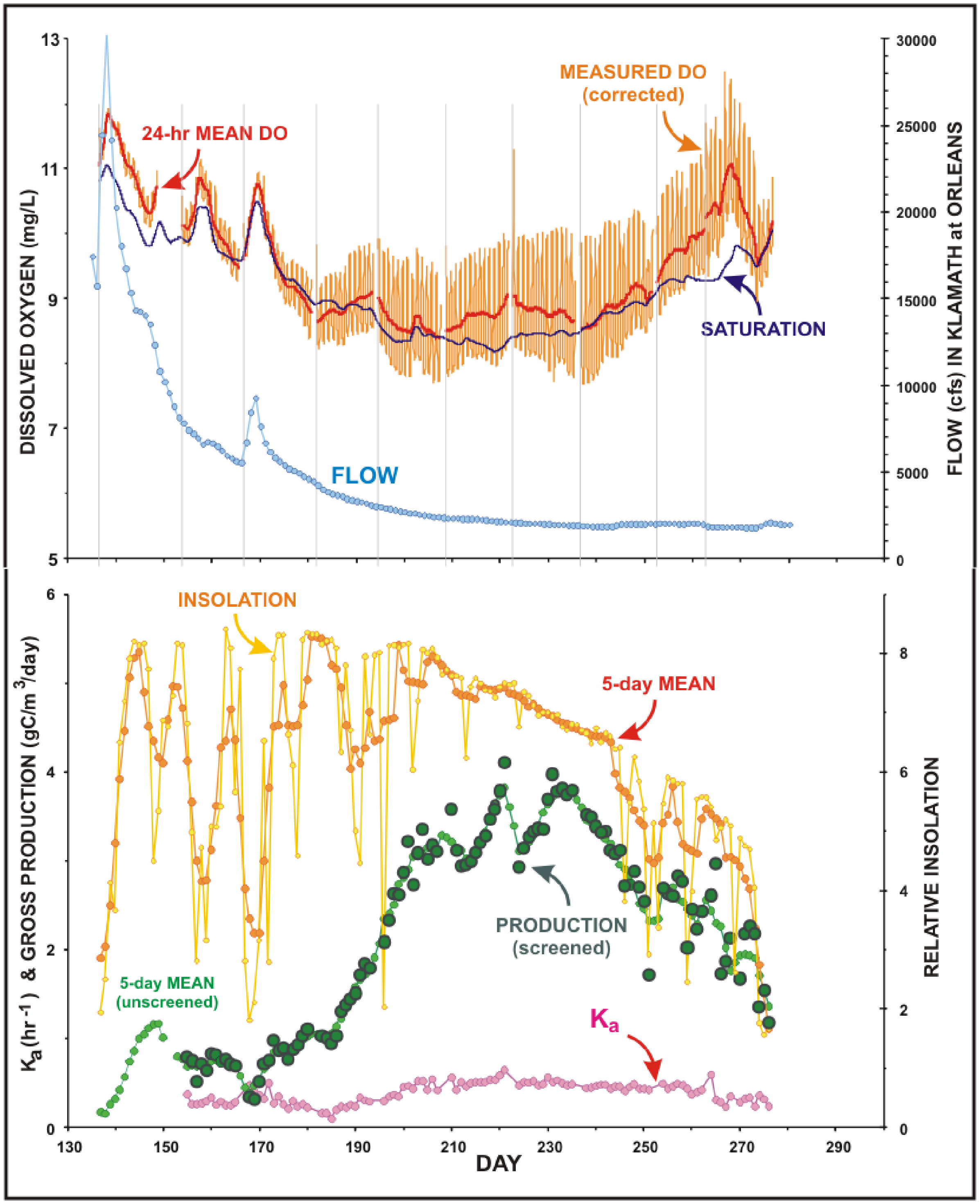

Figure 4-8. Measured DO time series (corrected) at the Weitchpec station, 2005, with streamflow, relative insolation, and computed kinetic variables.

Figure 4-9. Weitchpec station on the Klamath River, 8 September 2005 (cf. deployment break, Day 252, Figure 4-8).

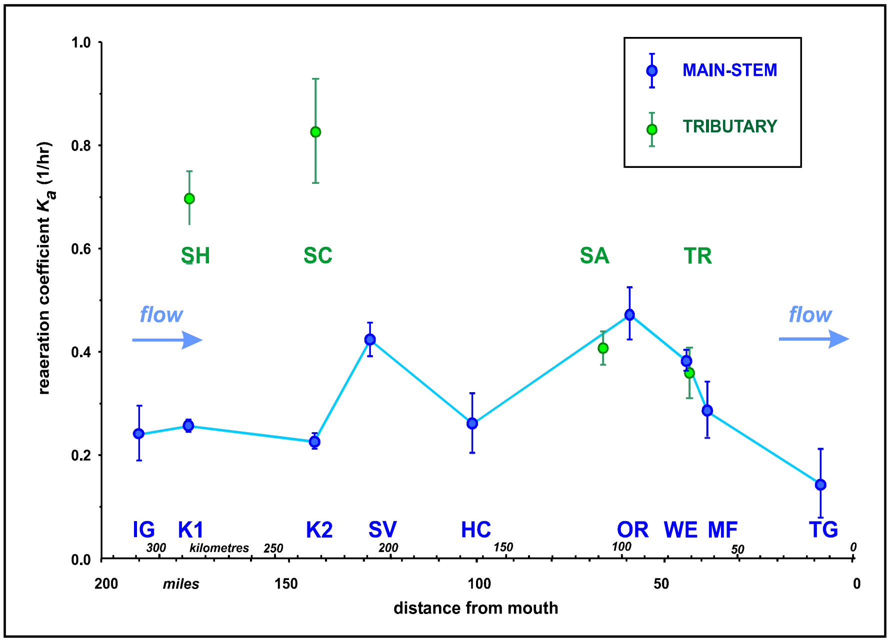

Figure 4-10. Longitudinal variation in the mean reaeration coefficients K_a during 2001-2005 from sonde data. Error bars are standard deviations of annual means about the 2001-2005 average at each station.

The reaeration coefficient K_a is a standard parameter in the analysis of stream water quality (Chapra 1997), for which many engineering formulae exist. Of these, the most widely used quasi-theoretical relation is that of O'Connor and Dobbins (1958) and the empirical CEB equation of Churchill et al. (1962), which are both appropriate for the Klamath. It is of interest to compare the values of K_a extracted from the sonde data with these standard equations. Both formulae require the depth and velocity of the watercourse, available for the USGS stations co-located with Klamath basin sonde stations. Figure 4-11 shows the average values of K_a determined both from the sonde data and by application of the O'Connor-Dobbins equation, averaged over the entire monitoring period of the sonde data[5]. The K_a values that are indicated by the O'Connor-Dobbins equation prove to be much smaller than those determined from the sondes, by a factor of 2 – 10. The one exception is the Scott station, where the O'Connor-Dobbins value was about 50% greater than that from the sonde (Figure 4-11).

The averaged values of kinetic parameters during June-September derived from the sonde records are displayed in Figures 4-12 through 4-16 as longitudinal profiles of the Klamath for each year and tabulated in Table 4-2. To facilitate year-to-year comparison, the figures have the same axes, and the 2001-2005 mean production (at each station) is plotted on every figure. Respiration is represented as the rate of oxygen demand, rather than (negative) oxygen production, so its sign is reversed from that of equation (4-2). The corresponding averaged daily flows (Table 4-2) include only those daily flows for which the corresponding diurnal sonde data passed QA/QC procedures, as these flows are employed in correlation analyses, presented in Chapter 5.

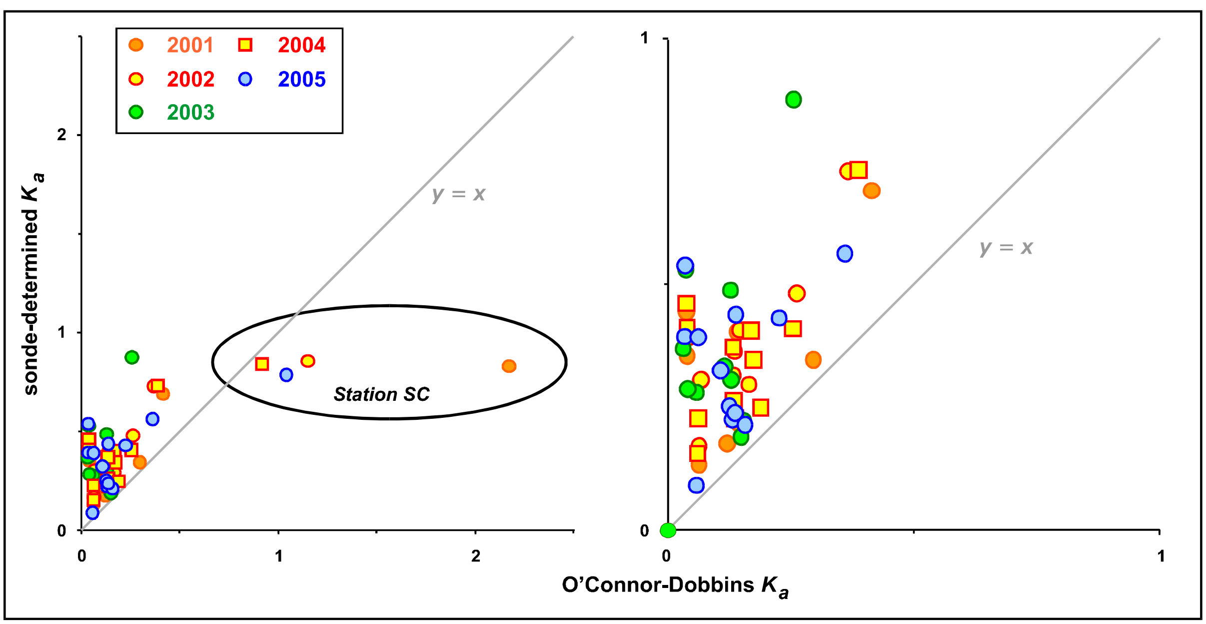

Figure 4-11. Comparison of annual averages of K_a from sonde data and from O'Connor-Dobbins equation.

[5] The CEB equation proved to be very close to O'Connor-Dobbins, so is not shown.

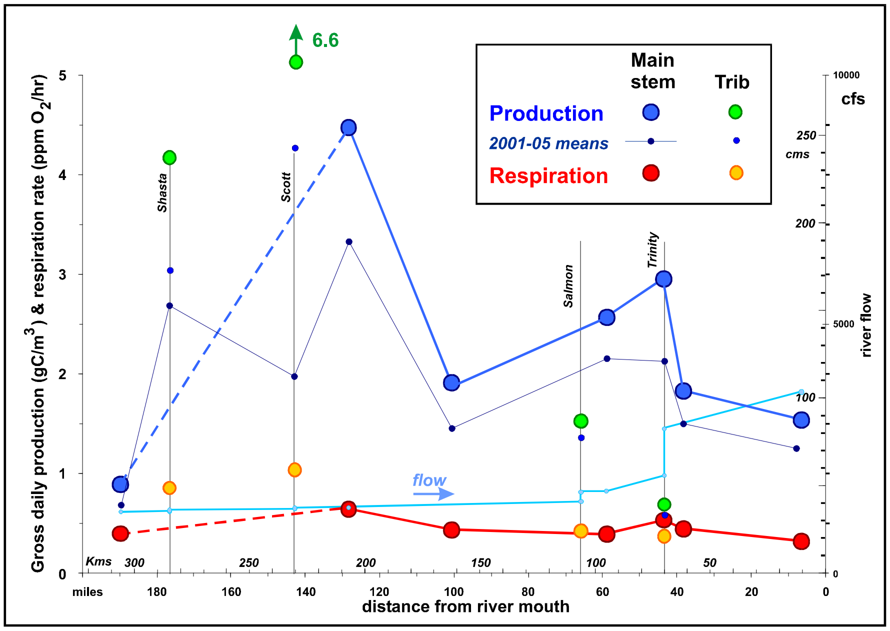

Figure 4-12. Gross production (daily) and daily-mean community respiration rates in the Klamath River, 2001.

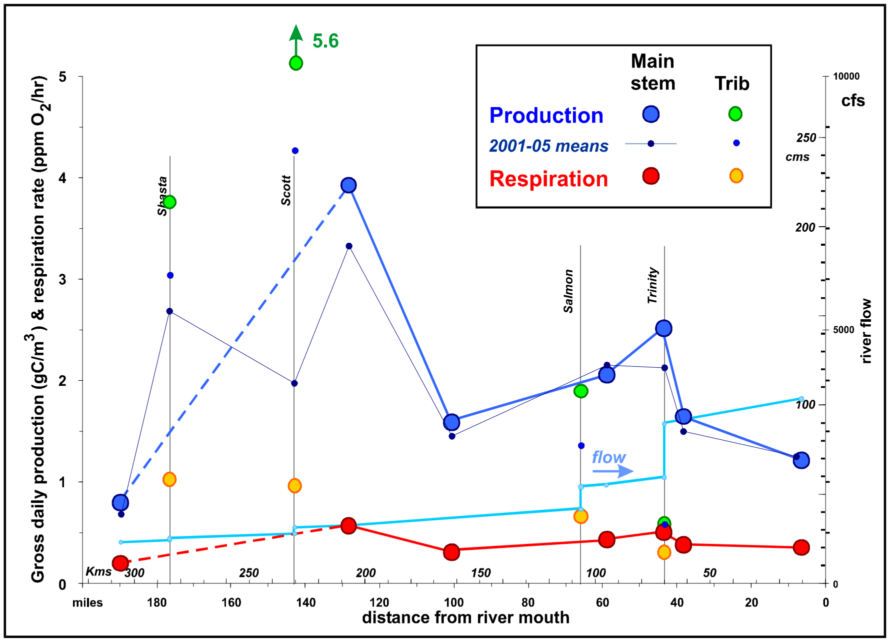

Figure 4-13. Gross production (daily) and daily-mean community respiration rates in the Klamath River, 2002.

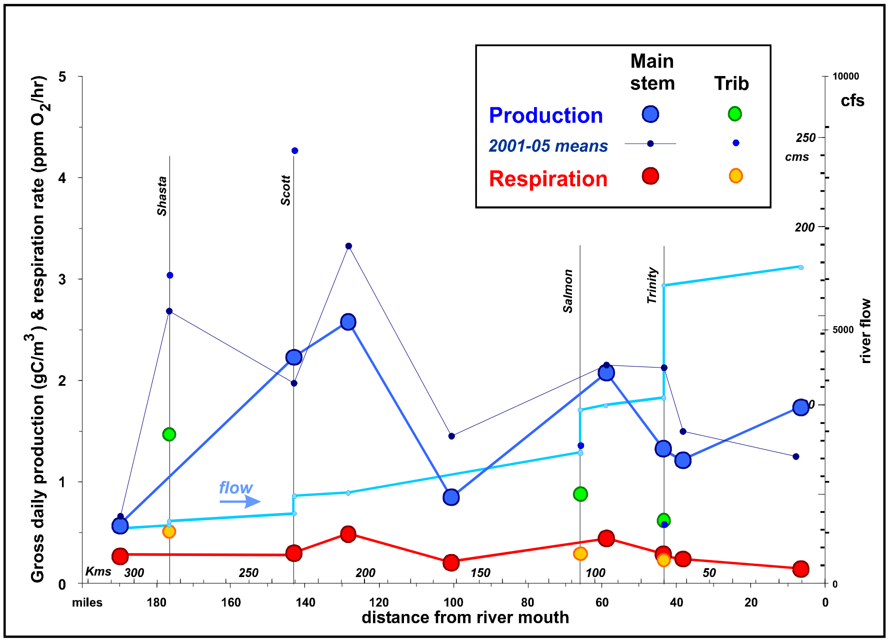

Figure 4-14. Gross production (daily) and daily-mean community respiration rates in the Klamath River, 2003.

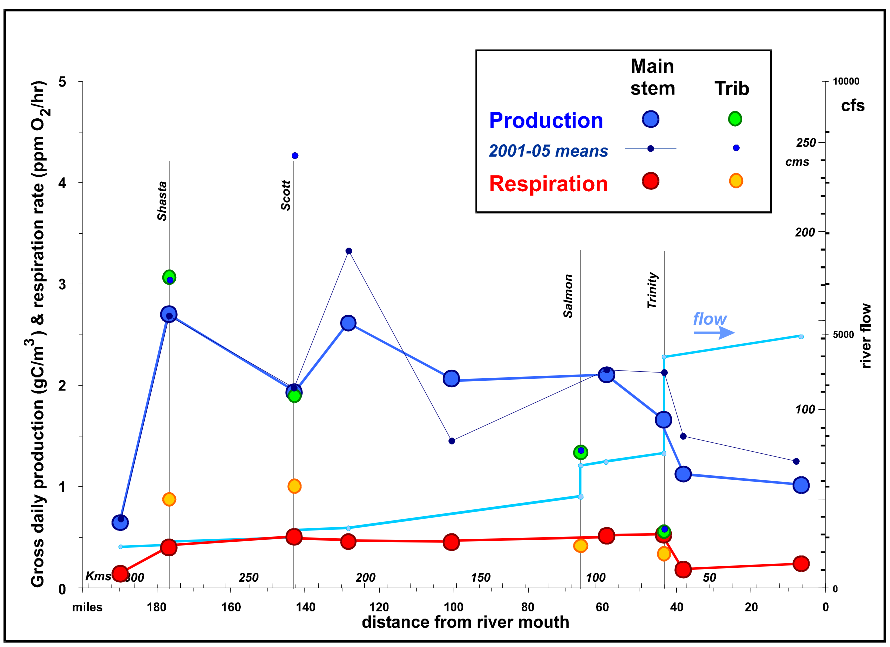

Figure 4-15. Gross production (daily) and daily-mean community respiration rates, 2004.

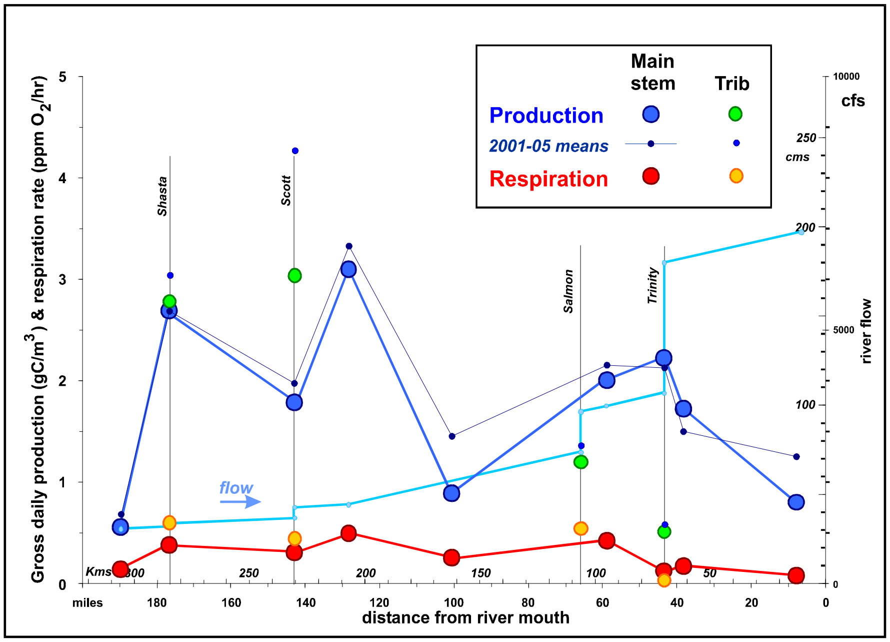

Figure 4-16. Gross production (daily) and daily-mean community respiration rates, 2005.

Additional kinetic parameters are given in Table 4-2 that are of use in characterizing the ecosystem function of the river. Average community respiration C_r in this table is converted to the daily carbon liberated in units of gC/m³/d. "Net ecoprod" is an abbreviation for net ecosystem production, or net community production, and is the (sined) difference between daily influx of DO by gross production and consumption of DO by community respiration, both expressed in carbon units. "Relative autotrophy" is the ratio of daily gross primary production to community respiration ("daily C_r" in Table 4-2) in the same units. Net ecoproduction (N) and relative autotrophy (R) are equivalent since relative autotrophy $R = 1/(1\text{-}N/P)$, but one index may be preferable to another for comparison to other systems (e.g. Dobbs and Cole 2007).

Three observations can be made about production and respiration in the Klamath:

(1) The longitudinal profile of respiration is remarkably consistent from year to year, being on the order of 0.4 mg O_2/L/hr, with a depressed value at Iron Gate, which is representative of the upper 10-meter surface layer of the reservoir since releases dominate the flow at this station, and with reduced values in the reach around Happy Camp and the reach below the Trinity.

(2) Production is lowest at Iron Gate, and increases with distance downstream, then declines in the reach from Orleans to the mouth, except for a depressed value at Happy Camp. This general pattern is manifested in each of the study years. The highest values of production are exhibited in the low-flow years of 2001 and 2002, at both the mainstem and tributary stations.

(3) The highest values of production encountered in the system was in the Shasta and Scott, typically a factor of 2-3 times the mainstem values, and respiration is typically about twice the mainstem value. In the Trinity, in contrast, both production and respiration are much lower than the mainstem values, with only slight year-to-year variation.

Table 4-2. Kinetic and metabolism indicators for Klamath derived from June through September sonde records.

Station: Mainstem	Station: Tributary	Flow (cfs)	Daily cr (gC/m3)	Net ecoprod (gC/m3)	Relative autotrophy	Flow (cfs)	Daily cr (gC/m3)	Net ecoprod (gC/m3)	Relative autotrophy
		2001				**2002**			
IG		1224	3.63	-2.74	0.25	809	1.85	-1.05	0.44
K1									
	SH	*26*	*7.74*	*-3.57*	*0.54*	*31*	*9.29*	*-5.53*	*0.40*
K2									
	SC	*17*	*9.37*	*-2.79*	*0.70*	*101*	*8.72*	*-3.13*	*0.64*
SV		1329	5.82	-1.34	0.77	1195	5.13	-1.20	0.77
HC		1319	3.96	-2.04	0.48	1066	2.85	-1.26	0.56
	SA	*180*	*3.84*	*-2.31*	*0.40*	*361*	*6.00*	*-4.10*	*0.32*
OR		1674	3.60	-1.03	0.71	1772	3.94	-1.87	0.52
WE		1647	4.83	-1.87	0.61	1724	4.64	-2.12	0.54
	TR	*925*	*3.38*	*-2.69*	*0.21*	*865*	*2.84*	*-2.25*	*0.21*
MF/TC/KBW		1980	4.07	-2.23	0.45	2539	3.49	-1.84	0.47
TG/KAT		3500	2.90	-1.35	0.53	3378	3.25	-2.03	0.38
		2003				**2004**			
IG		1107	2.46	-1.88	0.24	790	1.36	-0.71	0.48
K1						808	3.64	-0.94	0.74
	SH	*78*	*4.65*	*-3.18*	*0.32*	*46*	*7.94*	*-4.87*	*0.39*
K2		1086	2.71	-0.48	0.82	802	4.64	-2.70	0.42
	SC					*121*	*9.08*	*-7.18*	*0.21*
SV		2253	4.45	-1.87	0.58	1020	4.19	-1.57	0.63
HC		1292	1.89	-1.03	0.45	933	4.17	-2.10	0.50
	SA	*542*	*2.67*	*-1.78*	*0.33*	*197*	*3.80*	*-2.45*	*0.35*
OR		2184	4.03	-1.95	0.52	2275	4.72	-2.61	0.45
WE		3453	2.67	-1.34	0.50	1855	4.80	-3.13	0.35
	TR	*1895*	*2.10*	*-1.48*	*0.30*	*1517*	*3.11*	*-2.56*	*0.18*
MF/TC/KBW		5089	2.21	-0.99	0.55	4519	1.68	-0.55	0.67
TG/KAT		16300	1.33	0.41	1.31	4415	2.21	-1.18	0.46
		2005				**2001-2005 average**			
IG		1113	1.36	-0.80	0.41	1009	2.13	-1.43	0.36
K1		1086	3.49	-0.80	0.77	947	3.57	-0.87	0.76
	SH	*55*	*5.44*	*-2.65*	*0.51*	*47*	*7.01*	*-3.96*	*0.43*
K2		1078	2.86	-1.06	0.63	989	3.40	-1.41	0.62
	SC	*192*	*4.02*	*-0.98*	*0.76*	*107*	*7.80*	*-3.52*	*0.58*
SV		1568	4.54	-1.44	0.68	1473	4.82	-1.48	0.68
HC		1218	2.36	-1.47	0.38	1165	3.05	-1.58	0.47
	SA	*472*	*4.95*	*-3.75*	*0.24*	*350*	*4.25*	*-2.88*	*0.33*
OR		3363	3.85	-1.84	0.52	2254	4.03	-1.86	0.54
WE		3480	1.20	1.03	1.86	2432	3.63	-1.48	0.77
	TR	*2560*	*0.35*	*0.17*	*1.49*	*1553*	*2.36*	*-1.76*	*0.48*
MF/TC/KBW		3549	1.63	0.10	1.06	3535	2.61	-1.10	0.64
TG/KAT		7266	0.74	0.06	1.09	6972	2.09	-0.82	0.75

5. INTEGRATED SUMMARY

5.1. Relationships among physical, kinetic and ecometabolic variables

In inferring possible causal controls on the kinetic behavior evaluated in the preceding section, we combine river-hydrography data and water-chemistry analyses with the kinetic data extracted from the sondes. These data are averaged to exhibit a water quality "climate" of the river under summer "low-flow" conditions, especially as it is manifested in the behavior of DO. Most fundamental is the hydrological state of the river. The flow conditions for the 2001-2005 study period were summarized in Chapter 2. Generally, this five-year period exhibited below-normal river flows. The lowest flows were encountered in 2001 and 2002, most of whose monthly flows exceeded only about 10% of the period-of-record flows. While 2003 and 2005 represented the highest flows encountered, these were approximately at the period-of-record median.

The evaluation of metabolism parameters outlined in Chapter 4 is based upon the diurnal photocycle and the associated variation in DO, and therefore entails integration over a 24-hour period. It is tempting to think of the kinetic information derived from the sondes (e.g., Figure 4-12 *et seq.*) as applying to a parcel of water at the sonde location, but in fact the water monitored by the sonde is continually replaced by streamflow, so the sonde data represent a volume of water traversing some reach of the river. In a manner of speaking, the river's flow has the effect of "smearing" the inferred kinetic behavior along this length of the river (see Figure 5-1 as an illustration). Figure 5-1 shows the length of reach that will be moved past the sonde position in a 24-hour period, the basic time unit for the kinetic analyses carried out. For the assumptions underlying the analysis method to hold, the river must be longitudinally well mixed and subjected to essentially the same rates of insolation, reaeration and respiration over a considerable distance upstream from each sonde station. Put another way, the results from the sonde analyses represent the DO kinetics substantially integrated in space (30 to 60 km, Figure 5-1) and time (at least 24 hours, several to many days if results are cumulated as longer-period averages as done in Chapter 4). In addition, these results are implicitly aggregated over major components of the river ecosystem. As noted earlier, the production ascribed to photosynthesis implicitly includes all plants in the watercourse that effect an influx of DO during daylight, including plankton, benthic algae, and macrophytes (i.e., submerged aquatic vegetation). Community respiration includes algal respiration (both planktonic and benthic), bacterial stabilization of organics, respiration of zooplankton and higher heterotrophs in the water column, and oxygen demand by bacteria and benthic fauna in the sediments.

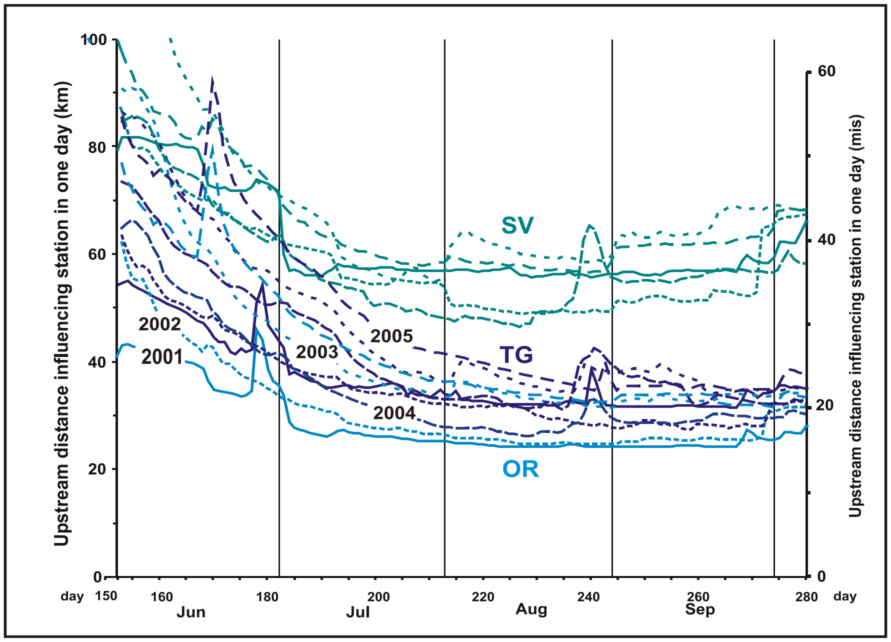

Figure 5-1. One-day replacement distances in mainstem of Klamath River, 2001-2005 (cf. Figure 2-14).

Figures 5-2 – 5-6 display longitudinal profiles of production and the associated relative autotrophy inferred from the sonde analyses, along with the nutrient concentrations (i.e., total organic and inorganic) determined in water samples of the AFWO program. To facilitate plotting on these multiple-axis graphs, the concentrations of phosphorus are scaled up by a factor of ten (i.e., represented in units of 0.1 mg/L) so that, for example, a plotted value of 1 (such as the mainstem value downstream from the Trinity confluence in Figure 5-2) represents a concentration of 0.1 mg/L. All data are averaged over the June – September period. These profiles are companions to Figures 4-12 – 4-16.

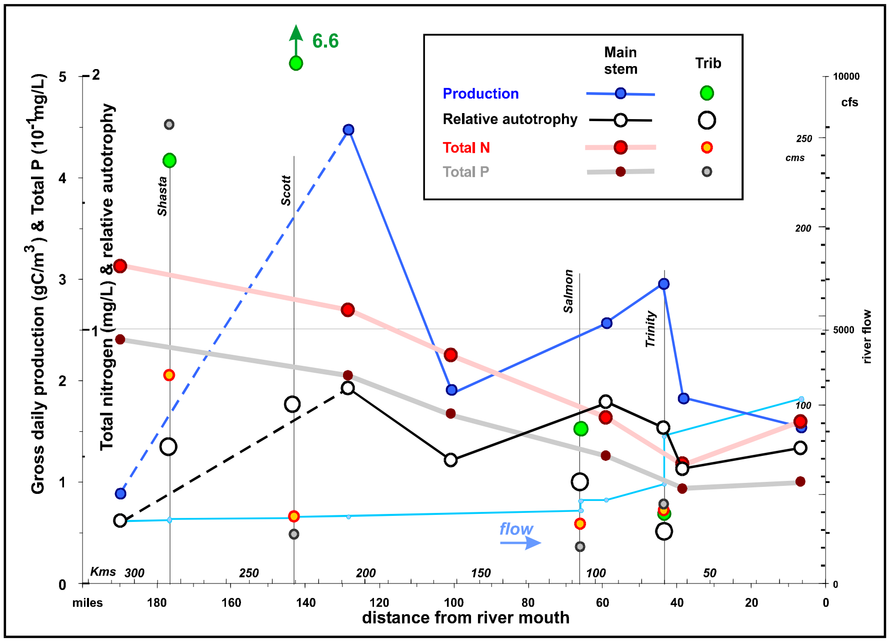

Figure 5-2. Mean gross production, relative autotrophy, and water chemistry in the Klamath River, June-September 2001.

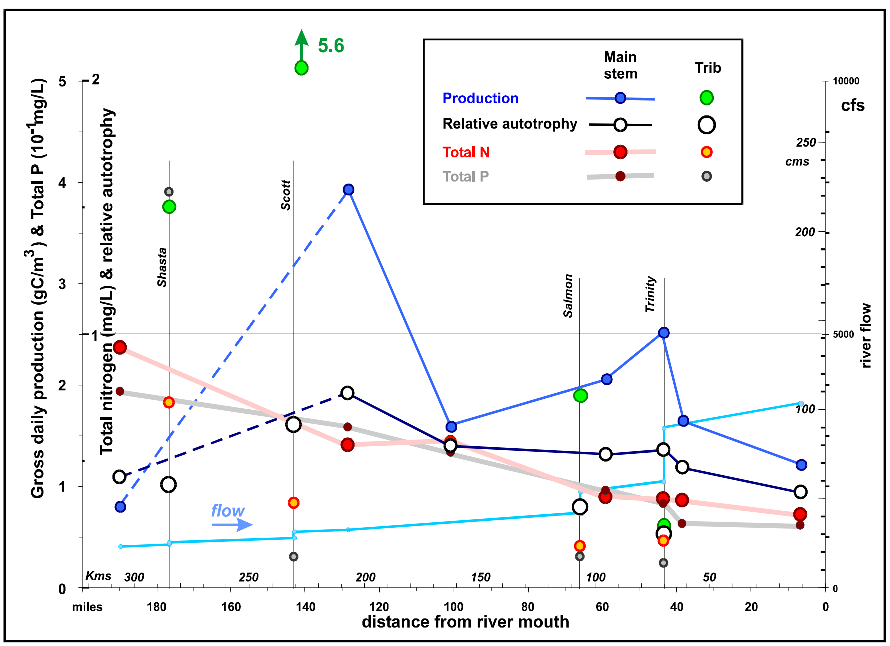

Figure 5-3. Mean gross production, relative autotrophy, and water chemistry in the Klamath River, June-September 2002.

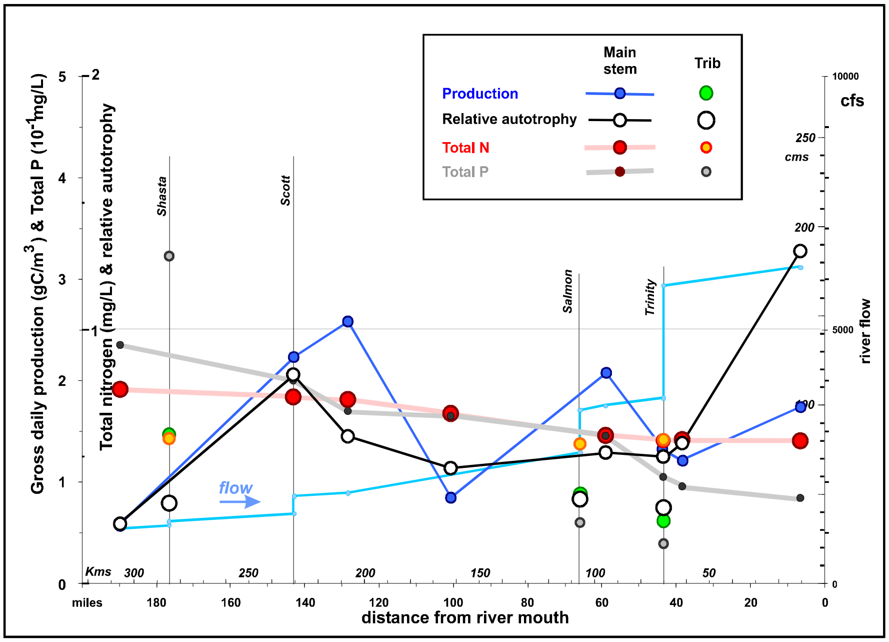

Figure 5-4. Mean gross production, relative autotrophy, and water chemistry in the Klamath River, Jun-Sep 2003.

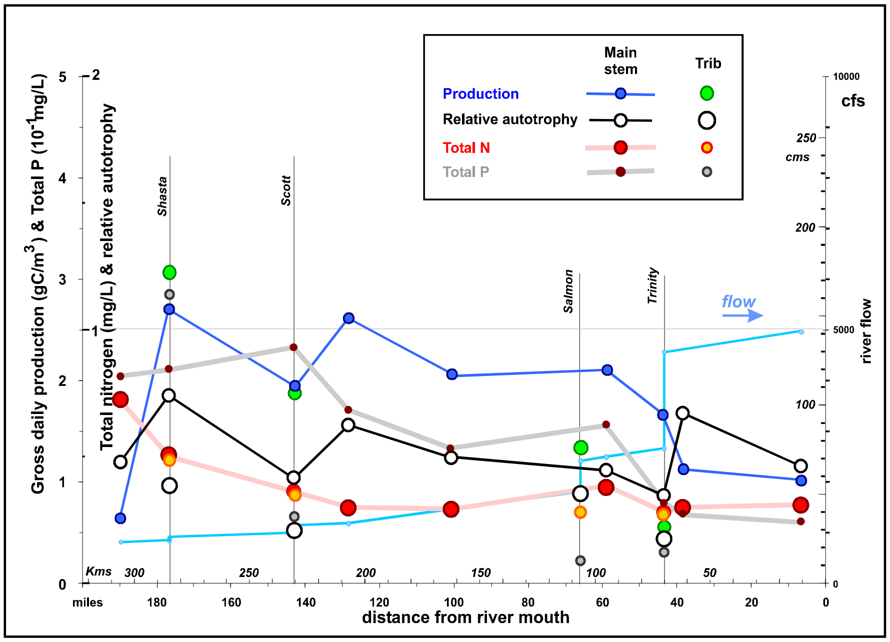

Figure 5-5. Mean gross production, relative autotrophy, and water chemistry in the Klamath River, Jun-Sep 2004.

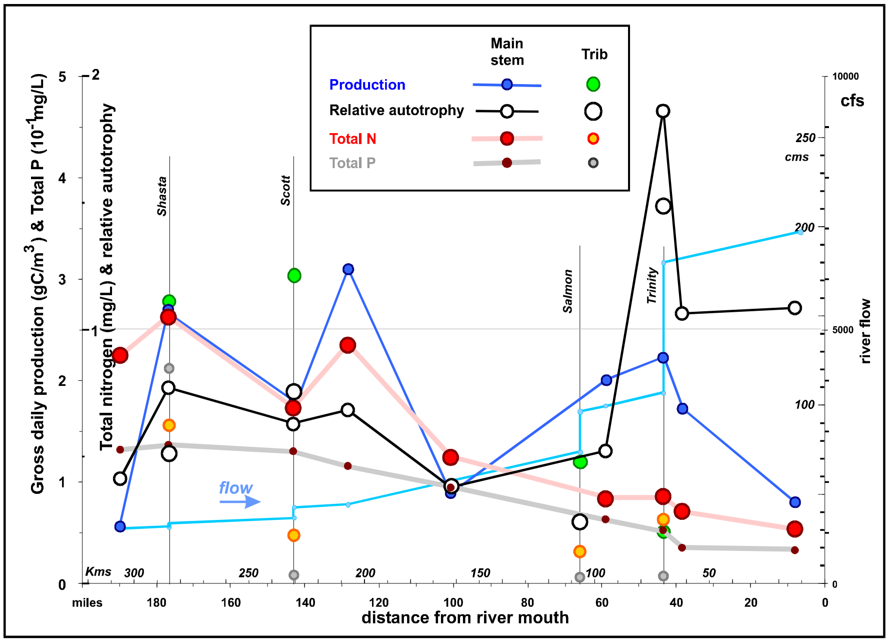

Figure 5-6. Mean gross production, relative autotrophy, and water chemistry in the Klamath River, Jun-Sep 2005.

Annually, the average concentrations of TN and TP generally decline along the length of the river from Iron Gate to the mouth. This is consistent with the mass-budget analyses of Chapter 3 and as presented by Armstrong and Ward (2008b), which concluded that concentrations in the river are driven by the releases from Iron Gate and are reduced downstream due to the combined effects of dilution by tributary inflows and decay, the former predominating. The very low values of production at Iron Gate reflect the released water from the reservoir and not a river-indigenous algal community. The rapid increase of production from Iron Gate to Seiad Valley, however, is consistent with establishment of an algal community in the high nutrient concentrations of nitrogen and phosphorus. Typically, the highest value of gross primary production in the river occurs at Seiad Valley. The behavior of primary production with distance further downstream is more complex, with a local minimum at Happy Camp, which often is also the mainstem minimum (except for the value at Iron Gate), an increase to higher values between Orleans and the Trinity confluence, then a decline to Terwer. The pattern of longitudinal profile of relative autotrophy is similarly complex. Above the Trinity confluence the river is heterotrophic, with a relative autotrophy of around 0.5. The highest values, around 0.7, are generally found in the reach from the Shasta to Seiad Valley and decline from there to the vicinity of the Trinity confluence. Below the Trinity confluence, the relative autotrophy is highly variable, being low in the lower-flow years (i.e., 2001, 2002 and 2004) and quite high—in fact, autotrophic—in the higher-flow years (i.e., 2003 and 2005), though it is far from clear that river flow *per se* is the operative factor.

As noted above, gross primary production in the two upper tributaries, the Shasta and the Scott, is generally much higher than the mainstem value, and typically the highest to be found in the Klamath system. These tributaries are shallow and, under summer conditions, have limited flow with much slower current speeds than those of the river mainstem. Both tributaries receive nutrient loads from upstream waste discharges, but nutrient concentrations are very different in the two tributaries. Nitrogen in the Shasta is on the same order as, but lower than the mainstem value, while in the Scott, it is lower yet, about half of that in the Shasta. There is even more disparity in phosphorus, being quite high in the Shasta, nearly twice the mainstem value, and very low in the Scott. This disparity was most exaggerated during the low-flow years of 2001 and 2002. This disparity is consistent with the higher nutrient loads in the Shasta, notably the Yreka wastewater, which would be magnified under reduced dilution of flows during drought periods[6]. Community respiration in these tributaries is higher than the mainstem values, and typically is the highest in the Klamath system. While both production and respiration are high, the relative autotrophy is about the same as the corresponding mainstem value, so these tributaries are net heterotrophic.

The Salmon River regularly exhibits about the same level of respiration as the mainstem value, but only about half the primary production, so the relative autotrophy is about half that of the mainstem. Nitrogen concentration is about half that of the mainstem, which has declined substantially from its level in the reach from Iron Gate to Seiad Valley. Phosphorus is even lower, typically much less than half the mainstem value.

The Trinity River is the most exceptional of the tributaries. Nitrogen and phosphorus are lower in concentration than the mainstem, especially phosphorus. Both respiration and production are lower than the mainstem values; indeed, primary production in the Trinity River is the lowest in the Klamath system. Consequently, the relative autotrophy in the Trinity River is the lowest in the Klamath system, except for the reservoir-dominated Iron Gate station. The one exception is 2005 (Figure 5-6 above), when the station was highly autotrophic, but this was a consequence of the extremely low value of community respiration. The lack of a high nutrient load in its headwater analogous to Iron Gate on the Klamath mainstem, offers an immediate hypothetical explanation for the much lower production in the Trinity River, although such a conclusion would require additional study. During the summer period, the Trinity system represents more than a third of the total flow in the Klamath River measured at the USGS gauge at Klamath (Table 2-3), and likely exerts a strong influence on the quality of the Klamath River downstream from the Trinity River confluence.

Table 5-1 presents the (linear) correlation coefficients of gross primary production with several other chemical, kinetic, and physical parameters that are thought to influence, or be influenced by, production (Ward and Armstrong 2010). For each year, the correlation was computed between the monthly-mean values of production and the monthly-mean values of the chemical parameters TN, TP, and chlorophyll-*a*. The chemical analyses are performed on water samples generally taken at the same time as the servicing of the sonde, approximately a two-week interval, so the number of measurements upon which the monthly mean is based can range from one to three. The nondetects are represented in the mean values as one half the method detection limit, as described in Section 3.1. For each year and each station, therefore, there are four pairs of values for which the correlations are computed, so these will be noisy and uncertain. In contrast, the sonde data yield daily values of gross production and community respiration (C_r),

[6] It is difficult to present more precise quantitative results because of the uncertainty arising from the high proportion of nondetects in the nutrients data (see Chapter 3).

furthermore daily values of the physical parameter of relative insolation are also available. As such, the June-September correlations for these parameters using the sonde data are based upon far more numerous data (i.e., 122 paired values, less the days lost to sonde maintenance, less the days rejected in the Q/A process, and less the days screened out for this analysis). The final set of data in Table 5-1 is the 2001-2005 averages of the annual values of correlation for each station/parameter pair. Generally, the correlation of production on nutrients is weak and variable, ranging both positive and negative. This is not surprising, because the causality can go either direction with opposite sign of the associated correlation (i.e., nutrients can stimulate production therefore initially be high when production is high, but as production increases nutrients are reduced due to assimilation). The correlation of daily production versus daily community respiration is consistently negative, but of generally modest magnitude, suggesting that while autotroph respiration is a major component of community respiration, so that the correlation is negative, the heterotrophic components of community respiration are sufficiently large to erode this correlation. This is consistent with the relative heterotrophy of the river.

The lack of substantial correlation of production with insolation is perhaps surprising but is illustrative of the relation of correlation to time scale, and the attendant need to carefully interpret correlations over lengthy time periods. There is a clear association of reduced production with low-insolation "events" arising from synoptic-scale disturbances and cloud cover over northern California. On the time scale represented by the June – September period, however, the correlated variation from these events is overbalanced by the anticorrelated seasonal decline in insolation and seasonal increase in the gross production, due to the integrated effect of increasing water temperatures, stable river flows, and the establishment of a growing algal community in the river (Figure 4-8).

An unexpected feature of the results of Table 5-1 is the unsystematic variation in correlation between primary production and the concentration of chlorophyll-*a*, a nearly universal index to algal biomass. In the mainstem, the averaged chlorophyll-*a* exhibits the same longitudinal decline as nutrients, while in the tributary stations the concentrations are all systematically low, as shown in Figure 5-7. While there is also a vague decline in production with distance down the mainstem (Figure 5-7, but compare the annual profiles in Figures 5-2 – 5-6), chlorophyll-*a* does not track the month-to-month, year-to-year, and inter-station variation of production, so the correlation between production and chlorophyll-*a* is similarly variable. The nature of the calculated primary production is that it measures the combined effect of all photosynthesizing organisms that affect the concentration of DO in the river, notably both phytoplankton and periphyton (attached algae), while chlorophyll-*a* is measured in a water sample and is therefore limited to phytoplankton. The high variability in correlation between production and chlorophyll-*a* could therefore be diagnostic of a substantial benthic algae community. It should also be noted, however, that the 2002-2004 phytoplankton enumeration data from the lower Klamath of PacifiCorp (unpublished data available from the PacifiCorp website: www.pacificorp.com/Article/Article82803.html) do not appear to correlate with the accompanying chlorophyll-*a* determinations, so there may be an unresolved issue with the relation of water-sample chlorophyll-*a* to both phytoplankton biomass and production in the Klamath.

Table 5-1. Correlations of screened data for June – September (boldface indicates absolute value >50%).

Station		*Monthly mean production versus:*			*Daily mean production vs:*	
Mainstem	*Tributary*	*TN*	*TP*	*Chlorophyll-a*	C_r	*Insolation*
2001						
IG		-0.12	0.34	0.29	-0.02	0.04
K1						
	SH	**0.91**	**0.50**	0.00	**-0.62**	0.36
K2						
	SC	**0.53**	**0.53**	-0.50	**-0.56**	-0.19
SV		-0.43	-0.41	0.22	**-0.75**	0.49
HC		-0.28	0.14	0.37	-0.30	0.17
	SA	**0.62**	**0.51**	0.24	-0.01	-0.03
OR		-0.27	0.27	**0.53**	-0.20	0.09
WE					-0.35	-0.18
	TR	0.42	**-0.56**	-0.01	**-0.70**	0.13
MF/TC/KBW					0.11	0.11
TG/KAT					-0.42	0.36
2002						
IG		0.14	-0.49	**-0.57**	-0.25	0.11
K1						
	SH	-0.32	-0.21	**-0.80**	**-0.56**	-0.04
K2						
	SC				-0.20	0.35
SV		-0.02	-0.33	-0.30	-0.30	-0.20
HC		-0.29	-0.11	0.01	**-0.71**	-0.45
	SA	-0.12	**-0.89**	0.29	-0.10	0.48
OR					-0.46	0.43
WE		-0.16	-0.16	**0.62**	-0.49	-0.21
	TR	**0.72**	0.18	-0.17	-0.30	0.12
MF/TC/KBW		-0.21	-0.32	**-0.50**	0.23	-0.12
TG/KAT					-0.31	**-0.52**

(continued)

Table 5-1 (continued). Correlations of screened data for June – September.

Station		Monthly mean production versus:			Daily mean production vs:	
Mainstem	*Tributary*	*TN*	*TP*	*Chlorophyll-a*	C_r	*Insolation*
2003						
IG					-0.31	-0.09
K1						
	SH				0.14	**-0.98**
K2					**-0.68**	**0.63**
	SC					
SV					-0.18	0.03
HC					-0.39	**0.62**
	SA				**-0.93**	**-0.92**
OR					0.02	-0.09
WE		-0.03	-0.08	**0.82**	**-0.58**	-0.09
	TR	0.18	**-0.88**	**0.76**	-0.19	**-0.57**
MF/TC/KBW		**-0.95**	**-0.98**	**0.74**	-0.50	-0.15
TG/KAT					-0.15	**-0.97**
2004						
IG					0.05	0.17
K1		**0.69**	**-0.81**	**-0.73**	-0.41	**0.51**
	SH				**-0.51**	-0.10
K2			0.22	**0.76**	0.22	**0.52**
	SC	**-0.54**	0.45	1[n]	0.06	**-0.63**
SV			**-0.79**	**-0.53**	-0.22	0.38
HC			**-0.65**	0.19	**-0.85**	0.38
	SA		**-1.00**	-1[n]	**-0.52**	**0.56**
OR		-0.29	**0.97**	-1[n]	-0.22	-0.02
WE			-0.10	-0.34	-0.42	0.19
	TR	**-0.92**	0.05	0.13	-0.49	-0.17
MF/TC/KBW			0.31	0.01	**-0.58**	0.00
TG/KAT		0.49	**0.74**	**0.90**	-0.12	-0.28

(continued)

[n] The correlation is numerically precise but is based upon only two data points.

Table 5-1 (continued). Correlations of screened data for June – September.

Station		*Monthly mean production versus:*			*Daily mean production vs:*	
Mainstem	*Tributary*	*TN*	*TP*	*Chlorophyll-a*	C_r	*Insolation*
2005						
IG					-0.23	0.34
K1		-0.46	-0.40	0.17	-0.45	0.38
	SH	-0.40	-0.15	**0.92**	-0.45	-0.05
K2		**-0.67**	-0.13	**0.69**	**-0.60**	**0.59**
	SC	-0.05	-0.36	**-0.88**	-0.48	0.36
SV		**0.88**	**0.84**	**0.94**	**-0.74**	0.31
HC		**1.00**	**0.98**		**0.52**	-0.45
	SA	**0.85**	**0.97**	1[n]	**-0.73**	**0.54**
OR		0.49	**0.57**	**0.56**	-0.47	0.26
WE		**0.80**	**0.67**	**0.92**	**-0.55**	0.33
	TR	0.14	**-0.95**	-0.44	**-0.61**	0.31
MF/TC/KBW		**0.92**	0.24	**0.89**	**-0.59**	0.35
TG/KAT		0.08	**0.64**	**0.85**	**-0.63**	-0.07
2001-2005 (average)						
IG		0.01	-0.07	-0.14	-0.15	0.11
K1		0.11	**-0.60**	-0.28	-0.43	0.45
	SH	0.07	0.05	0.04	-0.40	-0.16
K2		**-0.67**	0.05	**0.72**	-0.35	**0.58**
	SC	-0.02	0.20	**-0.69**	-0.29	-0.03
SV		0.14	-0.17	0.08	-0.44	0.20
HC		0.14	0.09	0.19	-0.34	0.05
	SA	0.45	-0.10	0.27	-0.46	0.13
OR		-0.02	**0.60**	**0.55**	-0.27	0.14
WE		0.21	0.08	**0.51**	-0.48	0.01
	TR	0.11	-0.43	0.05	-0.46	-0.04
MF/TC/KBW		-0.08	-0.19	0.28	-0.26	0.04
TG/KAT		0.29	**0.69**	**0.88**	-0.33	-0.29

[n] The correlation is numerically precise but is based upon only two data points.

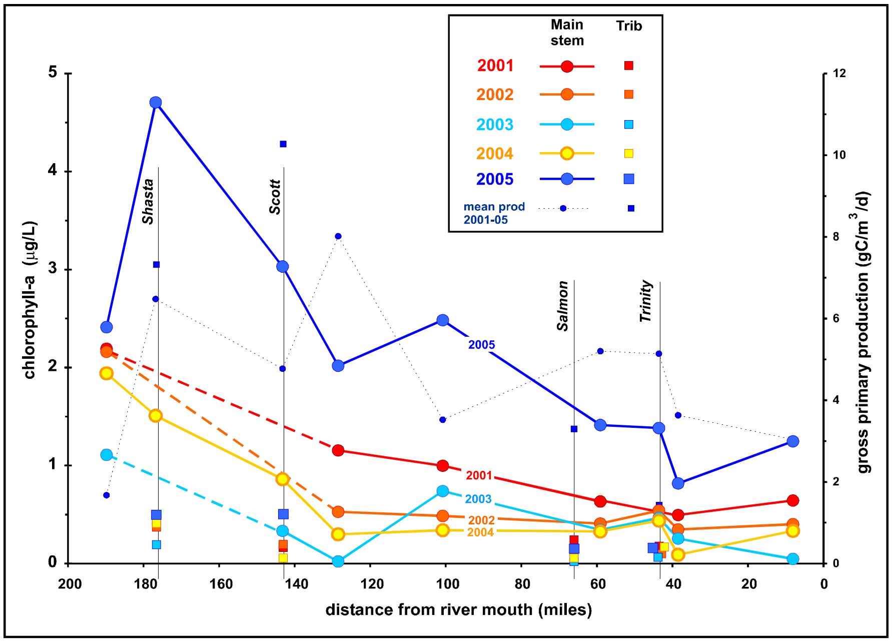

Figure 5-7. Annual profiles of mean chlorophyll-a in the Klamath during June-September.

In the simple plug-flow mass-budget model of Section 3.3, the variation of TN and TP along the Klamath mainstem was found to be well-explained by the high concentrations in the Iron Gate discharge, dilution by tributary inflows, and a first-order decay rate, whose value was determined by the best fit of the model profile to measurements for each month of the study period. These decay rates are presented in Table 3-4. Since one potential contributor to nutrient decay is biological assimilation, we inquire as to whether there is some association of these modeled decay rates with the values of gross primary production extracted from the sonde data. Since the model decay rate is applied uniformly along the length of the river, to be comparable, the production values were averaged over the mainstem stations. Further, this evaluation is limited to August production data, because August is typically the month of lowest and most stable river flow, as well as sufficiently late in the season that production values are generally highest. The results, shown in Figure 5-8, indicate that the sonde-derived production has a close association with the N decay rate (i.e., correlation 0.99), and a much weaker association with the P decay rate (i.e., correlation 0.41). It should be noted that (1) there is more uncertainty in the model-fitted total P decay rates because of the small P concentrations, and (2) the decay of nitrogen concentration is due almost entirely to biological assimilation, while substantial inorganic phosphorus is lost to the additional process of adsorption to particulates and settling, a process which is entirely physical and unrelated to biology, but implicit in the decay coefficients.

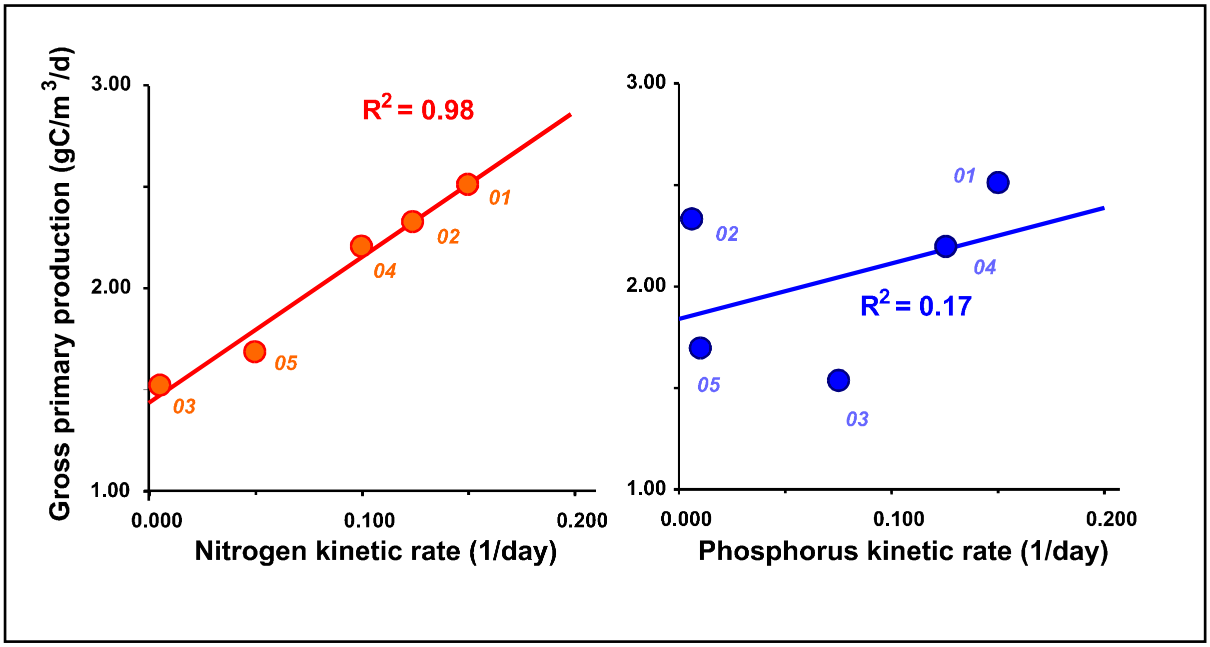

Figure 5-8. Association of sonde-derived average mainstem production with decay rates from model fits to nutrient data (Armstrong and Ward 2008b) for each year of the study period.

5.2. Overview and conclusions

The picture of the Klamath River community metabolism that emerges from these analyses is consistent in some respects with that of other large rivers, in being net heterotrophic but with a tendency for increasing relative autotrophy downstream toward the mouth (Dodds 2006, Dodds and Cole 2007). When the rates of respiration and production inferred from sonde data are converted to equivalent areal units (by multiplying by the prevailing depth under the ambient flow conditions), the rates are numerically consistent with literature values (Dodds 2006, Garnier and Billen 2007, McTammany et al. 2003) and indicate a mesotrophic system. That stated, we consider volumetric rates, rather than areal, to be more meaningful for the Klamath River (Smith 2007) and have employed them in this report.

The inferred metabolism parameters have been presented annually, to exhibit year-to-year variation, especially the extent to which river flow may be a controlling factor. When these results are further averaged over the 2001-2005 study period, they appear more coherent in their behavior than exhibited in the individual years (Figure 5-9). The most general features of the Klamath mainstem may be summarized as follows:

(1) The release from Iron Gate dominates the chemistry of the river: nutrient concentrations, as measured by TN, TP, and TOC, are maximal at Iron Gate, the station just below Iron Gate Dam, and decline with distance downstream, primarily because of dilution by tributary inflow, secondarily due to kinetic decay.

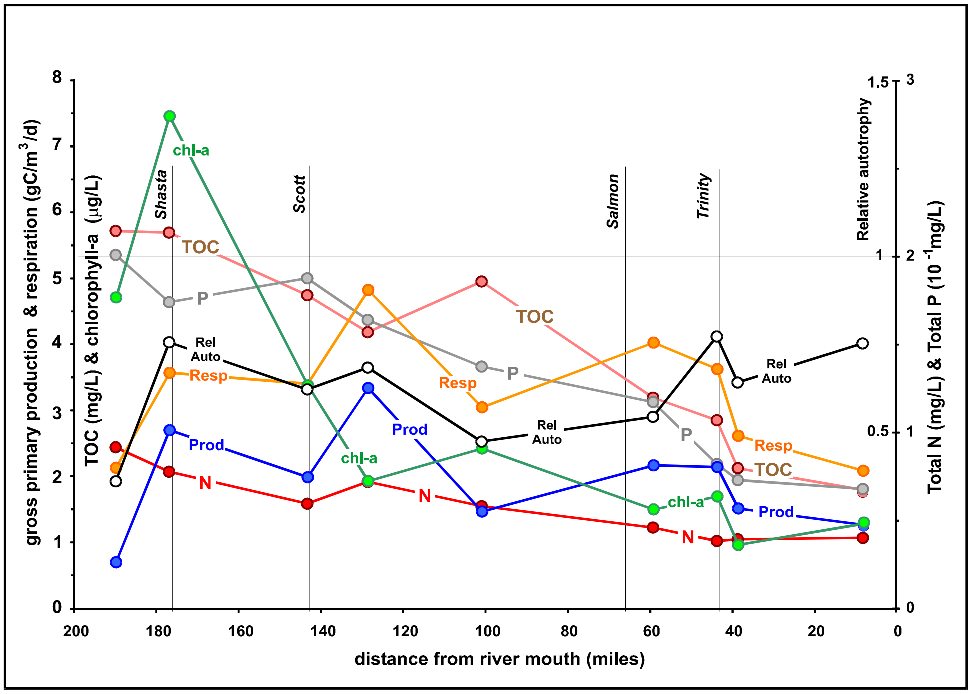

Figure 5-9. Mean profiles of metabolic parameters in the Klamath River during the summer (June-September), 2001-2005.

(2) Community production and respiration vary coherently down the mainstem to the mouth. This is suggestive that either production drives respiration, or that they are dominated by correlated controls (e.g., allochthonous inputs of nutrients and carbon).

(3) Respiration and production are typically lowest at Iron Gate, because this station, dominated by releases from the dam, is representative of the upper 10-meter water column of the reservoir. With the progression of summer stratification in the reservoir, DO-deficient water from levels below the thermocline is entrained into the release.

(4) In the reach immediately downstream from Iron Gate, primary production increases dramatically, indicative of the establishment of a riverine autotroph community. This level of production is generally maintained downstream through about rm 130 (the Seiad Valley station, and below the confluences of the Shasta and Scott). In the reach from Seiad Valley to the Salmon confluence, production diminishes, whose cause remains unknown. This phenomenon is represented, unfortunately, by a single station, Happy Camp, where production and respiration are consistently depressed in each year of the study. Production recovers below the Salmon River confluence, but declines again below the Trinity River confluence, most likely due to dilution with waters of the Trinity system.

(5) Relative autotrophy and chlorophyll-*a* concentrations increase markedly in the reach immediately downstream from Iron Gate, supporting the interpretation of establishment of a vigorous community of autotrophs in the shallow, nutrient-rich waters of the river. From the Shasta confluence to the Salmon confluence, relative autotrophy generally declines to a value of about 0.5, then increases from below the

Salmon to the mouth, and in a few years, exceeding unity. This increase in the lowermost reach is due primarily to a factor-of-two decline in respiration.

(6) Below the Trinity River confluence, all the metabolic parameters analyzed, *viz*. nutrients, chlorophyll, respiration, and primary production, with the sole exception of nitrogen, drop substantially due to dilution with flow from the Trinity River.

(7) Production and respiration in the principal tributaries, *viz*. the Shasta, Scott, Salmon and Trinity rivers, differ from each other and from the mainstem, and are consistent from year to year, suggesting very different kinetic processes and drivers in each tributary. Most exceptional is the Trinity River, with low values of production and respiration, along with low nutrients and chlorophyll-*a*.

These results pose questions that were beyond the scope of the present effort:

(1) While these results indicate the Klamath River to be net heterotrophic, the only major allochthonous source of carbon, *viz*. the discharge from Iron Gate, appears to be insufficient to fuel respiration in the lower Klamath River. This suggests that secondary production may be responsible for the high respiration, which would imply a vigorous community of herbivores, either benthic or planktonic[7].

(2) The lack of correlation between measured water-sample chlorophyll-*a* and daily primary production remains puzzling. This may be due to a major contribution to production by macrophytes and other benthic algae, which would not be included in a water-sample chlorophyll analysis, as suggested above. It may also be a simple manifestation of inadequate sampling; the heterogeneity of algae on short spatial and temporal scales may render a single grab sample taken at intervals of many days inadequate to measure the biomass of phytoplankton, particularly in comparison to the daily integrated values of production inferred from the sonde records. Certainly, the relative role of planktonic and benthal algae in the river system needs further study.

(3) Quantification of the reaeration coefficient is a by-product of the sonde analyses but is of interest because of the central role of reaeration in the oxygen budget. The estimations of reaeration coefficient from the nighttime DO time series are substantially higher, by a factor of 2-10, than the values given by the O'Connor-Dobbins and CEB equations. This result requires more detailed study, first to substantiate the sonde-derived coefficients, second to verify their functional dependence upon physical and hydraulic properties of the stream, and third to determine whether this disparity might extrapolate to other streams and rivers. Field measurements of reaeration are notoriously difficult to perform, consequently in water-quality analysis great reliance is placed upon the calculation of reaeration from relationships such as the O'Connor-Dobbins equation, particularly in the estimation of production from DO time series (Young and Huryn 1998, Bott 2007). Any limits to the applicability of these relations that might be indicated by the present data would be useful information in riverine water-quality investigations.

The data sets compiled by the USFWS and Karuk and Yurok tribes during 2001-2005, particularly after being subjected to QA/QC and other correction procedures, represent an

[7] The five-day BOD's were almost uniformly below the detection limit of 2 mg/L so bacteria appear to play only a minor role in the community respiration.

invaluable resource for diagnosing the behavior of the Klamath River and its response to various external and internal factors. This report represents a beginning in the analyses that can be supported by this rich data set. Two other parameters, pH and conductivity, have been processed using the same data-correction protocols, and are available for use in further studies of the river. Moreover, the response of DO and the inferred metabolic parameters to flow events, meteorology, and nutrient sources can be evaluated in much more detail on time scales from hours to days. There are sonde records in the AFWO database from additional stations, not examined in this study. Finally, other agencies and researchers have deployed sondes and instituted water sampling in the river, and once these data are verified and analyzed, their inclusion into a comprehensive database would greatly improve our ability to better understand the water quality dynamics in the lower Klamath River.

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APPENDICIES

Appendix A 1. USGS gauges active in Lower Klamath during this study.

Gauge Number	*Location*	*Useable record begins*	*Drainage area (mi^2)*
11516530	Klamath River below Iron Gate Dam	1960	4,630
11517500	Shasta River near Yreka	1944	793
11519500	Scott River near Fort Jones	1941	653
11520500	Klamath River near Seiad Valley	1951	6,940
11522500	Salmon River at Somes Bar	1927	751
11523000	Klamath River at Orleans	1927	8,475
11525500*	Trinity River at Lewiston	1911	719
11527000	Trinity River near Burnt Ranch	1956	1,439
11530000	Trinity River at Hoopa	1931	2,853
11530500	Klamath River near Klamath	1950**	12,100

* Longest continuous record, however gauge proved anomalous and was not used
** Data missing for 30 Oct 1995 - 30 Sep 1997

Appendix A 2. AFWO grab-sample stations in the Klamath River basin (sorted alphabetically). Location information includes river mile (rm), elevation, and GPS coordinates for each station.

Station	*Location*	*First order (rm)*	*Second order (rm)*	*Third order (rm)*	*Elevation (ft)*	*Latitude (dd mm ss)*	*Longitude (ddd mm ss)*
BC	Bogus Creek	189.6	0.2			41 55 46	122 26 30
BL	Bluff Creek @ mouth	49.5	0.1		320	41 14 25.6	123 39 11
BVC	Beaver Creek	161.1	0.1			41 52 15	122 48 57
C1	Klamath River above Copco 1	205.5			2530	41 57 57.3	122 12 57.9
C2	Klamath River below Copco 2	196.5			2130	41 58 23.7	122 21 48.9
CLR	Clear Creek	98.6	0.1		960	41 42 35.5	123 26 55.8
DLN	Dillon Creek	84.2	0.1		780	41 34 32	123 32 18
ELK	Elk Creek	105.5	0.1		1040	41 46 49.1	123 23 34.7
EM	Klamath River Estuary mainstem	0.1			40	41 32 37	124 04 44
GOF	Klamath River below Fort Goff, river access point 66 (Seattle Creek)	121.4				41 50 37	123 18 02
GOT	Klamath River below Gottville	164.9				41 51 30	122 45 03
HAM	Klamath River below Hamburg, river access point 56 (Rodney Pt.)	140				41 48 58	123 07 35
HC	Klamath River below Happy Camp	100.8			960	41 43 47	123 25 28
IG	Klamath River at Iron Gate Hatchery Bridge	189.8			2178	41 55 53	122 26 24
IGRB	Iron Gate Reservoir Bottom	190.1				41 56 20	122 25 53
IGRS	Iron Gate Reservoir Surface	190.1				41 56 20	122 25 53
JB	Klamath River before JC Boyle Powerhouse (Bypass)	220.5			3350	42 05 37	122 04 09
JC	Klamath River below JC Boyle return	217			3340	42 03 12.5	122 05 20.8
JP	Klamath River at JC Boyle Powerhouse	220.4			3340	42 05 35	122 04 15
K1	Klamath River above Shasta	176.8			1860	41 49 52	122 35 31
K2	Klamath River above the Scott River (small pullout across from green highway sign- Horse Creek 4 miles)	143.2			1520	41 46 45.7	123 01 59.2
KBC	Klamath River above Blue Creek	16.5			40	41 25 24	123 55 40
KD	Klamath River above Dillon Creek	84.3			780	41 34 37	123 32 21
KELK	Klamath River 200 yards below Elk Creek, above Waste Water Treatment Plant	105.4				41 46 45	123 23 38
KN	Klamath River below Keno Dam	223.2			4095	42 08 03	121 56 50

(continued)

Appendix A-2 (continued). AFWO grab-sample stations in the Klamath River basin.

Station	*Location*	*First order (rm)*	*Second order (rm)*	*Third order (rm*	*Elevation (ft)*	*Latitude (dd mm ss)*	*Longitude (ddd mm ss)*
KRSL	Klamath River at Stateline	209.2				42 00 26	122 11 15
KS	Klamath Straights Drain	240.5			4094.1	42 04 52	121 50 34
KSA	Klamath River above Salmon River	66.1			455	41 22 39.7	123 29 40.8
L1	Little Shasta River CDFG wildlife area	176.6	15.7	11.8	2400	41 42 25	122 26 12
L2	Little Shasta River	176.6	15.7	6.5	2100	41 43 23	122 22 06
LR	Link River below dam	253.2			4094.1	42 12 05	121 47 17
MF	Klamath River at Martins Ferry	40.4			160	41 12 26	123 45 19
OR	Klamath River at Orleans	59.1			400	41 18 12	123 32 00
RB	Klamath River at Round Bar pool, near town of Klamath River	158.5				41 51 3.6	122 50 7.9
RCC	Red Cap Creek, 150' upstream of Allen Bridge	52.7	0.3			41 15 34	123 36 01
S1	Shasta River at Louie Rd Crossing	176.6	32		2300	41 35 27	122 26 13
S2	Shasta River at A12 Bridge	176.6	22.6		2250	41 38 54	122 29 54
S3	Shasta River at Montague Grenada	176.6	15.1		2160	41 42 33	122 32 14
S4	Shasta River above Yreka Creek	176.6	7.9		2100	41 46 21	122 35 31
SA	Salmon River near mouth	66	1.01		480	41 22 36	123 28 33
SC	Scott River near mouth	143	1.5		1600	41 45 57	123 01 16
SH	Shasta River near mouth	176.6	0.5		2031	41 49 30	122 35 33
SRWC	Shasta River above Willow Creek (near rt 3)	176.6				41 43 35	122 33 31
SV	Klamath River at Seiad Valley	128.5			1320	41 51 15	123 13 49
TC	Klamath River above Tully Cr. (below MF)	38.5			280	41 13 41	123 46 20
TG	Klamath River at Terwer	6.7			8	41 30 55	123 59 56
TR	Trinity River near mouth	43.5	0.5		240	41 10 54	123 42 14
UL	Ullathorne Creek (Below Orleans)	56.1	0.1			41 17 30	123 34 10
WE	Klamath River at Weitchpec	43.6			240	41 11 09	123 42 03
Y2	Yreka Creek above Waste Water Plant	176.6	7.6			41 44 24	122 37 47
YR	Yreka Creek	176.6	7.6	0.6	2000	41 46 21	122 36 14

Appendix A 3. AFWO grab-sample stations in the Klamath River Basin (sorted by river mile). Location information includes river mile (rm), elevation, and GPS coordinates for each station.

Station	*Location*	*First order (rm)*	*Second order (rm)*	*Third order (rm)*	*Elevation (ft)*	*Latitude (dd mm ss)*	*Longitude (ddd mm ss)*
LR	Link River below dam	253.2			4094.1	42 12 05	121 47 17
KS	Klamath Straights Drain	240.5			4094.1	42 04 52	121 50 34
KN	Klamath River below Keno Dam	223.2			4095	42 08 03	121 56 50
JB	Klamath River before JC Boyle Powerhouse (Bypass)	220.5			3350	42 05 37	122 04 09
JP	Klamath River at JC Boyle Powerhouse	220.4			3340	42 05 35	122 04 15
JC	Klamath River below JC Boyle return	217			3340	42 03 12.5	122 05 20.8
KRSL	Klamath River at Stateline	209.2				42 00 26	122 11 15
C1	Klamath River above Copco 1	205.5			2530	41 57 57.3	122 12 57.9
C2	Klamath River below Copco 2	196.5			2130	41 58 23.7	122 21 48.9
IGRB	Iron Gate Reservoir Bottom	190.1				41 56 20	122 25 53
IGRS	Iron Gate Reservoir Surface	190.1				41 56 20	122 25 53
IG	Klamath River at Iron Gate Hatchery Bridge	189.8			2178	41 55 53	122 26 24
BC	Bogus Creek	189.6	0.2			41 55 46	122 26 30
K1	Klamath River above Shasta	176.8			1860	41 49 52	122 35 31
S1	Shasta River at Louie Rd Crossing	176.6	32		2300	41 35 27	122 26 13
S2	Shasta River at A12 Bridge	176.6	22.6		2250	41 38 54	122 29 54
L1	Little Shasta River CDFG wildlife area	176.6	15.7	11.8	2400	41 42 25	122 26 12
L2	Little Shasta River	176.6	15.7	6.5	2100	41 43 23	122 22 06
S3	Shasta River at Montague Grenada	176.6	15.1		2160	41 42 33	122 32 14
S4	Shasta River above Yreka Creek	176.6	7.9		2100	41 46 21	122 35 31
YR	Yreka Creek	176.6	7.6	0.6	2000	41 46 21	122 36 14
Y2	Yreka Creek above Waste Water Plant	176.6	7.6			41 44 24	122 37 47
SH	Shasta River near mouth	176.6	0.5		2031	41 49 30	122 35 33
SRWC	Shasta River above Willow Creek (near rt 3)	176.6				41 43 35	122 33 31
GOT	Klamath River below Gottville	164.9				41 51 30	122 45 03
BVC	Beaver Creek	161.1	0.1			41 52 15	122 48 57
RB	Klamath River at Round Bar pool, near town of Klamath River	158.5				41 51 3.6	122 50 7.9
K2	Klamath River above the Scott River (small pullout across from green highway sign- Horse Creek 4 miles)	143.2			1520	41 46 45.7	123 01 59.2

(continued)

Table A-3 (continued). AFWO grab-sample stations in the Klamath River Basin.

Station	*Location*	*First order (rm)*	*Second order (rm)*	*Third order (rm)*	*Elevation (ft)*	*Latitude (dd mm ss)*	*Longitude (ddd mm ss)*
SC	Scott River near mouth	143	1.5		1600	41 45 57	123 01 16
HAM	Klamath River below Hamburg, river access point 56 (Rodney Pt.)	140				41 48 58	123 07 35
SV	Klamath River at Seiad Valley	128.5			1320	41 51 15	123 13 49
GOF	Klamath River below Fort Goff, river access point 66 (Seattle Creek)	121.4				41 50 37	123 18 02
ELK	Elk Creek	105.5	0.1		1040	41 46 49.1	123 23 34.7
KELK	Klamath River 200 yards below Elk Creek, above Waste Water Treatment Plant	105.4				41 46 45	123 23 38
HC	Klamath River below Happy Camp	100.8			960	41 43 47	123 25 28
CLR	Clear Creek	98.6	0.1		960	41 42 35.5	123 26 55.8
KD	Klamath River above Dillon Creek	84.3			780	41 34 37	123 32 21
DLN	Dillon Creek	84.2	0.1		780	41 34 32	123 32 18
KSA	Klamath River above Salmon River	66.1			455	41 22 39.7	123 29 40.8
SA	Salmon River near mouth	66	1.01		480	41 22 36	123 28 33
OR	Klamath River at Orleans	59.1			400	41 18 12	123 32 00
UL	Ullathorne Creek (Below Orleans)	56.1	0.1			41 17 30	123 34 10
RCC	Red Cap Creek, 150' upstream of Allen Bridge	52.7	0.3			41 15 34	123 36 01
BL	Bluff Creek @ mouth	49.5	0.1		320	41 14 25.6	123 39 11
WE	Klamath River at Weitchpec	43.6			240	41 11 09	123 42 03
TR	Trinity River near mouth	43.5	0.5		240	41 10 54	123 42 14
MF	Klamath River at Martins Ferry	40.4			160	41 12 26	123 45 19
TC	Klamath River above Tully Cr. (below MF)	38.5			280	41 13 41	123 46 20
KBC	Klamath River above Blue Creek	16.5			40	41 25 24	123 55 40
TG	Klamath River at Terwer	6.7			8	41 30 55	123 59 56
EM	Klamath River Estuary mainstem	0.1			0	41 32 37	124 04 44