TECHNICAL MEMORANDUM:

EVALUATION OF PACIFICORP'S KLAMATH RIVER WATER QUALITY MODEL PREDICTIONS FOR SELECTED WATER QUALITY PARAMETERS

PREPARED FOR THE

YUROK TRIBE ENVIRONMENTAL PROGRAM

BY

KIER ASSOCIATES, FISHERIES AND WATERSHED PROFESSIONALS
BLUE LAKE AND ARCATA, CALIFORNIA

AND

AQUATIC ECOSYSTEM SCIENCES LLC
ASHLAND, OREGON

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INTRODUCTION

Building upon earlier efforts (Deas and Orlob 1999, Watercourse Engineering 2003), PacifiCorp has developed a water quality model for the Klamath River from the outlet of Upper Klamath Lake (UKL) at Link Dam downstream to Turwar Creek near the Klamath estuary. The model combines two different models: CE-QUAL-W2 for reservoir reaches and RMA-11 for river reaches. The model simulates flow, temperature, and various water quality parameters, including dissolved oxygen, pH, nutrients, and algae. PacifiCorp has completed several rounds of modeling and has published the results in several reports (PacifiCorp 2004, 2005a, 2005b, 2005c; and Scott 2006).

Flow and temperature are based on the laws of physics, and modeling them is a well-settled practice. Dissolved oxygen, nutrients, and algae are subject not only to the laws of physics, but also to chemistry, biology, and ecology, which are far more complex, unpredictable, and difficult to represent mathematically. Further, for the Klamath River there is far less data available for these parameters than for temperature and flow, making model calibration and verification difficult.

Model calibration and verification for water quality and fish passage (PacifiCorp 2005c and 2005d) shows that the model accurately predicts flow and temperature (to within approximately one degree Celsius for temperature, for example), but does not accurately predict dissolved oxygen, nutrients, or algae. These results are similar to those arrived at by Wells (2004).

Because PacifiCorp has used its water quality modeling outputs to portray river and reservoir dynamics and to support conclusions that have important management implications, an assessment of how well the model represents the magnitude of Klamath River water quality values, as well as the spatial/temporal dynamics of those values, is essential. For example, in its conclusion that the reservoirs of its Klamath Hydroelectric Project (KHP - particularly Iron Gate and Copco reservoirs) trap organic matter and therefore serve as net nutrient sinks, PacifiCorp (2006a) states "However, detailed modeling and analysis by PacifiCorp indicates that the Project reservoirs provide an annual net reduction in the enormous load of organic matter and nutrients to the river in the Project area (that comes) from UKL."

In addition, in an October, 2005 submittal to FERC, PacifiCorp (2005b) provided charts and discussion illustrating differences in predicted D.O. concentrations between different model scenarios and stated that:

> "Algal growth plays a predominant role in sequestering nutrients from the water column. As such, algal biomass diminishes in the downstream direction under existing conditions. By comparison, attached algae growth in the Klamath River below Iron Gate is estimated to be equal to or greater under the without-dams scenarios, due to the relatively rapid transit of nutrient and organic loads from Upper Klamath Lake and the absence of nutrient retention PacifiCorp Klamath Hydroelectric Project effects in the existing reservoirs. Higher primary production (algal growth) is also evident in the greater diel variation in DO levels seen in model simulation results under the without dams scenarios compared to the EC scenario"

Similarly, PacifiCorp (2005b) uses modeling outputs for nutrients, dissolved oxygen, and attached algae, to state that pH and ammonia toxicity in the WOP (Without the KHP Project) scenario are the same or higher in the river below Iron Gate dam than the EC (existing condition) scenario.

Since nutrients are primary drivers of the dynamics of algae and macrophytes, which in turn are primary drivers of the D.O./pH conditions in the river, having a model that accurately represents the spatial and temporal dynamics of nutrients is a critical first step before such model-based conclusions as those in the examples above can be relied upon.

PacifiCorp has done only limited calibration for the inorganic forms of nitrogen (ammonia and nitrate), and no calibration for parameters containing organic nitrogen, such as Kjeldahl nitrogen (ammonia N + organic N) or total nitrogen (organic N + ammonia N + nitrate/nitrite N). Because organic nitrogen is by far the most abundant form of nitrogen in the Klamath River, calibration for this component as well as for the total forms of both N and P is necessary for evaluation of those nutrient dynamics that drive algal production and the resulting D.O. and pH dynamics.

The purpose of this technical memorandum is to provide a brief assessment of how nutrient concentrations and nutrient loads predicted by the PacifiCorp water quality model fit available observed field data for the years 2000-2004. The parameters examined here include nitrogen, phosphorus, chlorophyll, and organic carbon.

PROCESSING MODEL OUPUTS FOR THE ANALYSIS OF PREDICTED VALUES

PacifiCorp (2005c) filed final versions of its model input and output files for the years 2000-2004 with the Federal Energy Regulatory Commission (FERC) in December 2005, as part of its KHP federal relicensing request. To facilitate our analysis, we first compiled the many model output files from riverine sites into a single database. This database is included as an electronic appendix to this technical memorandum. Because all model scenarios other than the Existing Condition (EC) scenario are hypothetical, in this technical memorandum we use only model outputs from the EC scenario so that model predictions can be compared to existing data that have been directly measured (observed).

Model results for the existing conditions scenario at Iron Gate Dam in 2000 were inadvertently omitted during compilation of the database. Due to time constraints we were unable to add these data back into the database once the omission was discovered. Thus, comparisons for Iron Gate for all years except 2000 are analyzed below.

Because PC's model outputs were published as hourly values, all parameters were summarized by calculating daily means to enable their comparison to the observed field data.

It should be noted that using daily average model outputs has the potential to introduce error in the above-Copco site (river mile 203.6). As discussed in Asarian and Kann (2006), flows and concentrations at this location are influenced by hydropower peaking operations from the J.C. Boyle Powerhouse. Thus, using hourly model outputs to calculate a simple arithmetic mean daily average gives equal weight to low-flow and high-flow periods during a day, resulting in daily average concentrations that differ from flow-weighted concentrations. Due to the complexity and file size of the model output data, we opted not to calculate flow-weighted daily means for any of the parameters. It should also be noted here that for the same reasons described above, hydropower peaking also influences the field samples collected in the peaking reach. We did not specifically examine what time of day each sample was taken. Thus, specific trends in predicted-versus-observed data at this location are not emphasized below.

In the model, parameters related to organic matter and algae are not represented in ways that are identical to parameters that can be measured/observed in the field. For example, organic nitrogen is represented by several non-overlapping model parameters: algae (ALGAE), organic matter (OM), and biochemical oxygen demand (BOD) (Figure 1 from PacifiCorp 2005d). As such, we utilized model outputs and applied the same stoichiometric ratio reported by PacifiCorp (2005d) to calculate derived parameters that could then be directly compared to field data (see below).

PacifiCorp's model assumes a constant stoichiometric ratio of 0.07 to convert between nitrogen and these parameters (PacifiCorp 2005d). For example, when 1 mg/L of OM decays in the model, 0.07 mg/L of ammonia nitrogen is released (PacifiCorp 2005d). The formula for deriving organic nitrogen from model outputs (in units of mg/L as N) is:

$$\text{Organic nitrogen} = (0.07)*(\text{ALGAE}+\text{OM}+\text{BOD})$$

Total nitrogen (TN) is the sum of the inorganic (ammonia, nitrate, nitrite) and organic forms, so it can be calculated (in units of mg/L as N) using this formula:

$$\text{TN} = \text{Organic nitrogen} + \text{NH3} + \text{NO3} + \text{NO2}$$

Organic phosphorus is represented in the model by the same parameters as organic nitrogen, ALGAE, OM, and BOD. The stoichiometric ratio between phosphorus and these parameters is 0.01 (PacifiCorp 2005d); hence, the formula (in units of mg/L as P) for organic phosphorus is:

$$\text{Organic phosphorus} = (0.01)*(\text{ALGAE}+\text{OM}+\text{BOD})$$

Total phosphorus (TP) is the sum of the inorganic (orthophosphorus) and organic forms, so it can be calculated using this formula:

$$\text{TP} = \text{Organic phosphorus} + \text{PO4}$$

As with organic nitrogen and organic phosphorus, total organic carbon (TOC) is not an explicitly modeled parameter in the water quality model, but is instead represented by ALGAE, BOD, and OM. The stoichiometric ratio between carbon and these parameters is 0.45 (PacifiCorp 2005d); hence, the formula (in units of mg/L as C) for total organic carbon:

$$\text{TOC} = 0.45 * (\text{ALGAE} + \text{BOD} + \text{OM})$$

Chlorophyll *a* is also not an explicitly modeled parameter in the water quality model. Algae are included in the model as total algal biomass (presumably dry-weight, though model documentation did not state this), rather than as chlorophyll pigment. The conversion factor between algal biomass in mg/L and chlorophyll *a* in µg/L is 67 (PacifiCorp 2005d). Using this conversion factor, we calculated chlorophyll *a* concentrations from model outputs and compared them to measured data.

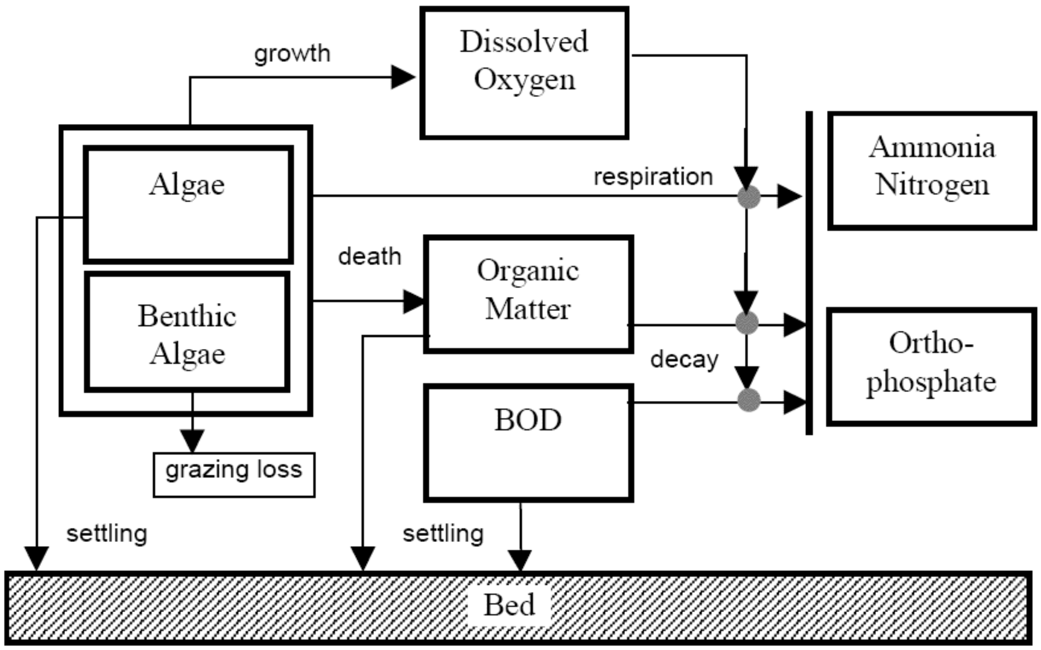


Figure 1. Schematic of organic matter modeling in PacifiCorp's RMA-11-OM2 river model. Figure from PacifiCorp (2005d).

FIELD DATA SETS UTILIZED FOR ANALYSIS OF OBSERVED VALUES

Much of the nutrient and automated probe water quality data collected in the Klamath River and its tributaries has been compiled into a single Microsoft Access database. The entities who collected the data that is assembled in the database include PacifiCorp, U.S. Geologic Survey (USGS), U.S. Fish and Wildlife Service (USFWS) Arcata Office, U.S. Bureau of Reclamation (USBR), the Karuk Tribe, Yurok Tribe, North Coast Regional Water Quality Control Board (NCRWQCB, including its Surface Water Ambient Monitoring Program, SWAMP), California Department of Water Resources, the Oregon Department of Environmental Quality (ODEQ), and various private companies and contractors. There were varying degrees of coordination between these agencies in terms of sampling protocols; the dates and frequency of sample collection; the location of samples; and the laboratories used for analysis.

The database used here was initiated by PacifiCorp (2004) and added to through other studies like the development of Total Maximum Daily Load plans (Tetra Tech 2004a, St. John 2004), nutrient budgets for Iron Gate and Copco Reservoirs (Kann and Asarian 2005), and analyses of nitrogen loading and retention dynamics (Asarian and Kann 2006). Various versions of the database have been published. This technical memorandum uses the same version of the database as Asarian and Kann (2006). Details regarding the datasets are included in that report and are not repeated here. Locations of sampling stations are shown in Figure 2 and Table 1.

We also used additional data (not included in the Klamath TMDL database) collected by the Klamath Tribes (Kann 2006) at two sites near the outlet of Upper Klamath Lake: Pelican Marina and Freemont Street Bridge (Figure 3).

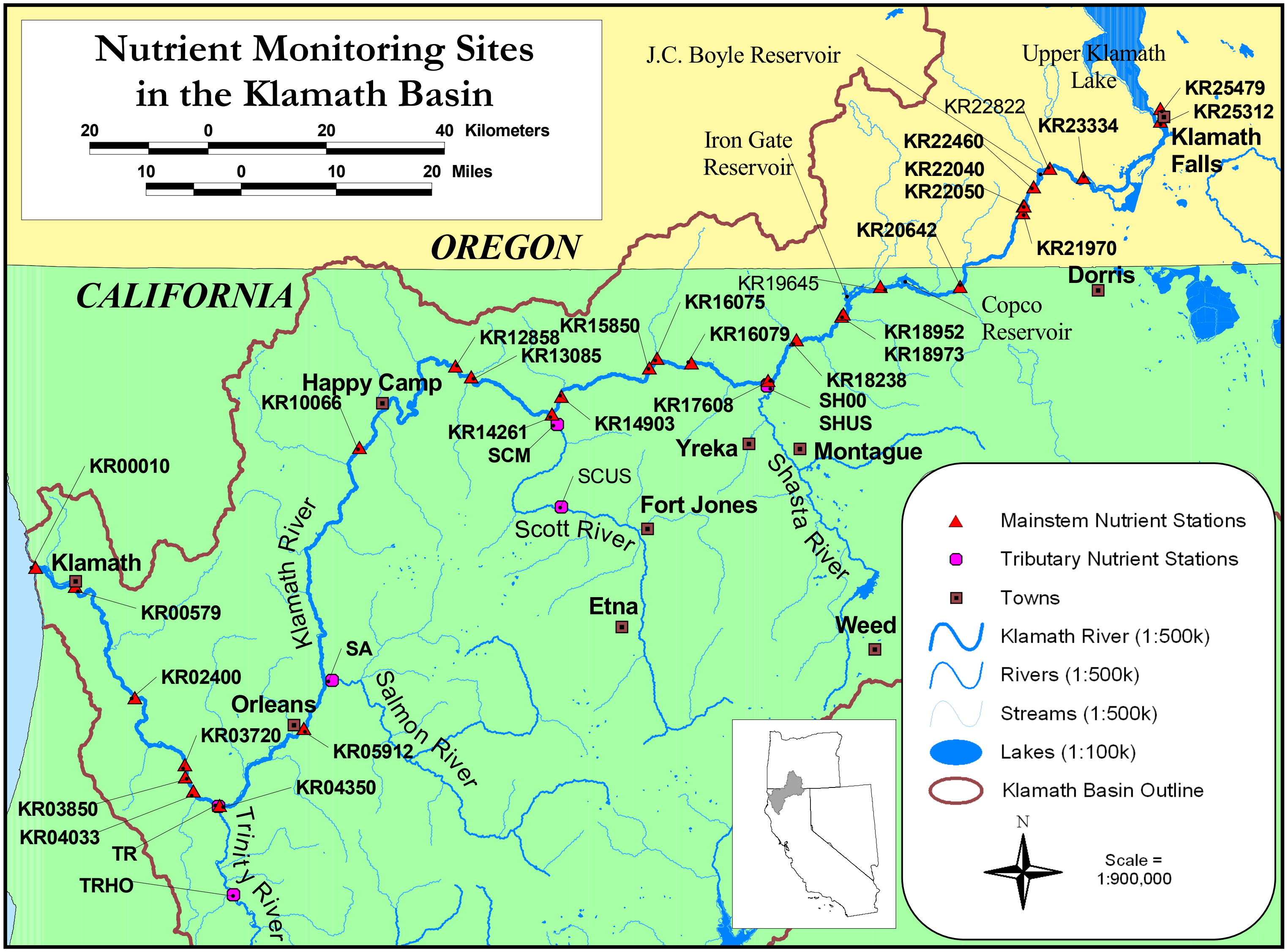
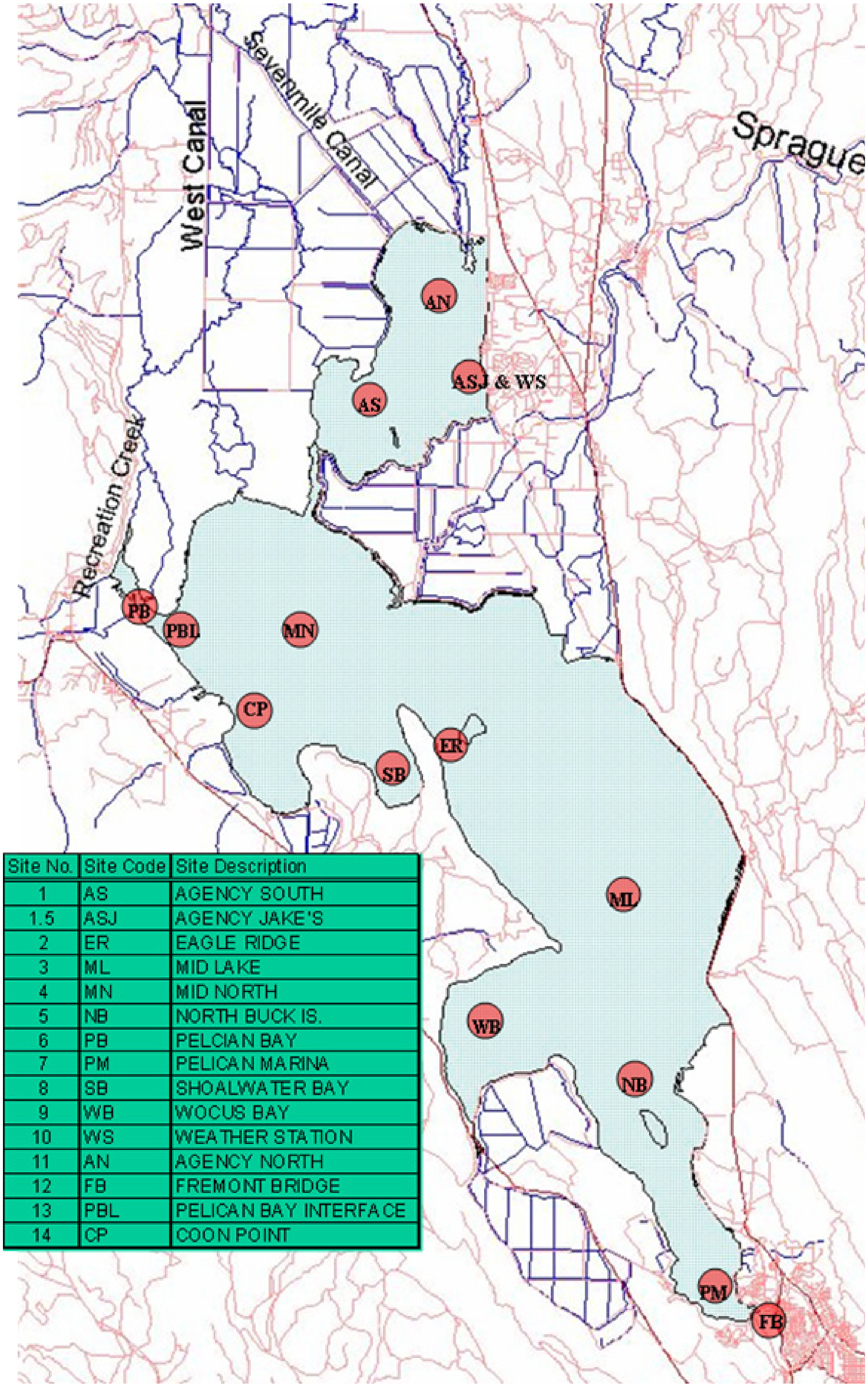


Figure 2. Location of nutrient sampling sites in the mainstem Klamath River and its tributaries. Note that the Site ID code for mainstem stations begins with "KR", followed by 5-digit river mile (i.e. KR18973 is river mile 189.73). Note that river miles are slightly different than in the model outputs (see Table 1 for key to locations). Figure from Asarian and Kann (2006)

Table 1. Key and description for nutrient sampling locations shown in Fig. 1. Note that the Site ID code for mainstem stations begins with "KR", followed by 5-digit river mile (i.e. KR18973 is river mile 189.73). Note that river miles are slightly different than in the model outputs. Latitude and longitude are from field data (coordinates for most model reporting sites are included in PacifiCorp 2005d).

Site ID	Field Data River Mile	Model River Mile	Site Name	Latitude	Longitude
KR00010	0.10		Klamath River Estuary Mainstem	41.543610	-124.078890
KR00579	5.79	5.28	Klamath River at Klamath Glen (Turwar)	41.515280	-123.998890
KR02400	24.00		Klamath River at Johnson's Point	41.347630	-123.876000
KR03720	37.20		Klamath River at Young's Bar	41.246600	-123.773300
KR03850	38.50		Klamath River above Tully Creek	41.228060	-123.772220
KR04033	40.33	39.5	Klamath River at Martins Ferry	41.207220	-123.755280
KR04350	43.50	43.33	Klamath River at Weitchpec	41.185830	-123.703056
KR05912	59.12	57.58	Klamath River at Orleans	41.303330	-123.533330
KR10066	100.66	99.04	Klamath River below Happy Camp	41.729720	-123.424440
KR12858	128.58	129.04	Klamath River at Seiad Valley	41.854170	-123.230280
KR13085	130.85		Klamath River at Seiad Valley (2.25 mi above gage)	41.837333	-123.197500
KR14261	142.61	143.86	Klamath River above Scott River	41.781530	-123.033110
KR14903	149.03		Klamath River below Everill Creek	41.808133	-123.014067
KR15850	158.50	156.79	Klamath River at Round Bar Pool	41.851000	-122.835530
KR16075	160.75		Klamath River d/s Beaver Creek	41.865800	-122.819300
KR16079	160.79		Klamath River at Gottsville River Access	41.858450	-122.750220
KR17608	176.08	177.52	Klamath River above Shasta River	41.831280	-122.593467
KR18238	182.38		Klamath River u/s Cottonwood Creek	41.892730	-122.535400
KR18952	189.52		Klamath River below Iron Gate Dam (USGS Gage)	41.928056	-122.443056
KR18973	189.73	190.54	Klamath River below Iron Gate Dam (Hatchery Br.)	41.931600	-122.440000
KR19645	196.45		Copco Dam Outflow	41.973250	-122.363580
KR20642	206.42	203.6	Klamath River u/s Shovel Creek	41.972100	-122.201600
KR21970	219.70	219.64	Klamath River below Boyle powerhouse at USGS gage	42.083112	-122.071746
KR22040	220.40	220.02	Klamath River at J.C. Boyle Powerhouse	42.093060	-122.070830
KR22050	220.50	220.20	Klamath River above J.C. Boyle Powerhouse	42.093610	-122.069170
KR22460	224.60	224.32	Klamath River below J.C. Boyle Reservoir	42.121700	-122.049400
KR22822	228.22	227.57	Klamath River above J.C. Boyle Reservoir	42.149900	-122.015400
KR23334	233.34	232.86	Klamath River below Keno Dam	42.135300	-121.947220
KR25312	253.12	252.67	Link River at Mouth	42.218900	-121.788300
		253.88	Link Dam		
KR25479	254.79		Upper Klamath Lake at Fremont St Bridge	42.238300	-121.788060
SA	-		Salmon River at Somes Bar	41.376900	-123.477200
SCM	-		Scott River at Mouth	41.765830	-123.022800
SCUS	-		Scott River at USGS Gage	41.640500	-123.014500
SH00	-		Shasta River at Mouth	41.825000	-122.595100
SHUS	-		Shasta River at USGS Gage	41.823167	-122.595000
TR	-		Trinity River at Weitchpec	41.184330	-123.704167
TRHO	-		Trinity River at Hoopa	41.050400	-123.673300



Site No.	Site Code	Site Description
1	AS	AGENCY SOUTH
1.5	ASJ	AGENCY JAKE'S
2	ER	EAGLE RIDGE
3	ML	MID LAKE
4	MN	MID NORTH
5	NB	NORTH BUCK IS.
6	PB	PELCIAN BAY
7	PM	PELICAN MARINA
8	SB	SHOALWATER BAY
9	WB	WOCUS BAY
10	WS	WEATHER STATION
11	AN	AGENCY NORTH
12	FB	FREMONT BRIDGE
13	PBL	PELICAN BAY INTERFACE
14	CP	COON POINT

Figure 3. Location of Klamath Tribes' water quality sampling sites in Upper Klamath Lake and Agency Lake. Figure adapted from Kann (2006).

COMPARISON OF MODEL PREDICTIONS AND OBSERVED (MEASURED) DATA

Seasonal patterns

To examine how the model characterized seasonal patterns in total nitrogen (TN) and total phosphorus (TP) concentrations, we plotted the time series of predicted and observed data at both Link Dam and Iron Gate Dam (Figures 4-7). Note that for Link Dam modeled data are not predicted but rather it consists of the model input data for the boundary condition.

Link Dam boundary condition
Figure 3 shows a comparison of daily model input data and observed total nitrogen (TN) concentrations in the model's upstream boundary condition at Link Dam (river mile 253.88) for the years 2000-2004. The results show that model input data for the boundary condition reasonably track the seasonal pattern of observed data, with lower TN in the winter and spring, peaking during the summer months, and declining again in the fall.

Although the seasonal pattern is captured reasonably by the model, several trends are evident regarding magnitude. For example, model input magnitude was generally good from March to the mid-June period, but for the mid-June to the end-of-September period, the match was varied with some over-predictions and some under-predictions. In 2001, however, observed data were substantially over-predicted by the model in this period, with relative percent bias (RPB) often in the range of 50-100%. In addition, for all years in which there were data, the model underestimated TN from the October through January period.

A comparison of total phosphorus (TP) at Link Dam for the years 2000-2004 shows that seasonal tracking is more variable than for TN, and that the model consistently over-predicts TP in most years (Figure 4). From June through September, modeled concentrations were often >50% higher than observed data, with RPB frequently exceeding 100%. It should be noted that it is likely that the 1.99 mg/L TP concentration observed in late July 2000 was anomalous.

Iron Gate Dam
Figure 5 shows a comparison of daily predicted and observed total nitrogen (TN) concentrations at Iron Gate Dam (river mile 190.54) for the years 2001-2004. Compared to model performance at the Link River boundary location, these results show that the model predicted seasonal timing poorly, and consistently and strongly under-predicted TN concentrations. With the exception of a 30-day period in 2002, there were no days in which the predicted TN concentration was greater than that observed. The under-prediction was especially pronounced during the late summer and early fall months when the model tended to predict seasonal low TN concentrations. Values were often under-predicted by 2-9X, equating to an RPB of -50% to -90%

Although model performance for total phosphorus (TP) at Iron Gate was somewhat better than for TN, it was still poor (Figure 6). For example, in 2001 and 2002 the model under-predicted TP for the entire season except brief periods in April, May, and June. In 2003 and 2004, the model generally over-predicted TP from mid-September through the end of the monitoring season (November in 2003, December in 2004).

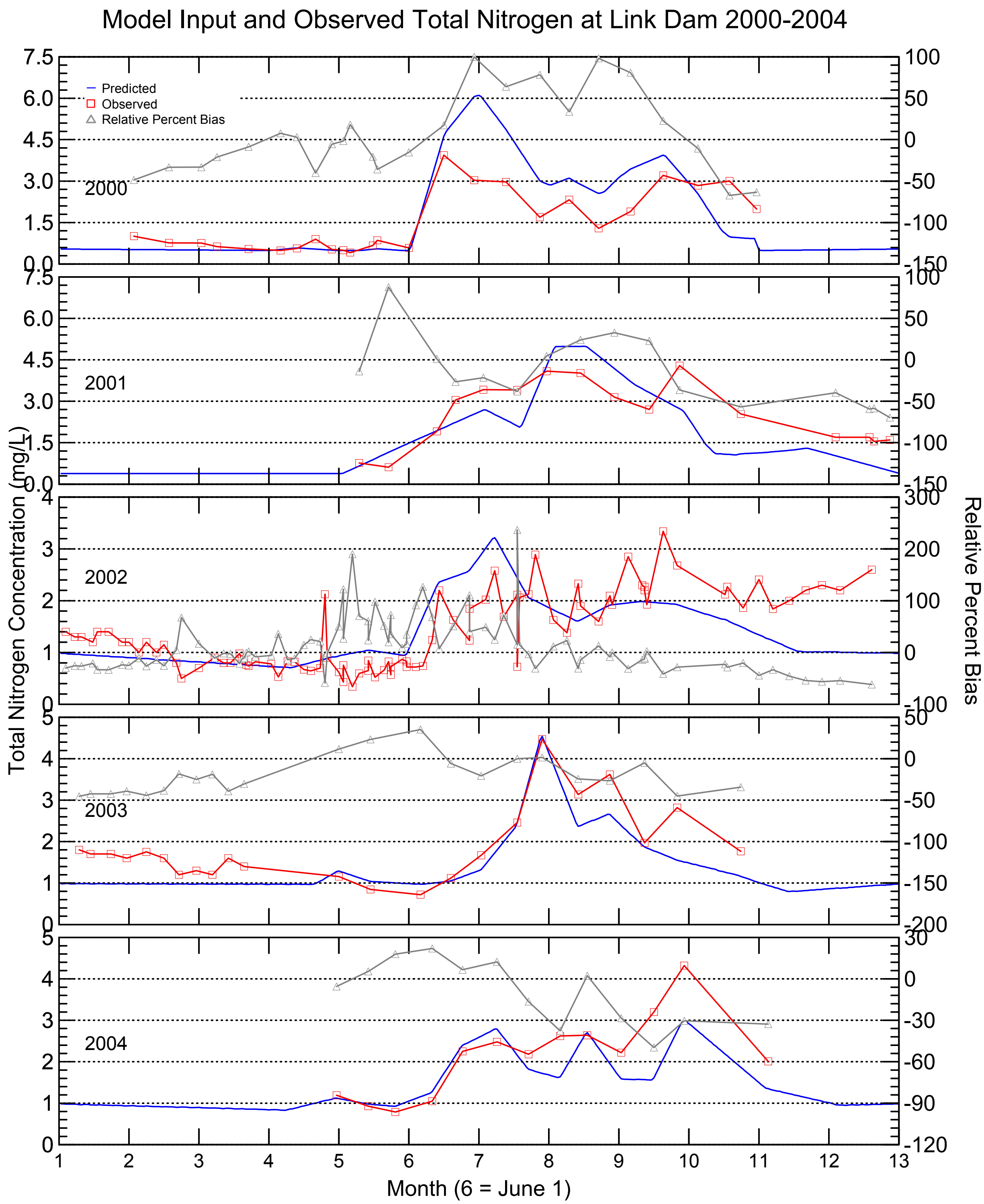


Figure 4. Comparison of daily model input (predicted) and observed total nitrogen (TN) concentrations at Link Dam (river mile 253.88) for the years 2000-2004. Also shown is the relative percent bias (RPB) of the model input compared to observed data. RPB was calculated as 100*(model input-observed)/observed. Measured concentrations for Link Dam are a combination of two Upper Klamath Lake stations: Freemont Bridge and Pelican Marina.

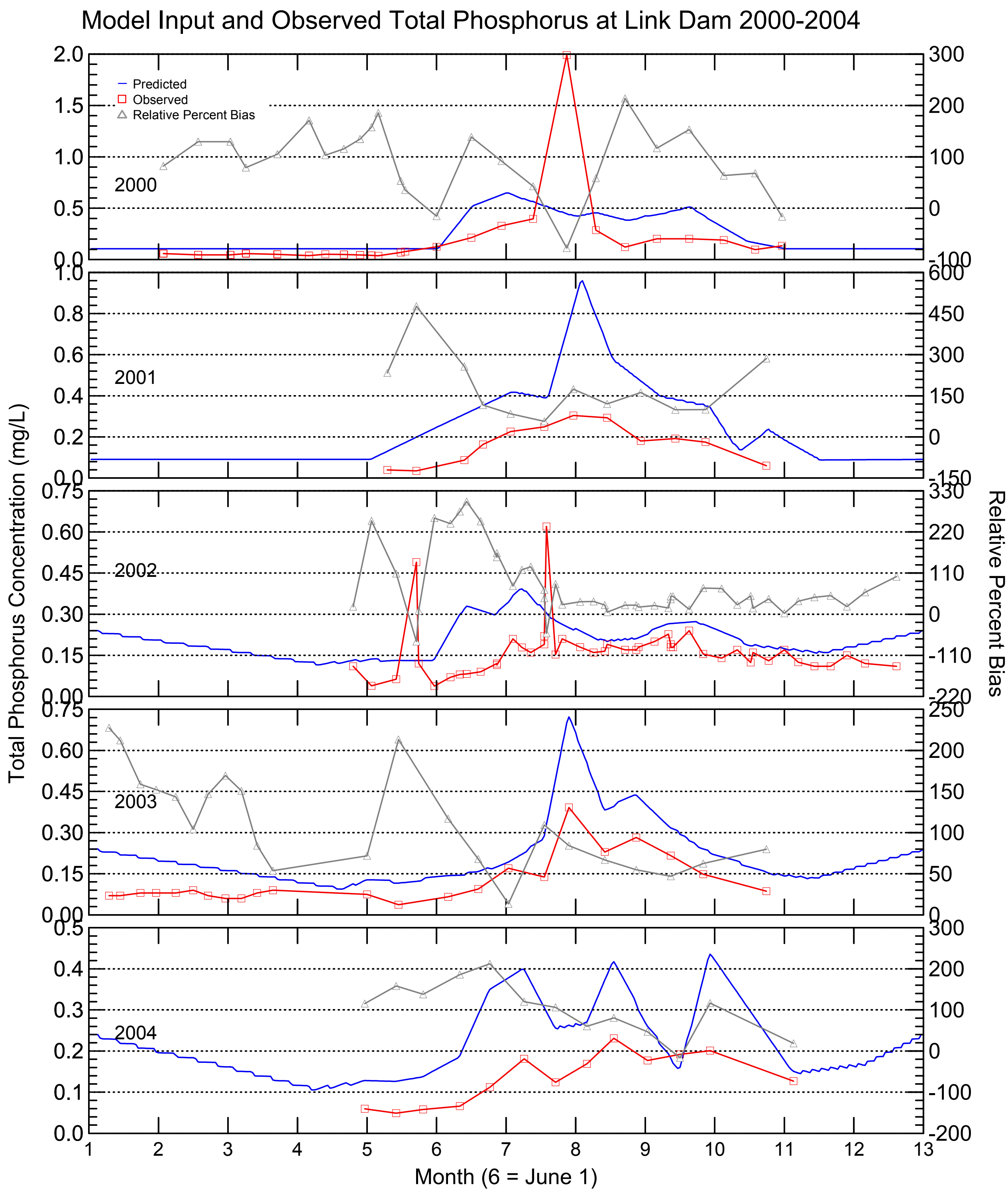


Figure 5. Comparison of daily model input (predicted) and observed total phosphorus (TP) concentrations at Link Dam (river mile 253.88) for the years 2000-2004. Also shown is the relative percent bias (RPB) of the model input compared to observed data. RPB was calculated as 100*(model input-observed)/observed. Measured concentrations for Link Dam are a combination of two Upper Klamath Lake stations: Freemont Bridge and Pelican Marina.

Predicted and Observed Total Nitrogen at Iron Gate Dam 2001-2004

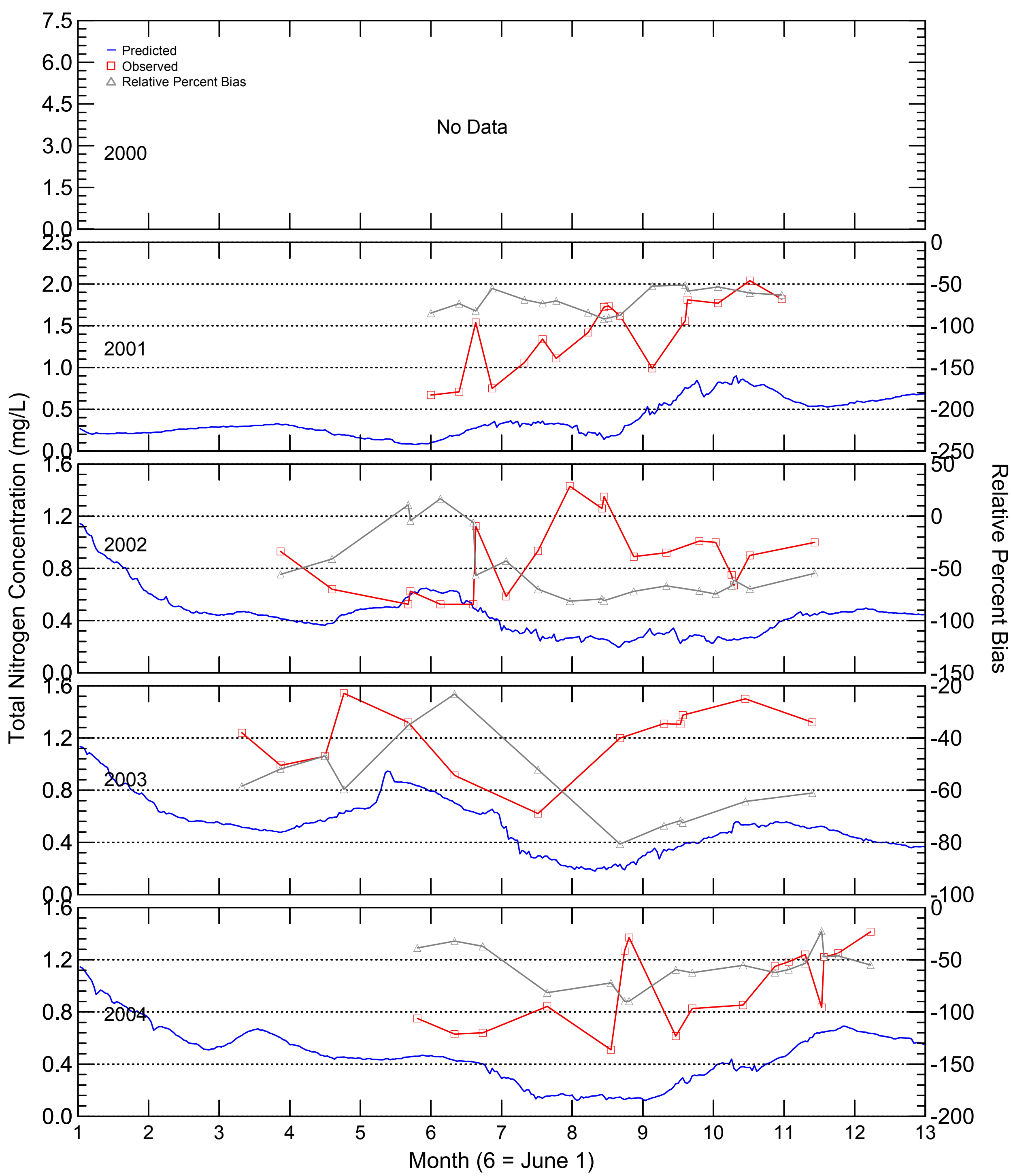


Figure 6. Comparison of daily predicted and observed total nitrogen (TN) concentrations in the Klamath River at Iron Gate Dam for the years 2001-2004. Also shown is the relative percent bias (RPB) of the predicted compared to observed data. RPB was calculated as 100*(predicted-observed)/observed.

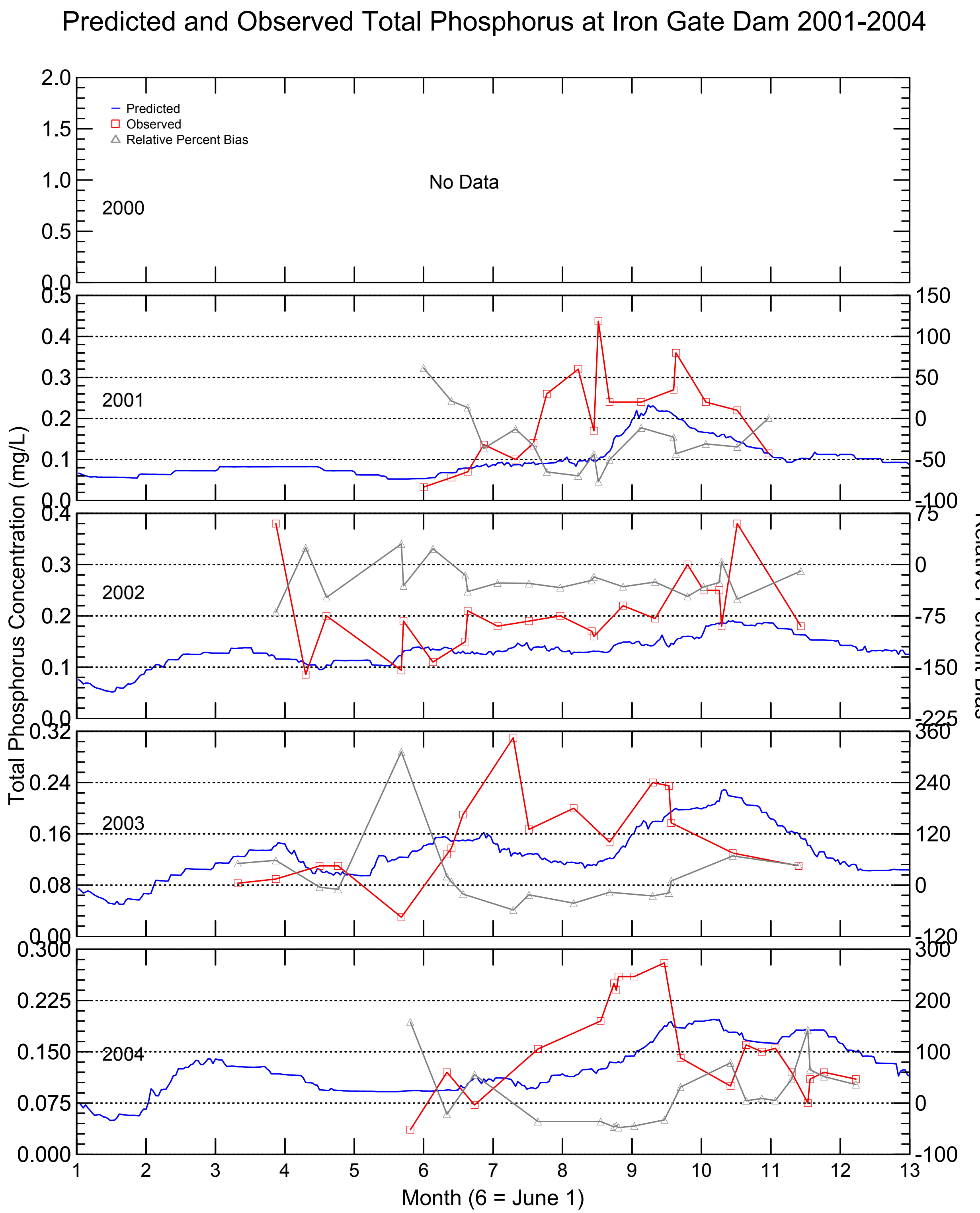


Figure 7. Comparison of daily predicted and observed total phosphorus (TP) concentrations in the Klamath River at Iron Gate Dam for the years 2001-2004. Also shown is the relative percent bias (RPB) of the predicted compared to observed data. RPB was calculated as 100*(predicted-observed)/observed.

Longitudinal patterns

To examine how the model characterized longitudinal patterns in discharge, total nitrogen (TN) concentration, total phosphorus (TP) concentration, total organic carbon concentrations, and chlorophyll *a* concentrations, we constructed box plots for each site and year in which there were field data collected (Figures 8-15). Each box plot presents data for the 13 most commonly sampled sites in the mainstem Klamath River. Boxes are shown only for those sites with five or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. The whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while the individual points shown are outliers. Although the boxes are adequate for evaluating trends in model prediction versus observed values, they do not always provide a useful longitudinal comparison of the parameters. For example, because the days on which samples were collected varied between sites, a site that was sampled monthly from February through November might show a larger range of concentrations than a site sampled biweekly from July through September. However, when sampling dates in a given year were consistent among stations we discuss the longitudinal patterns for those stations and years.

Nutrients

Nitrogen

Overall, the PacifiCorp model poorly predicted TN dynamics in the Klamath River. Predicted TN concentrations matched the observed data poorly and showed consistent bias in the prediction of spatial (longitudinal) trends. In particular:

1. The model outputs indicated that TN concentrations were substantially lower below J.C. Boyle (rm 224.32) and Copco/Iron Gate (rm 190.54) reservoirs than at sites immediately upstream (rm 227.57 and rm 203.6, respectively). In contrast, field samples showed either that no such decrease occurred (2000 and 2004) or that the decrease was minor (2002 and 2003) resulting in a large under-prediction of TN (Figure 8).

2. The model outputs indicated that TN concentrations remain essentially unchanged from Iron Gate Dam (rm 190.54) to the Klamath estuary (rm 5.28). In contrast, field samples showed that nitrogen concentrations typically decrease substantially between those two sites (Figure 8).

These patterns are also visible in the relative percent bias (RPB) for TN (Figure 9 and Table 2). Within each year, graphs of RPB for TN show a U-shaped pattern, with Iron Gate Dam at the bottom of the U (the most negative RPB). RPB typically decreases from Link Dam (rm 253.88) to Iron Gate Dam (rm 190.54), and then rises from there to Turwar Creek (rm 5.28). For example, in the year 2002, the median (50th percentile) RPB for TN was 1.5% at Link Dam, -64% at Iron Gate Dam, and 27% at Turwar (Table 2).

Aside from the lack of model agreement with observed nitrogen data for the longitudinal trend, within-site comparisons of predicted vs. observed values indicate that for many of the stations below Keno Dam the entire distribution of predicted data do not overlap the observed data (Figure 8). This is further illustrated by the distribution of RPB (Figure 9; Table 2), where often the entire distribution (box) is negative (or less than 0% bias). Such skewing of relative prediction error is indicative of structural bias in the model; whereas the error for an unbiased prediction would be expected to show both positive and negative values (i.e., the box would straddle the 0% RPB line).

Possible misspecification of model coefficients or structure appears to bias the magnitude of predicted trends as well as the direction of the predicted trend.

<u>Phosphorus</u>

Comparison of model predictions to measured data for TP shows a similar overall pattern to TN, though it is not as pronounced and longitudinal trends are less consistent (Figure 10). There is a general trend of decreasing RPB from Link Dam to Iron Gate, then increasing from Iron Gate downstream to Turwar Creek. A fairly consistent exception to the trend is river mile 220.2 above the J.C. Boyle Powerhouse where TP concentrations were consistently over-predicted relative to the sites immediately upstream and downstream. This same patterns is evident for TN only in 2004 (Figure 9), though it is of a much lower magnitude than TP. The cause for this is unclear but it could be that the model assigns too high a phosphorus concentration to the high-volume springs that enter the Klamath River in that reach.

Also note that the skewed TP box plots for 2004, especially for Klamath River above the Shasta River (rm 177.52) and Klamath River above the Scott River (rm 143.86), are likely due to a higher frequency of sampling in August of 2004. During that time, four to five samples were taken between 8/23/2004 and 9/1/2004 as part of a special study of the Iron Gate pulse flow.

Overall, bias in predicted versus observed data for TP was better than that for TN, with the distribution of predicted and observed data often overlapping (Figure 10). However, specific evaluation of observed versus predicted values shows poor agreement in many cases (Figure 11). The median RPB was, for example, often greater than +/- 25%.

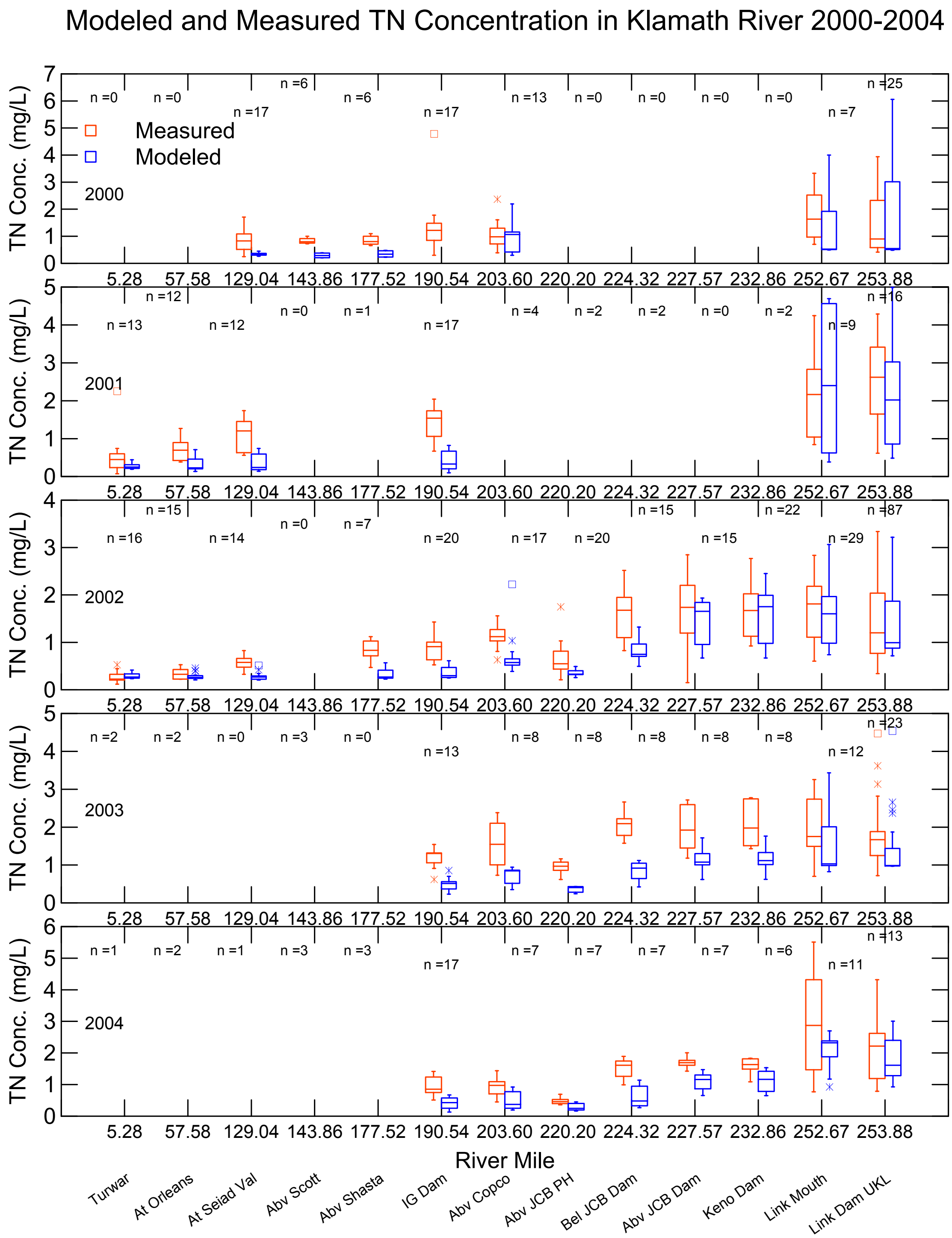


Figure 8. Box plots comparing predicted (modeled) and observed (measured) total nitrogen (TN) concentrations at mainstem Klamath River sites for the years 2000-2004. N is the number of days sampled for each site and year. Boxes are shown only for sites with five or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. The whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while individual points shown are outliers. Note: the left box in each pair is measured data; the right box is modeled data.

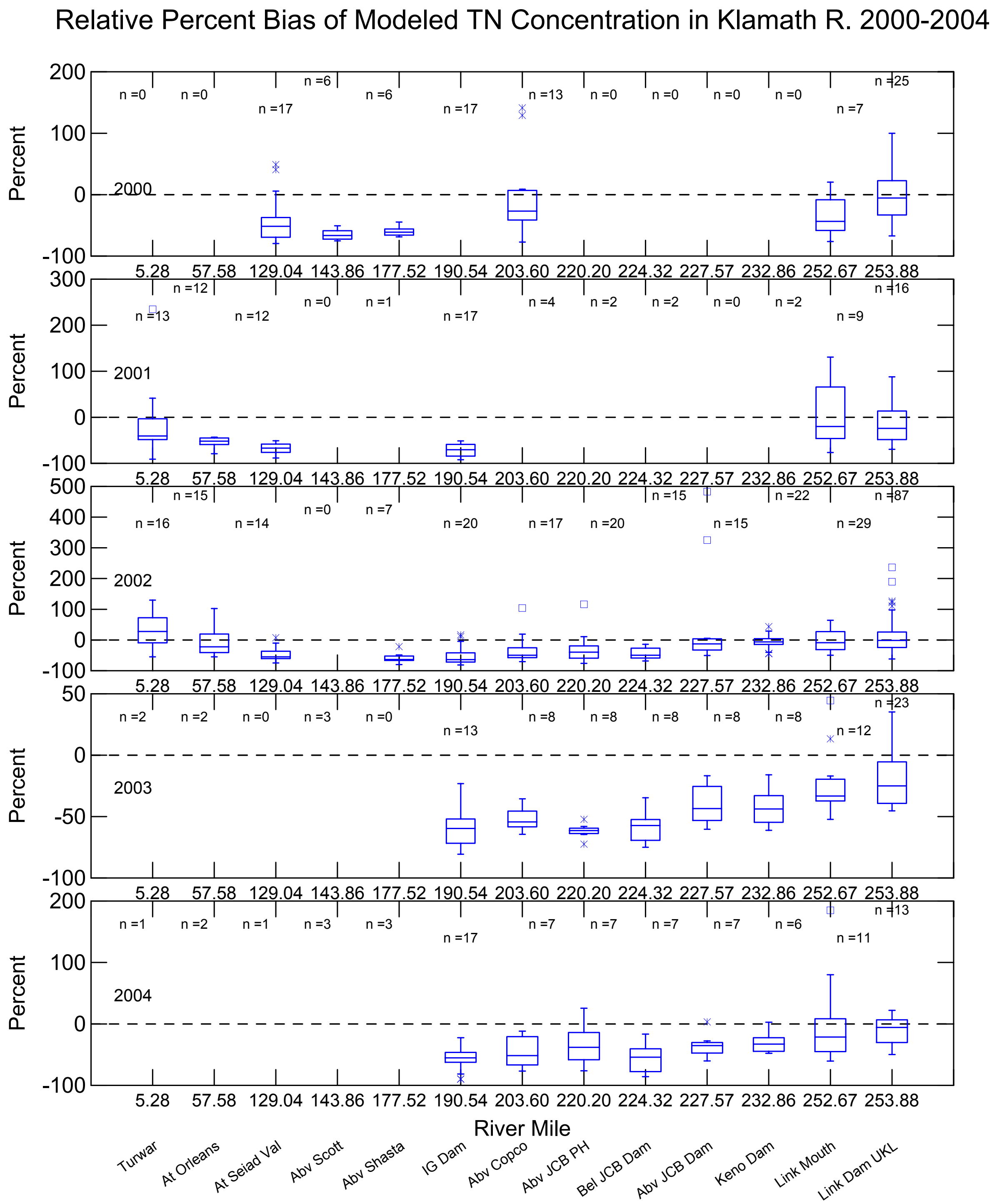


Figure 9. Box plots showing the relative percent bias (RPB) of modeled vs. measured total nitrogen (TN) concentrations at mainstem Klamath River sites for the years 2000-2004. RPB was calculated as 100*(modeled-measured)/measured. N is the number of days sampled for each site and year. Boxes are shown only for sites with five or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. Whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while individual points shown are outliers. Note that the y-axis scale is not constant between years.)

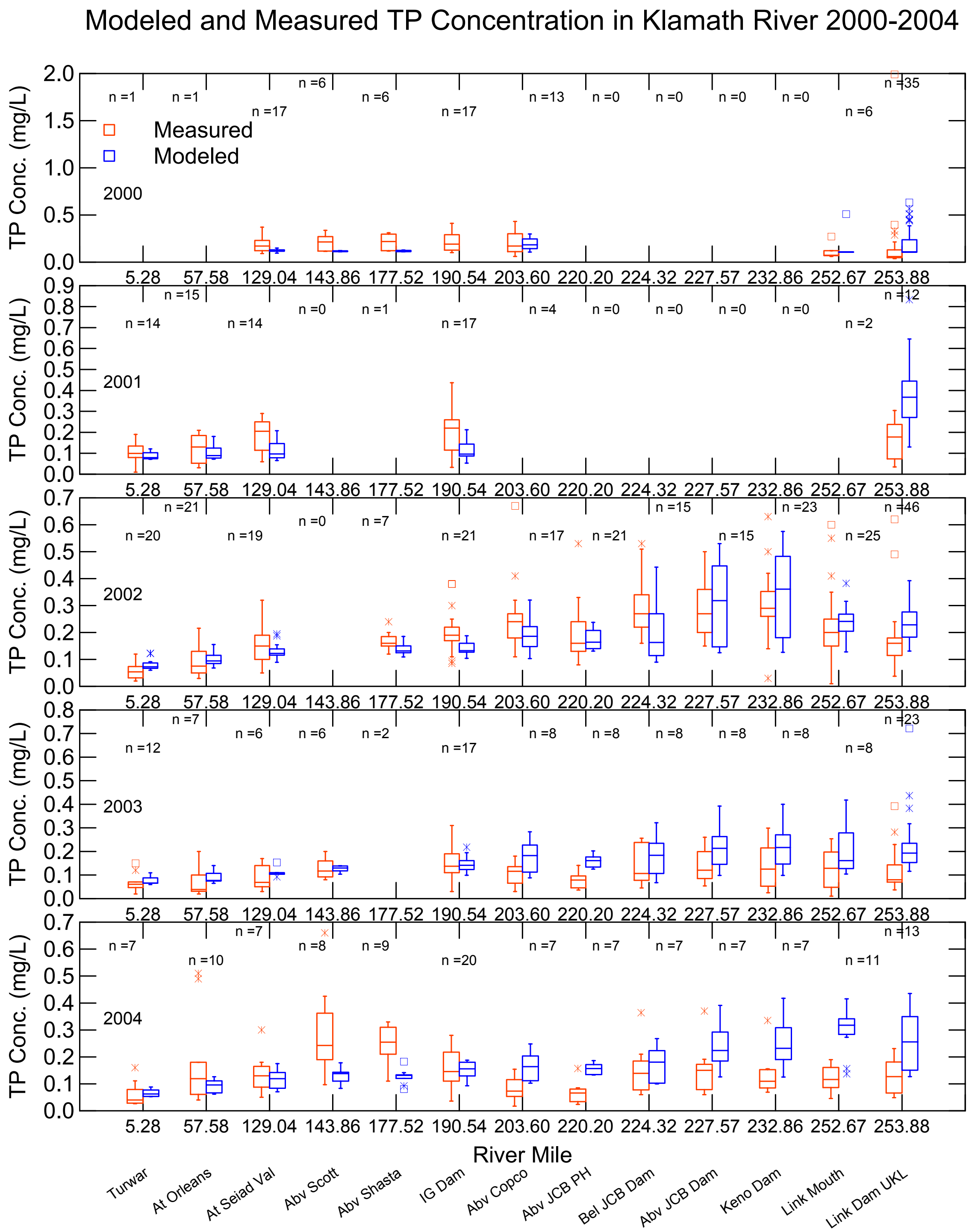


Figure 10. Box plots comparing predicted (modeled) and observed (measured) total phosphorus (TP) concentrations at mainstem Klamath River sites for the years 2000-2004. N is the number of days sampled for each site and year. Boxes are shown only for sites with five or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. Whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while individual points shown are outliers. Note that y-axis scale is not constant between years.

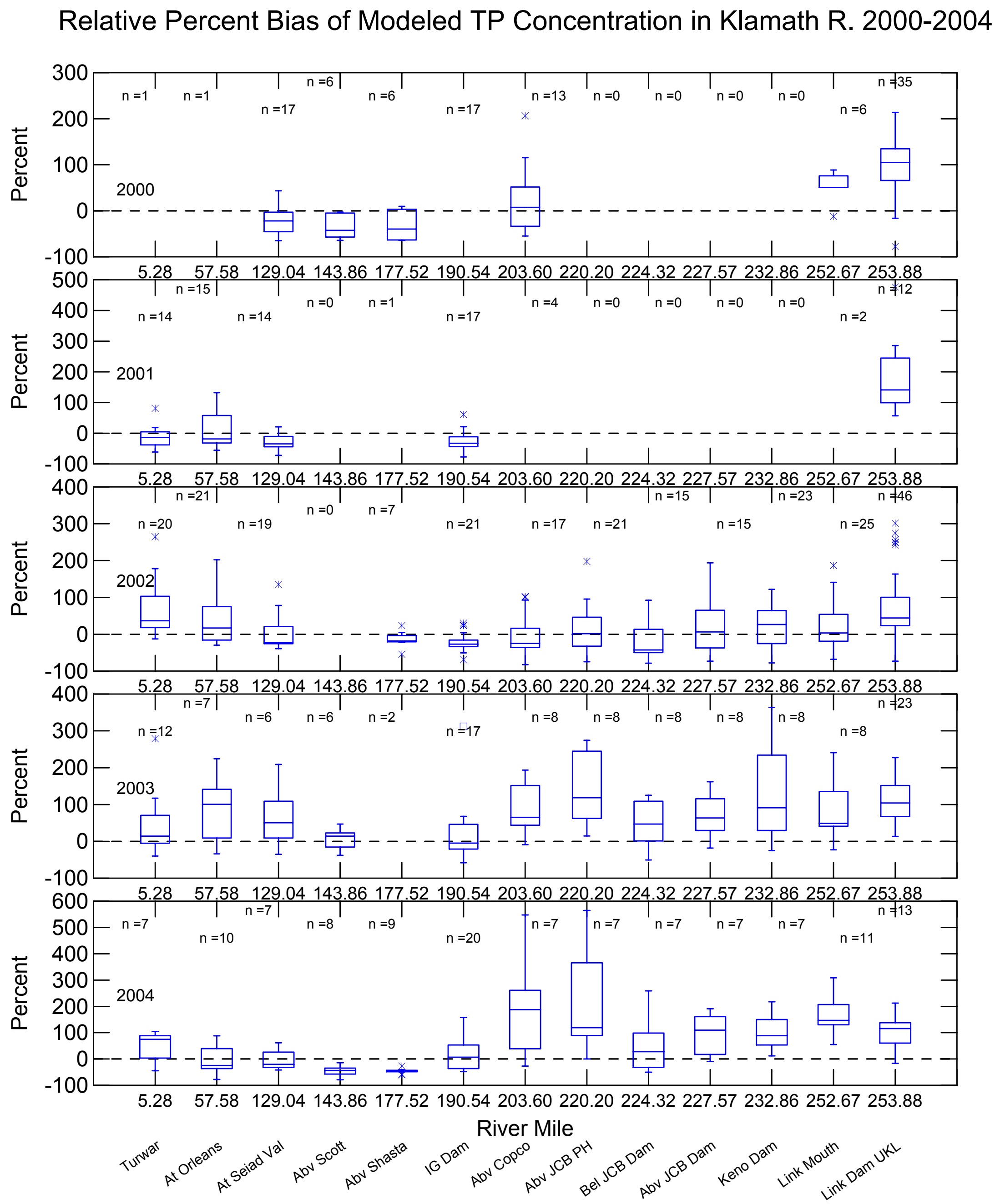


Figure 11. Box plots showing the relative percent bias (RPB) of modeled vs. measured total phosphorus (TP) concentrations at mainstem Klamath River sites for the years 2000-2004. RPB was calculated as 100*(modeled-measured)/measured. N is the number of days sampled for each site and year. Boxes are shown only for sites with five or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. Whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while individual points shown are outliers. Note: to make figure more legible, maximum value for the y-axis was constrained in 2001 (excluding two high points at river mile 5.28), 2002 (excluding one high value each at 232.86 and 252.67), and 2003 (excluding one high point at 252.67). Note that y-axis scale is not constant between years.

Table 2. Relative percent bias (RPB) of predicted vs. observed total nitrogen (TN) and total phosphorus (TP) concentrations at mainstem Klamath River sites for the years 2000-2004. RPB was calculated as 100*(modeled-measured)/measured. N is the number of days sampled for each site and year. Only sites with five or more samples in a year are shown. Note: additional sites are shown in this table (mostly from Iron Gate to estuary) that are not shown in the figures above; these were sampled less frequently and only the most consistent stations are shown in the figures.

			Total Nitrogen				**Total Phosphorus**			
				Relative Percent Bias				**Relative Percent Bias**		
				Percentile				Percentile		
Year	**River Mile**	**Short Name**	N	25th	50th	75th	N	25th	50th	75th
2000	253.88	Link Dam UKL	25	-33.2	-5.5	22.7	35	65.7	105.0	134.7
2000	252.67	Link Mouth	7	-58.3	-43.4	-8.3	6	50.6	50.6	69.6
2000	203.60	Abv Copco	13	-41.4	-26.9	7.0	13	-33.6	7.4	51.5
2000	177.52	Abv Shasta	6	-65.6	-61.1	-56.3	6	-62.9	-39.6	-1.9
2000	143.86	Abv Scott	6	-72.3	-66.6	-59.3	6	-56.6	-42.5	-11.3
2000	129.04	At Seiad Valley	17	-69.5	-51.6	-37.3	17	-45.3	-22.0	-3.2
2001	253.88	Link Dam UKL	16	-43.9	-24.0	9.2	12	99.4	141.3	239.2
2001	252.67	Link Mouth	9	-46.0	-19.9	65.8	0			
2001	190.54	IG Dam	17	-84.1	-70.2	-58.6	17	-43.6	-33.1	-11.5
2001	129.04	At Seiad Valley	12	-76.2	-66.9	-60.2	14	-43.7	-34.7	-11.2
2001	99.04	Above Clear	12	-71.8	-64.4	-57.0	12	-49.7	-35.8	-9.6
2001	57.58	At Orleans	12	-59.0	-51.7	-45.3	15	-31.7	-18.5	57.9
2001	39.50	Martins Ferry	12	-54.3	-39.0	12.2	12	-36.1	-12.6	82.0
2001	5.28	Turwar	13	-48.3	-40.4	-3.2	14	-24.7	-6.8	16.3
2002	253.88	Link Dam UKL	87	-24.4	-1.6	25.8	46	23.5	44.0	95.5
2002	252.67	Link Mouth	29	-31.2	-8.7	27.3	25	-15.0	9.0	55.9
2002	232.86	Keno Dam	22	-13.9	-6.0	3.2	23	-22.1	27.3	65.0
2002	227.57	Abv JCB Dam	15	-32.6	-12.7	4.0	15	-37.5	6.2	65.1
2002	224.32	Bel JCB Dam	15	-58.5	-49.4	-26.5	15	-50.0	-42.9	13.2
2002	220.20	Abv JCB PH	20	-59.2	-39.6	-19.5	21	-32.4	1.5	46.1
2002	209.16	Stateline	13	-47.2	-26.3	-5.1	13	-44.8	-10.2	97.8
2002	203.60	Abv Copco	17	-57.3	-49.8	-25.4	17	-36.1	-25.0	15.9
2002	190.54	IG Dam	20	-71.6	-64.0	-42.4	21	-33.5	-26.9	-15.7
2002	177.52	Abv Shasta	7	-66.4	-63.5	-52.4	7	-20.6	-18.2	-3.8
2002	129.04	At Seiad Valley	14	-59.5	-54.6	-37.3	19	-25.9	-22.5	20.8
2002	99.04	Above Clear	12	-62.9	-46.4	-24.1	14	-27.9	-14.9	-10.1
2002	57.58	At Orleans	15	-41.0	-22.1	19.7	21	-15.8	17.1	74.8
2002	43.33	Abv Trinity	17	-36.4	-19.6	10.7	15	-7.6	14.9	41.1
2002	39.50	Martins Ferry	11	-9.9	19.4	229.8	12	0.4	8.3	41.9
2002	5.28	Turwar	16	-6.6	27.7	69.7	20	18.9	36.9	96.0
2003	253.88	Link Dam UKL	23	-39.3	-25.0	-5.4	23	67.3	104.1	151.6
2003	252.67	Link Mouth	12	-36.9	-33.2	-20.8	8	44.3	56.7	215.0
2003	232.86	Keno Dam	8	-52.3	-43.8	-34.1	8	31.1	91.3	182.5
2003	227.57	Abv JCB Dam	8	-51.8	-43.5	-28.0	8	35.6	63.5	106.1
2003	224.32	Bel JCB Dam	8	-67.0	-57.2	-53.0	8	14.0	46.9	107.1
2003	220.20	Abv JCB PH	8	-63.4	-61.4	-60.1	8	62.8	118.3	243.5
2003	203.60	Abv Copco	8	-58.4	-54.3	-48.1	8	43.9	65.2	130.8
2003	190.54	IG Dam	13	-71.7	-59.7	-51.9	17	-20.9	-4.8	46.1
2003	143.86	Abv Scott	0				6	-8.2	14.2	20.8
2003	129.04	At Seiad Valley	0				6	19.2	50.5	94.6

			Total Nitrogen				Total Phosphorus			
			Relative Percent Bias				Relative Percent Bias			
			Percentile				Percentile			
Year	River Mile	Short Name	N	25th	50th	75th	N	25th	50th	75th
2003	57.58	At Orleans	0				7	9.0	100.6	141.4
2003	43.33	Abv Trinity	0				12	-5.6	11.7	40.1
2003	39.50	Martins Ferry	0				9	-29.4	-8.2	18.6
2003	5.28	Turwar	0				12	0.3	14.0	63.5
2004	253.88	Link Dam UKL	13	-30.4	-5.5	6.6	13	60.2	115.5	138.0
2004	252.67	Link Mouth	11	-44.9	-21.3	8.3	11	130.3	146.4	207.0
2004	232.86	Keno Dam	6	-43.6	-32.9	-23.2	7	53.0	88.7	149.9
2004	227.57	Abv JCB Dam	7	-47.4	-35.1	-30.3	7	17.0	109.7	161.0
2004	224.32	Bel JCB Dam	7	-77.6	-54.0	-40.4	7	-31.9	27.7	98.7
2004	220.20	Abv JCB PH	7	-58.1	-38.2	-14.1	7	89.2	119.0	365.9
2004	203.60	Abv Copco	7	-66.8	-51.4	-20.7	7	38.9	187.4	261.2
2004	190.54	IG Dam	17	-62.4	-55.3	-46.3	20	-36.1	6.9	52.5
2004	177.52	Abv Shasta	0				9	-48.6	-47.5	-42.8
2004	143.86	Abv Scott	0				8	-52.6	-43.7	-37.2
2004	129.04	At Seiad Valley	0				7	-32.1	-20.3	26.2
2004	57.58	At Orleans	0				10	-36.0	-25.1	30.5
2004	43.33	Abv Trinity	0				5	-38.3	4.0	56.8
2004	5.28	Turwar	0				7	3.6	75.1	88.7

Total Organic Carbon

Calculated TOC concentrations from model outputs (see above) were compared to measured data from samples collected in the field (Figures 12 and 13). With the exception of 2004, the Link Dam boundary conditions were typically underestimated although overlap in the predicted versus observed values was also demonstrated (Figure 12). Overall, however, the model substantially underestimated TOC at subsequent downstream locations, often by as much as an order of magnitude (Figure 12). In addition, longitudinal boxplots show the same upstream to downstream U-shaped pattern as for TN and TP, with differences between modeled and measured data typically greatest at Iron Gate Dam (Figures 12 and 13). For instance, measured TOC values at Iron Gate Dam were typically in the range of 5 to 10 mg/L, whereas the model typically predicted values of 0.1 to 0.5 mg/L (Figure 12) with relative percent bias almost always greater than -90%.

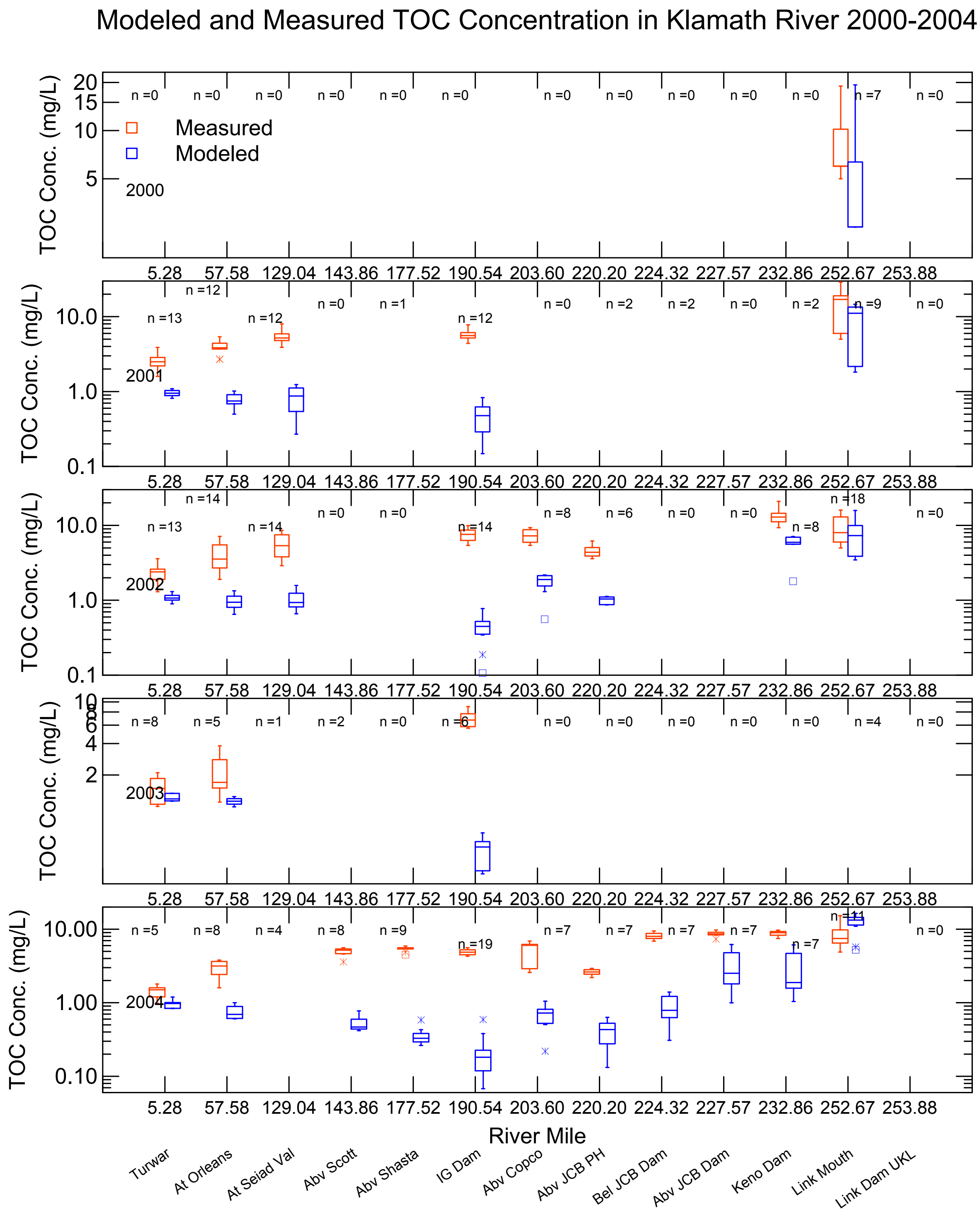


Figure 12. Box plots comparing predicted (modeled) and observed (measured) total organic carbon (TOC) concentrations at mainstem Klamath River sites for the years 2000-2004. TOC was calculated from model outputs as 0.45*(organic matter + biochemical oxygen demand + algae). N is the number of days sampled for each site and year. Boxes are shown only for sites with five or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. Whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while individual points shown are outliers. Note that y-axis scale is logged and is not constant between years.

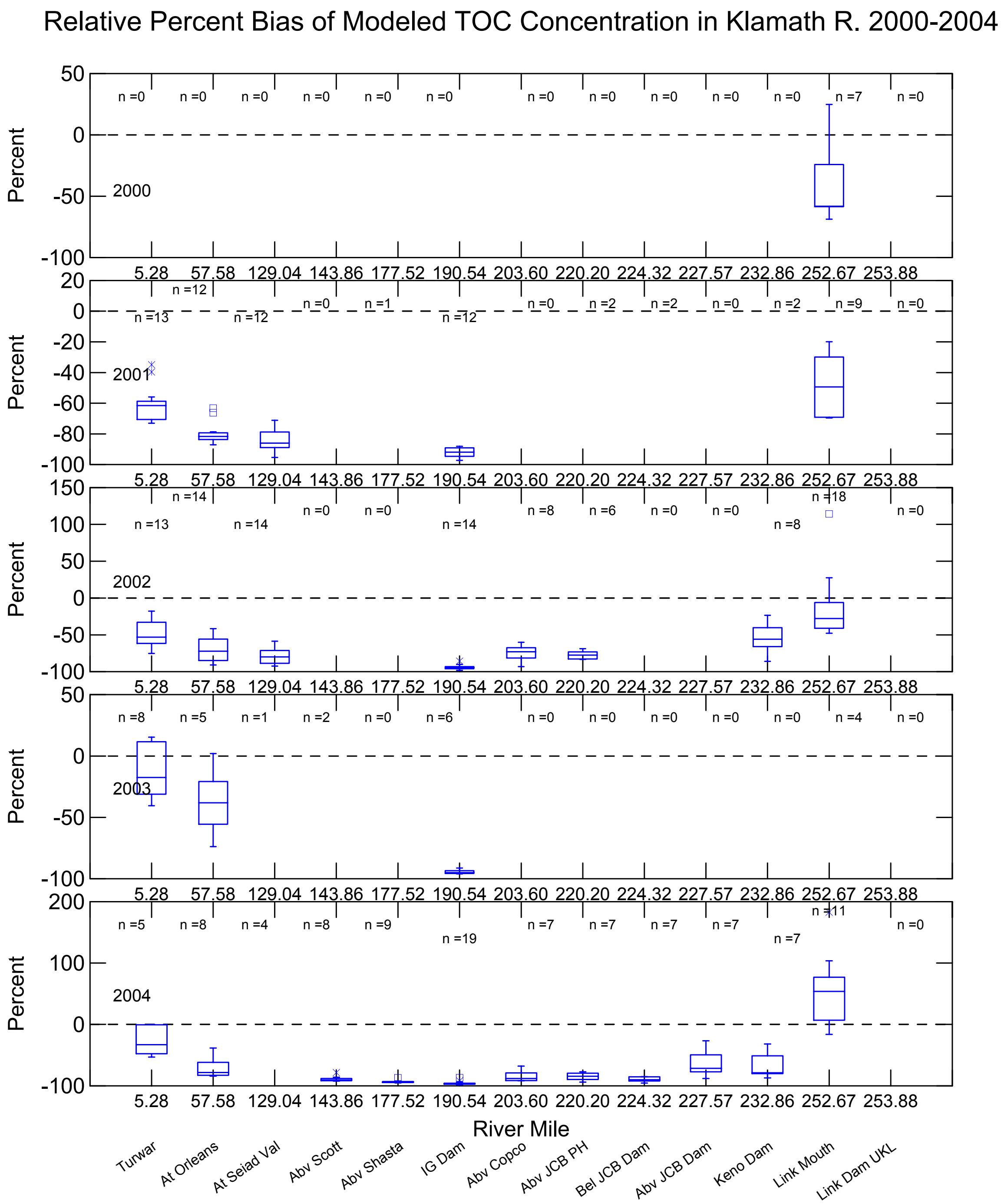


Figure 13. Box plots showing the relative percent bias (RPB) of modeled versus measured total organic carbon (TOC) concentrations at mainstem Klamath River sites for the years 2000-2004. TOC was calculated from model outputs as 0.45*(organic matter + biochemical oxygen demand + algae). RPB was calculated as 100*(modeled-measured)/measured. N is the number of days sampled for each site and year. Boxes are shown only for sites with five or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. Whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while individual points shown are outliers. Note that y-axis scale is not constant between years.

Chlorophyll a

The model typically substantially over-estimated chlorophyll *a*, often by an order of magnitude or more (Figures 14 and 15). The differences between modeled and measured chlorophyll *a* follow a different and more complex pattern than TN, TP and TOC. Where the longitudinal boxplots of relative percent bias (RPB) for TN, TP, TOC were U-shaped, with Iron Gate showing the most negative RPB, RPB plots for chlorophyll *a* tended to show a pattern of lower RPB at Link Dam, then generally increasing downstream to Iron Gate, then variable further downstream to Turwar. The sites with the highest RPB are between Keno Dam (rm 232.86) and above Copco (rm 203.6). As with TN concentration, the entire distribution of predicted and observed data often did not overlap (Figure 14). Moreover, the distribution of prediction bias was almost entirely positive (Figure 15).

Organic and inorganic forms of nitrogen and phosphorus

Using 2001 as an example, we investigated the predicted vs. observed concentrations of the various forms of nitrogen and phosphorus. Again, note that since Link Dam is a boundary condition, the comparison is of model input data rather than of a model prediction at this site. At Link Dam, for May through September, model input ammonia concentrations were typically many times lower than observed data, with RPB >-80% (Figure 16). During August to mid-October, model inputs for nitrate+nitrite were orders of magnitude higher than observed data, with RPB over 6000% for most of that period (Figure 16). The model's general trend for organic nitrogen was correct, but the timing of the peaks was off by several months. For phosphorus, the model over-estimated both particulate and orthophosphorus over the entire season (Figure 17). For orthophosphorus, the RPB ranged from approximately 100 to 1100%. For particulate phosphorus, RPB ranged from 30-400%.

At Iron Gate Dam, ammonia concentrations were under-predicted from July though mid-September, with RBB >-50% for most of the period (Figure 18). Nitrate+nitrite was under-predicted for the entire period, with RPB most often in the -20 to -50% range. Organic nitrogen concentrations were dramatically under-predicted over the entire season with RBB often >-80%, accounting for most of the model's under-prediction of total nitrogen. The model predicted orthophosphorus fairly well, with most absolute RPB values less than 30% and no clear directional bias; however, the model dramatically under-estimated particulate phosphorus, with RPB >-80% most of the time (Figure 19). The trends of total nitrogen load bias and total phosphorus loads bias follow concentration bias very closely, as load is driven by both concentration and discharge, and predicted and observed discharges were nearly identical (Figures 18-19).

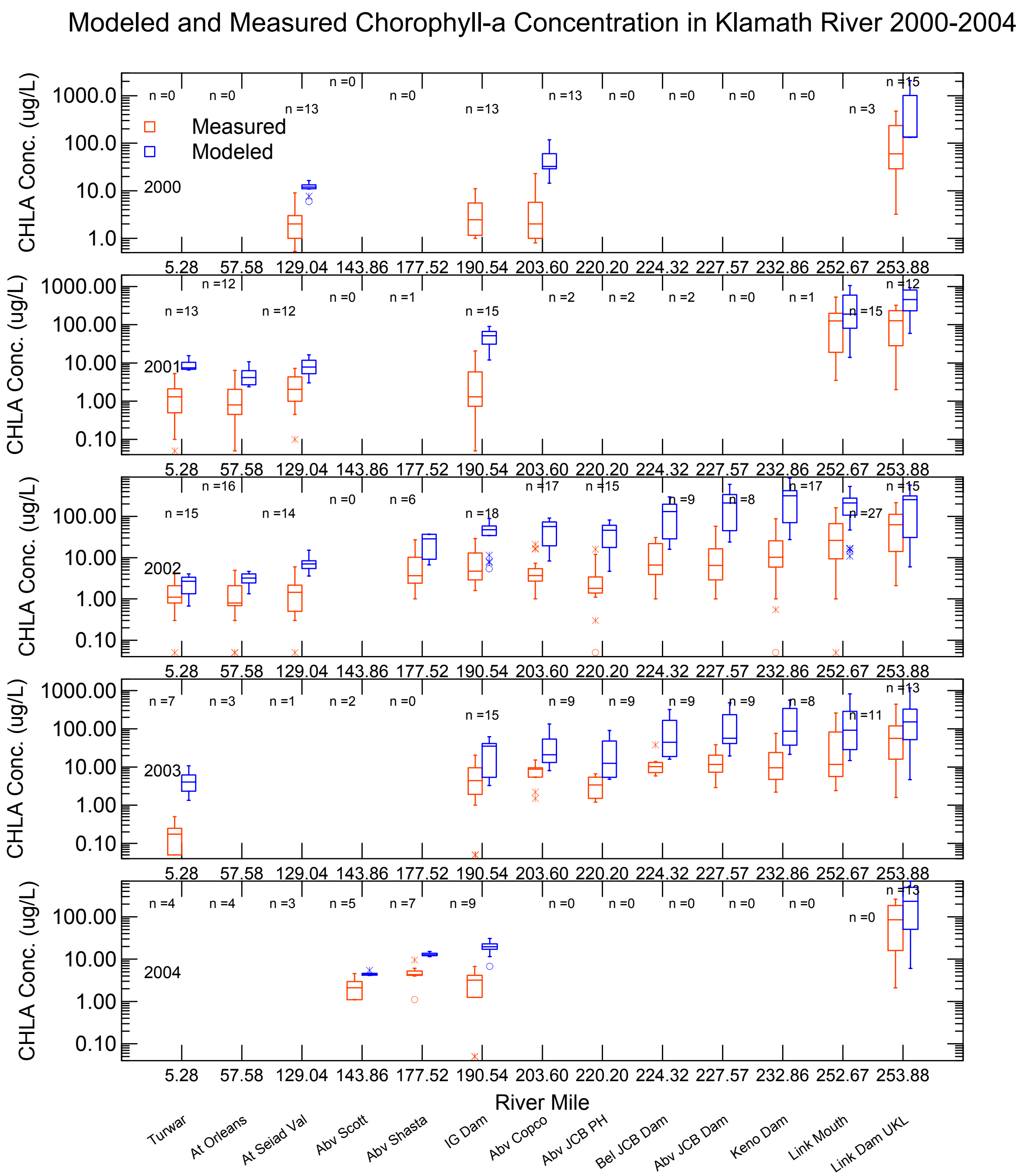


Figure 14. Box plots comparing predicted (modeled) and observed (measured) chlorophyll *a* (CHLA) concentrations at mainstem Klamath River sites for the years 2000-2004. Chlorophyll *a* was calculated from model outputs as 67*algae. N is the number of days sampled for each site and year. Boxes are only shown for sites with 5 or more samples in a year. The line inside each box is the median and the edges of each box are the 25^{th} and 75^{th} percentiles. Whiskers represent data points beyond 1.5 times the interquartile (75^{th}-25^{th}) range, while individual points shown are outliers. Note that y-axis scale is logged and is not constant between years.

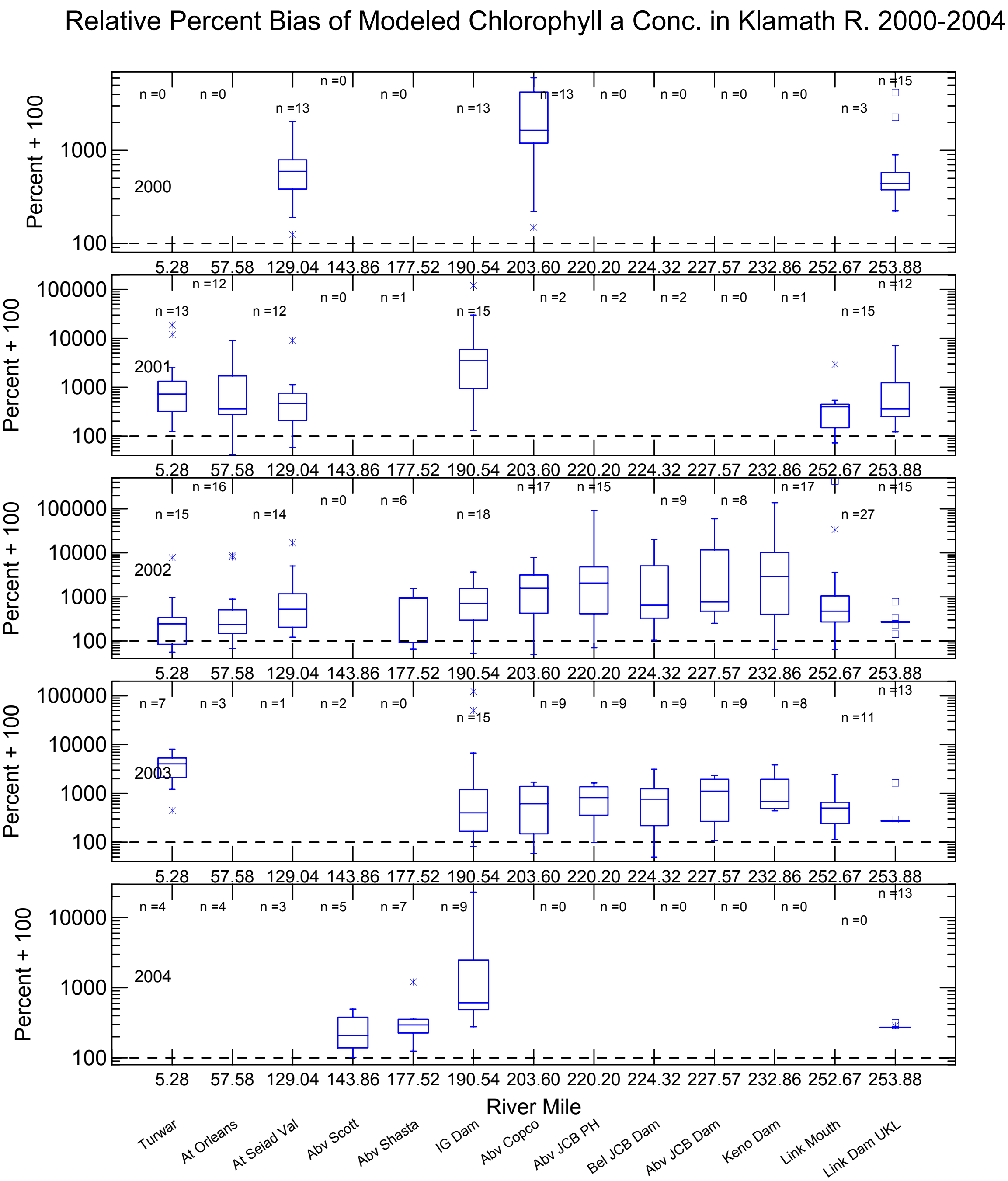


Figure 15. Box plots showing the relative percent bias (RPB) of modeled chlorophyll *a* (CHLA) concentrations, compared to measured chlorophyll *a* concentrations at mainstem Klamath River sites for the years 2000-2004. Chlorophyll *a* was calculated from model outputs as 67*algae. RPB was calculated as 100*(modeled-measured)/measured. N is the number of days sampled for each site and year. Boxes are only shown for sites with 5 or more samples in a year. The line inside each box is the median and the edges of each box are the 25th and 75th percentiles. Whiskers represent data points beyond 1.5 times the interquartile (75th-25th) range, while individual points shown are outliers. Note that y-axis scale is logged and is not constant between years. Also note that all RPB values have been adjusted upwards by 100 so that some slightly negative values could be logged; hence, an adjusted RPB of 100 would mean measured and modeled data are identical.

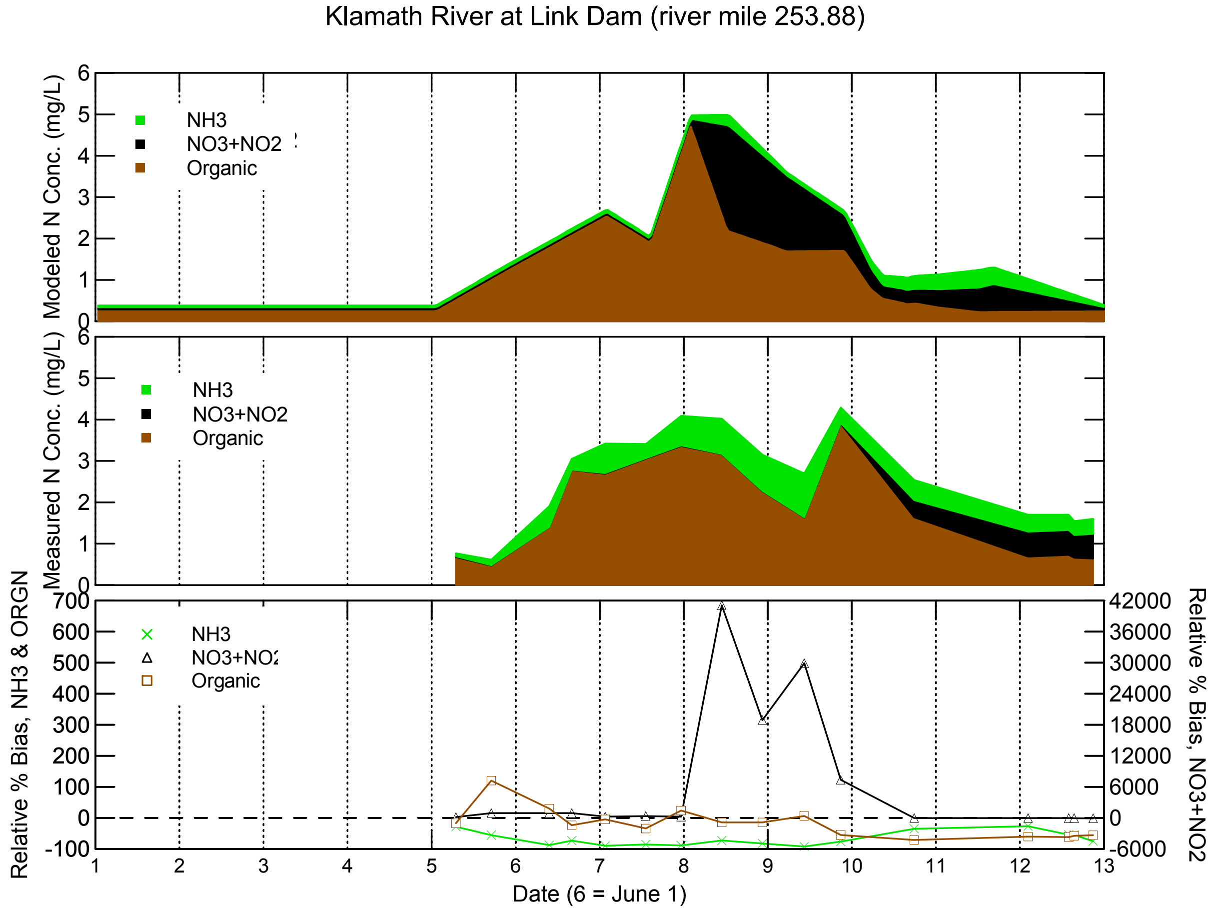


Figure 16. Comparison of predicted and observed values for organic nitrogen (Organic), nitrate+nitrite nitrogen (NO3+NO2), and ammonia nitrogen (NH3) at Link Dam for the year 2001. Also shown is the relative percent bias (RPB) of modeled total nitrogen concentration. RPB was calculated as 100*(modeled-measured)/measured. Measured concentrations for Link Dam are a combination of two Upper Klamath Lake stations: Freemont Bridge and Pelican Marina. Note that the Y-axis for NO3+NO2 is plotted on a different scale than organic nitrogen and NH3. Also note that this graph does not show discharge or load because model outputs for flow at Link Dam are not directly comparable to the Link River USGS gaging station due to their locations relative to diversion canals.

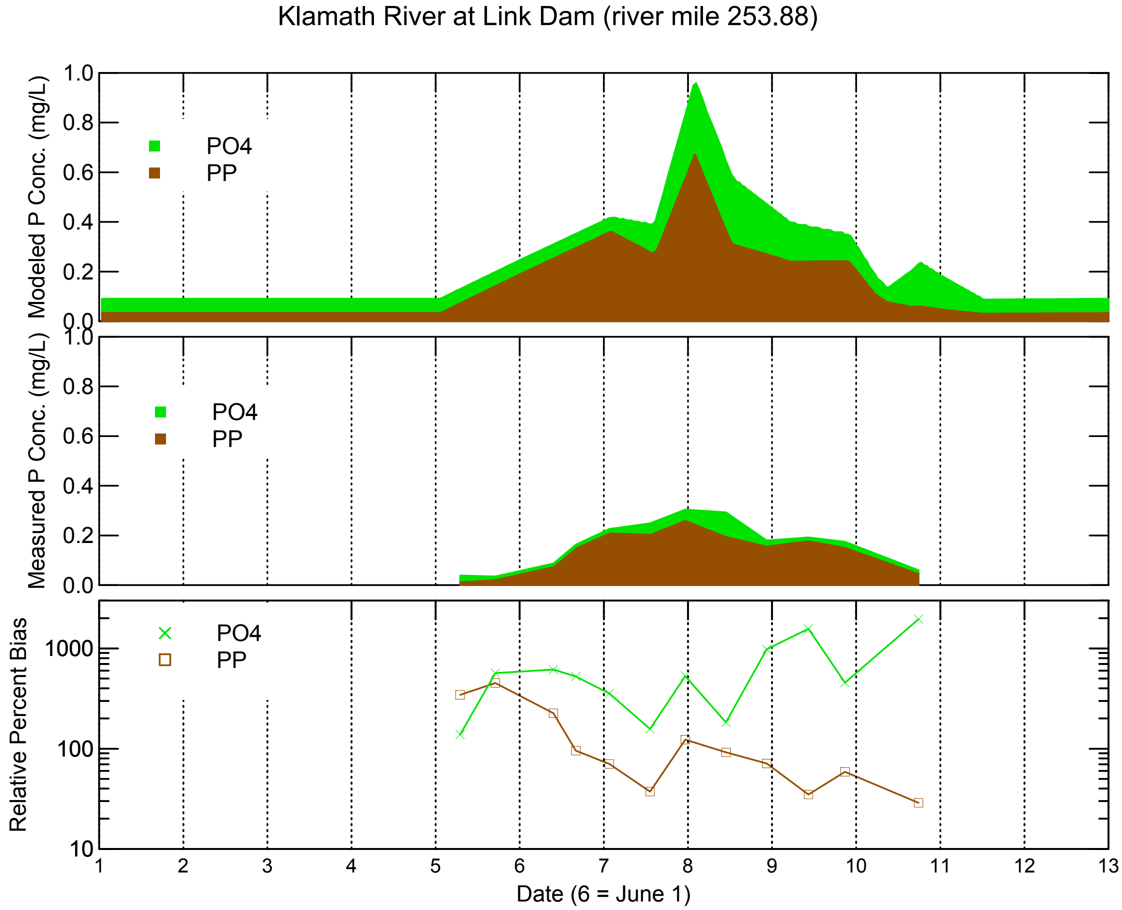


Figure 17. Comparison of predicted and observed values for discharge, particulate phosphorus (PP), orthophosphorus (PO4), total phosphorus (TP) concentration, and TP load at Link Dam for the year 2001. Also shown is the relative percent bias (RPB) of modeled total phosphorus concentration. RPB was calculated as 100*(modeled-measured)/measured. Note that the Y-axis scale for RPB is reversed. Measured concentrations for Link Dam are a combination of two Upper Klamath Lake stations: Freemont Bridge and Pelican Marina. Note that Y-axis for RPB is logged. Also note that this graph does not show discharge or load because model outputs for flow at Link Dam are not directly comparable to the Link River USGS gaging station due to their locations relative to diversion canals.

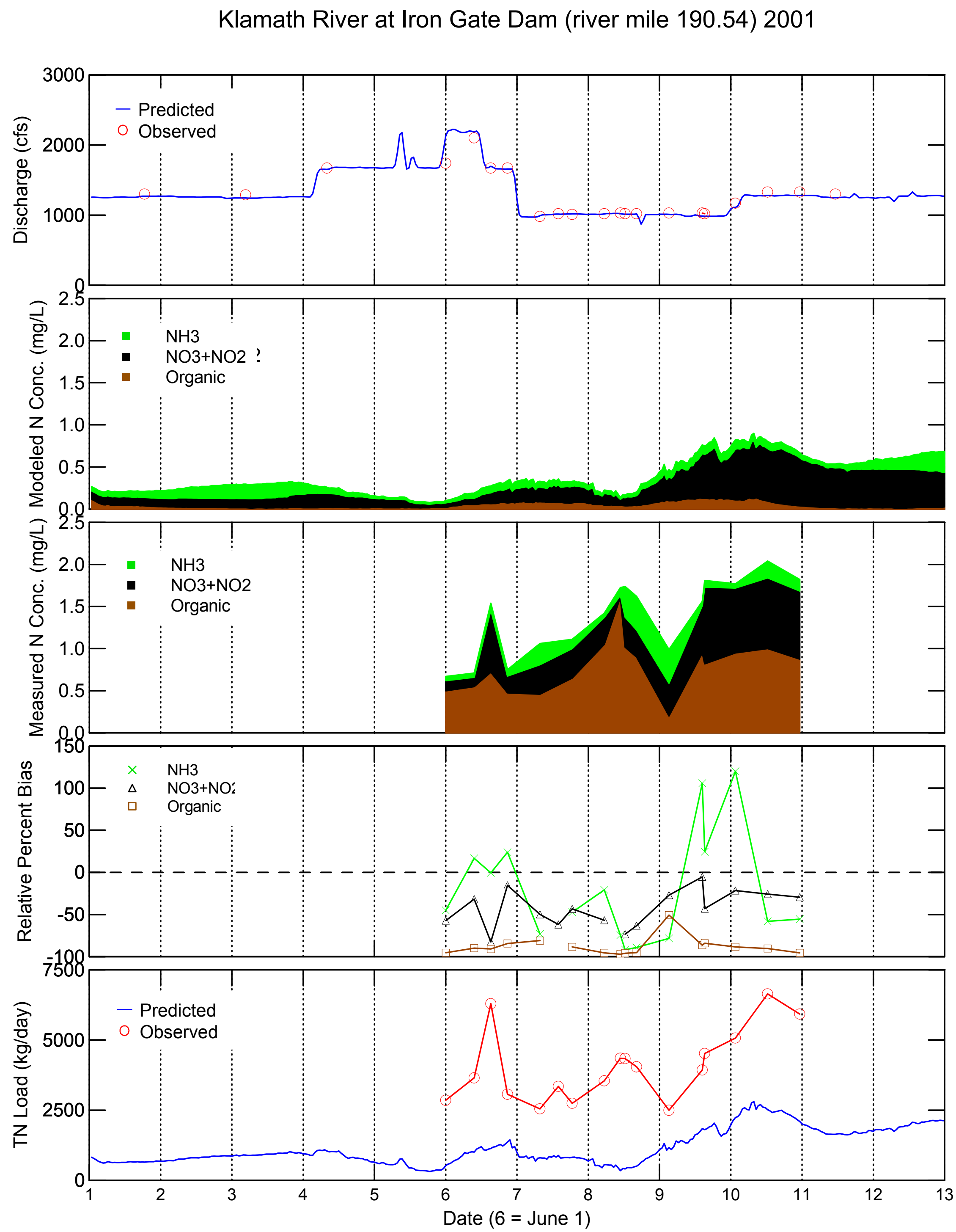


Figure 18. Comparison predicted and observed values for discharge, organic nitrogen (Organic), nitrate+nitrite nitrogen (NO3+NO2), ammonia nitrogen (NH3), total nitrogen (TN) concentration, and TN load in the Klamath River at Iron Gate Dam for the year 2001. Also shown is the relative percent bias (RPB) of modeled total nitrogen concentration. RPB was calculated as 100*(modeled-measured)/measured.

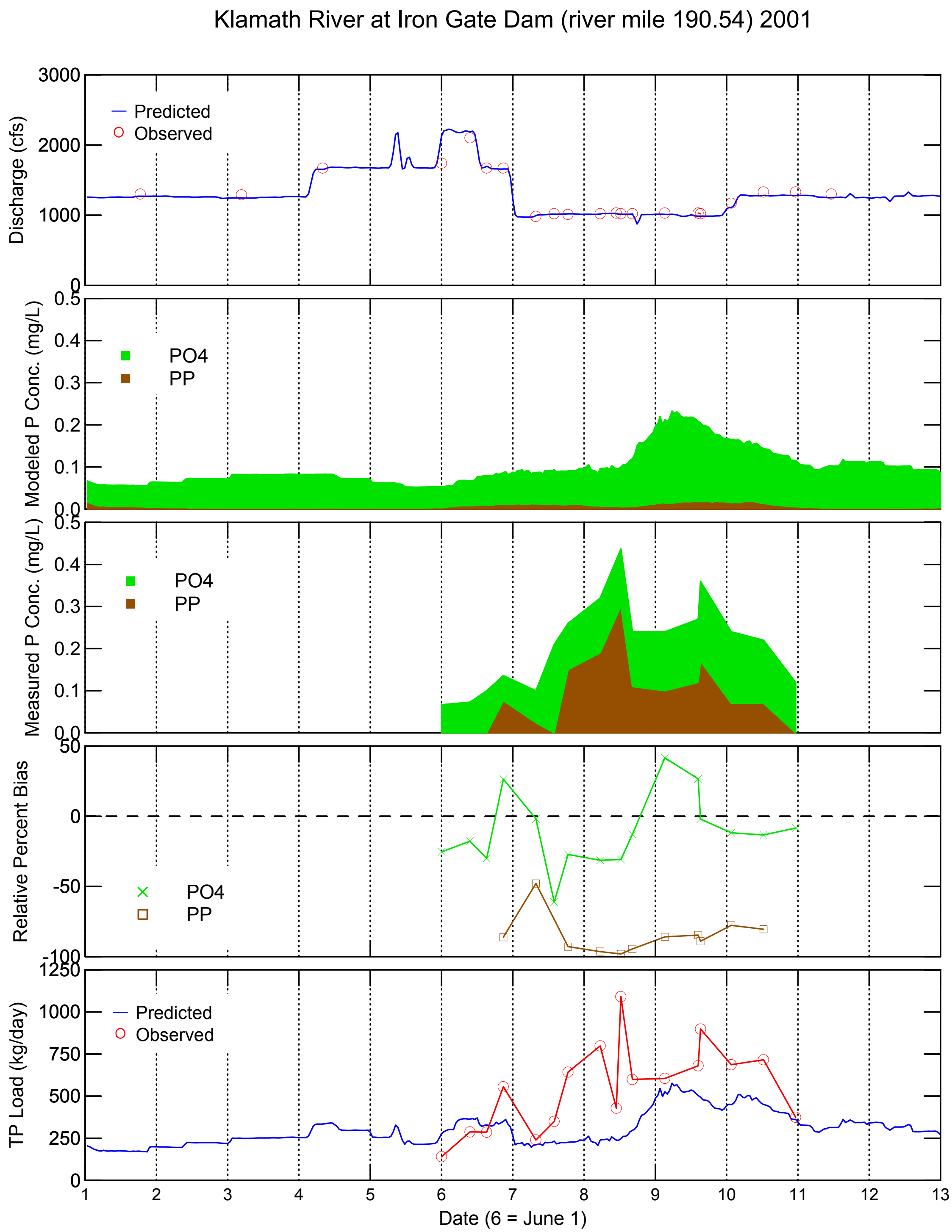


Figure 19. Comparison of predicted and observed values for discharge, particulate phosphorus (PP), orthophosphorus (PO4), total phosphorus (TP) concentration, and TP load in the Klamath River at Iron Gate Dam for the year 2001. Also shown is the relative percent bias (RPB) of modeled total phosphorus concentration. RPB was calculated as 100*(modeled-measured)/measured.

CONCLUSIONS

As discussed in detail above, substantial differences between model predictions and measured data were determined by our analyses. It was not the goal of this study, however, to dissect model mechanics to determine why the model is not predicting observed data for many parameters. Possible reasons that could be explored further include: 1) setting Link Dam boundary conditions for organic matter based on BOD instead of using nitrogen and phosphorus data, 2) not using all available nutrient data for the Link Dam boundary condition, 3) setting settling rates for organic matter too high in the reservoir reaches, and 4) setting organic matter and algae concentrations too high in the tributaries below Iron Gate Dam (Yurok Tribe 2006).

Overall, the model poorly predicts nutrient dynamics in the Klamath River. Not only was the magnitude of predicted nutrient concentrations typically either consistently under- or over-predicted relative to observed data, but the modeled data showed strong consistent spatial bias that was absent in the field data. In particular:

1. The model outputs indicated that total nitrogen and total phosphorus concentrations were substantially lower below J.C. Boyle and Copco/Iron Gate reservoirs than they were at sites immediately upstream. In contrast, field samples showed that either no such decrease occurred or that the decrease was less pronounced than the model predicted.

2. The model outputs suggest that nitrogen concentrations remain essentially unchanged from Iron Gate Dam to the Klamath River estuary. In contrast, field samples show that nitrogen concentrations typically decrease substantially between those sites. It is unclear if the discrepancy is caused by improperly set tributary boundary conditions, inadequate calibration, or other model limitations.

Further, prediction bias in TOC and chlorophyll *a* were substantial, with TOC consistently under-predicted and chlorophyll *a* consistently over-predicted. The entire distribution of predicted and observed data often did not overlap

The degree to which additional calibration could improve the model's performance is unclear at this time. Substantial improvement may require the inclusion of additional processes such as multiple algal groups and nitrogen fixation.

Reliable predictions depend upon an adequately calibrated model and knowledge of residual model uncertainty. The skewed relative prediction errors shown above for the parameters that we analyzed indicate inadequate model calibration and substantial uncertainty.

Given the substantial discrepancies between modeled and measured data, until model performance can be improved, model results for nutrient-dependent parameters (dissolved oxygen, pH, nutrients, phytoplankton, and attached algae) that show substantial bias cannot be used to make objective management decisions.

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ELECTRONIC APPENDICES ON CD

A. Spreadsheet comparing model data and field data, including relative percent bias [filesize: 20.4 MB]

B. MS Access database of PacifiCorp 2000-2004 model outputs for all scenarios. Includes three tables: hourly data, calculated daily data (minimum, maximum, average), and a key to locations. [filesize: 242 MB as zip file, expands to 1.65 GB when unzipped]