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Nutrient Loads in the Lost River and Klamath River Basins, South-Central Oregon and Northern California, March 2012–March 2015

Scientific Investigations Report 2018–5075

U.S. Department of the Interior
U.S. Geological Survey

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2018

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Suggested citation:
Schenk, L.N., Stewart, M.A., and Eldridge, S.L.C., 2018, Nutrient loads in the Lost River and Klamath River Basins, south-central Oregon and northern California, March 2012–March 2015: U.S. Geological Survey Scientific Investigations Report 2018–5075, 55 p., https://doi.org/10.3133/sir20185075.

ISSN 2328-0328 (online)

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Flow rate	
inch per second (in/s)	25.4	millimeter per second (mm/s)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
micron (µm)	0.00003937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
milliliter (mL)	0.03382	ounce, fluid (fl. oz)
liter (L)	33.82	ounce, fluid (fl. oz)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	70.07	cubic foot per second (ft^3/s)
	Mass	
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
kilogram per day (kg/d)	2.205	pound avoirdupois per day (lb/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F = (1.8 \times °C) + 32.$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

AFA	*Aphanizomenon flos-aquae*
AIC	Akaike Information Criterion
AMLE	adjusted maximum likelihood estimation
BO	Biological Opinion
BOD_5	5-day biochemical oxygen demand
Bp	load bias in percent
$CBOD_5$	5-day carbonaceous biochemical oxygen demand
DI	deionized
DOC	dissolved organic carbon
EWI	equal-width-increment
HDPE	high-density polyethylene
MLE	maximum likelihood estimation
MRL	minimum reporting level
N	Nitrogen
NH_3	dissolved ammonia as N
NO_3+NO_2	dissolved nitrate plus nitrite as N
NWQL	National Water Quality Laboratory
ODEQ	Oregon Department of Environmental Quality
ortho-P	dissolved orthophosphate as P
P	Phosphorus
PPCC	probability plot correlation coefficient
QA	quality assurance
R^2	coefficient of determination
Reclamation	Bureau of Reclamation
RPD	relative percent difference
SPCC	Schwarz Posterior Probability Criterion
SRWQL	Sprague River Water Quality Laboratory
TKN	Total Kjelhahl Nitrogen
TMDL	Total Maximum Daily Load
TN	total nitrogen
TP	total phosphorus
TPC	total particulate carbon
TPN	total particulate nitrogen
USGS	U.S. Geological Survey
WY	water year

Nutrient Loads in the Lost River and Klamath River Basins, South-Central Oregon and Northern California, March 2012–March 2015

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Significant Findings

The U.S. Geological Survey and Bureau of Reclamation collected water-quality data from March 2012 to March 2015 at locations in the Lost River and Klamath River Basins, Oregon, in an effort to characterize water quality and compute a nutrient budget for the Bureau of Reclamation Klamath Reclamation Project. The study described in this report resulted in the following significant findings:

- Total phosphorus (TP), total nitrogen (TN), 5-day biochemical oxygen demand (BOD_5), and 5-day carbonaceous biochemical oxygen demand ($CBOD_5$) loads, calculated using the U.S. Geological Survey LOADEST software package at the upper and lower boundaries of the Klamath Reclamation Project, indicated higher loads at the upper boundary on the southern end of Upper Klamath Lake upstream of the Bureau of Reclamation A Canal diversion compared to the lower boundary on the Klamath River downstream of Keno Dam. Accounting for the diversion of loads down A Canal, BOD_5 and $CBOD_5$ loads decreased between these two sites during irrigation season, indicating that the Klamath Reclamation Project is not a large source of oxygen-demanding material and that much of the oxygen demand at study site FMT, the northern boundary of the study area, has been expressed by the time the same water passes through site KRK, the southern boundary of the study area.

- An evaluation of the nutrient balance along the Klamath River flowpath from sites FMT to KRK indicated that, during irrigation season in the 3 years of the study period (March 2012–March 2015), more loads of TP, TN, BOD_5, and $CBOD_5$ were being diverted from the Klamath River than were being added to the Klamath River from the combination of Klamath Straits Drain, regulated point sources along the Klamath River, and internal loading from the bottom sediments in the river. By contrast, during non-irrigation seasons, more loads were added to the Klamath River than were diverted through Ady and North Canals, and this difference primarily was due to additional loads to the river from the Lost River Diversion Channel.

- At the Lost River Diversion Channel, BOD_5 loads were higher during irrigation season than non-irrigation season in all three study years owing to the high concentrations of oxygen-demanding cyanobacterial biomass from the seasonal blooms of *Aphanizomenon flos-aquae* in the Klamath River and Upper Klamath Lake. The difference between the two seasons was particularly large in years 2 and 3, when the low flows of these two drought years resulted in smaller non-irrigation period loads than in year 1. $CBOD_5$ loads also were higher during irrigation season in years 2 and 3 than during non-irrigation season, indicating that the largest oxygen demand was coming from senescence of *Aphanizomenon flos-aquae* cells that are present in the Klamath River during the summer. However, during irrigation season in year 1, $CBOD_5$ loads were lower than in the non-irrigation season, which may indicate that at times high concentrations of ammonia or cellular organic nitrogen leaving Upper Klamath Lake contribute a large nitrogenous oxygen demand as well.

- The smallest loads were computed for the farthest upstream sites in the Lost River Basin, suggesting that the upper Lost River Basin does not contribute substantial loads of TP, TN, BOD_5, and $CBOD_5$ to the Klamath Reclamation Project.

- Median concentrations of BOD_5 and $CBOD_5$ were lowest among the upper Lost River Basin sites and highest at site PPD (however, this comparison is based on only four samples collected at site PPD over the 3-year study). Median concentrations of BOD_5 and $CBOD_5$ also were elevated at sites KSDH (6.60 and 4.70 milligrams per liter [mg/L], respectively) and KSD97 (4.47 and 3.45 mg/L, respectively). The highest maximum BOD_5 and $CBOD_5$ concentrations were reported at the Lost River Diversion Channel (39.0 and 26.5 mg/L, respectively) when water was flowing from the Klamath River toward the Klamath Reclamation Project, and site FMT (25.0 and 23.9 mg/L, respectively), the study site at the southern end of Upper Klamath Lake. Carbonaceous oxygen demand, as represented by $CBOD_5$, typically dominated the composition of the samples at all sites.
- The highest concentrations of dissolved organic carbon were present at sites KSDH (the headworks of Klamath Straits Drain) and KSD97 (Klamath Straits drain before it enters the Klamath River), and PPD (outlet of Tule Lake).
- Median concentrations of TN and TP at the upper Lost River Basin sites in years 1 and 2 were variable, but site MCRV showed a smaller range of values in those years compared to the other upper Lost River Basins sites, and an overall lower median concentration during irrigation seasons in years 1 and 2, suggesting that Gerber Reservoir does not contribute high concentrations of nutrients to the Lost River during irrigation season.
- Total Maximum Daily Load (TMDL) load allocations for TP and TN in Klamath Straits Drain were exceeded in all three study years. BOD_5 load allocations were exceeded in years 1 and 2, but not year 3.
- TMDL load allocations for TP were exceeded in the Lost River Diversion Channel for all 3 years. Load allocations for TN were exceeded in year 1, but not in years 2 and 3. BOD_5 loads were less than the TMDL load allocation for all three study years.
- The dearth of samples collected at the Klamath Straits Drain just downstream of the Lower Klamath National Wildlife Refuge did not allow for direct assessment of the Klamath Straits Drain acting as a nutrient source or sink.
- TP, TN, BOD_5, and $CBOD_5$ loads estimated during the study period likely were smaller than long-term average conditions because of persistent drought conditions in the Upper Klamath Basin. The study results, therefore, fail to characterize loads from the Klamath Reclamation Project to the Klamath River that could be present in typical years, and suggest the need for load assessments during average or above-average streamflow years.

Introduction

Background

Water quality in parts of the Lost River and upper Klamath River is considered impaired with respect to dissolved oxygen, pH, chlorophyll-*a* (algae), and ammonia toxicity (Oregon Department of Environmental Quality, 2017). In 2017, the Oregon Department of Environmental Quality (ODEQ) revised the 2010 Total Maximum Daily Load (TMDL) and Water Quality Management Plans for the Lost River and Upper Klamath Basins to establish water-quality goals for included waterbodies. The ODEQ established load allocations (amount of pollutant that point and nonpoint sources can contribute to the stream without exceeding State water-quality standards) for the TMDL for the Lost River Diversion Channel and Klamath Straits Drain, which represent drainage water to the Klamath River from irrigation lands within the Bureau of Reclamation (Reclamation) Klamath Reclamation Project (hereinafter, "Klamath Project" or "the project"). Reclamation manages water delivery to numerous irrigation districts within the project boundary. Nonpoint source load allocations were established for total phosphorus (TP), total nitrogen (TN), and the 5-day biochemical oxygen demand (BOD_5).Additionally, load allocations for 5-day carbonaceous biochemical oxygen demand ($CBOD_5$) and dissolved inorganic nitrogen were established for nonpoint sources within the Lost River Basin. These load allocations have a direct effect on the Klamath Project because Reclamation has a leading role in the storage, delivery, and management of water in the surrounding areas, and agricultural drains with nonpoint source load allocations originate within Klamath Project boundaries.

In addition to the 2017 TMDL, a Biological Opinion (BO) addressing the effects of Klamath Project operations on endangered suckers and salmon from 2013 to 2023 was issued by the National Marine Fisheries Service and U.S. Fish and Wildlife Service in May of 2013 that required measures to assess and restore habitat for the endangered Lost River (*Deltistes luxatus*) and shortnose (*Chasmistes brevirostris*) suckers (National Marine Fisheries Service and U.S. Fish and Wildlife Service, 2013). The BO specifies improvements within a defined geographic area called the "Lost River Recovery Unit" based on species occurrence in Tule Lake, Clear Lake, and the Lost River, all waterbodies managed by Reclamation for irrigation deliveries.

Purpose and Scope

This study was initiated by Reclamation in 2012 with the goals of computing a nutrient budget for the Klamath Project and to better characterize water quality in the Lost River and Klamath River Basins in Oregon for 3 years beginning in March 2012 and ending March 2015. Reclamation staff collected water-quality samples, field parameter data, and streamflow measurements from March 2012 to February 2013, and the U.S. Geological Survey (USGS) collected water-quality samples, field parameter data, and streamflow measurements from March 2013 to March 2015. The objectives of this study were to calculate TP, TN, BOD_5, and $CBOD_5$ loads at specified sites within the Klamath Project. Sites were selected by Reclamation in year 1 of the study to allow for reach-scale assessments of constituent loads to determine if there was an increase or decrease in loads, and to determine the reasons for those differences (Jason Cameron, Bureau of Reclamation, oral commun., August 5, 2016). Additionally, constituent concentrations were analyzed to identify spatial and temporal patterns in nutrient, organic carbon, and BOD_5/$CBOD_5$ concentrations. An improved understanding of water-quality loads in the Klamath River and Lost River Basins will provide important information for Reclamation in managing the Klamath Project for water quality.

Description of Study Area

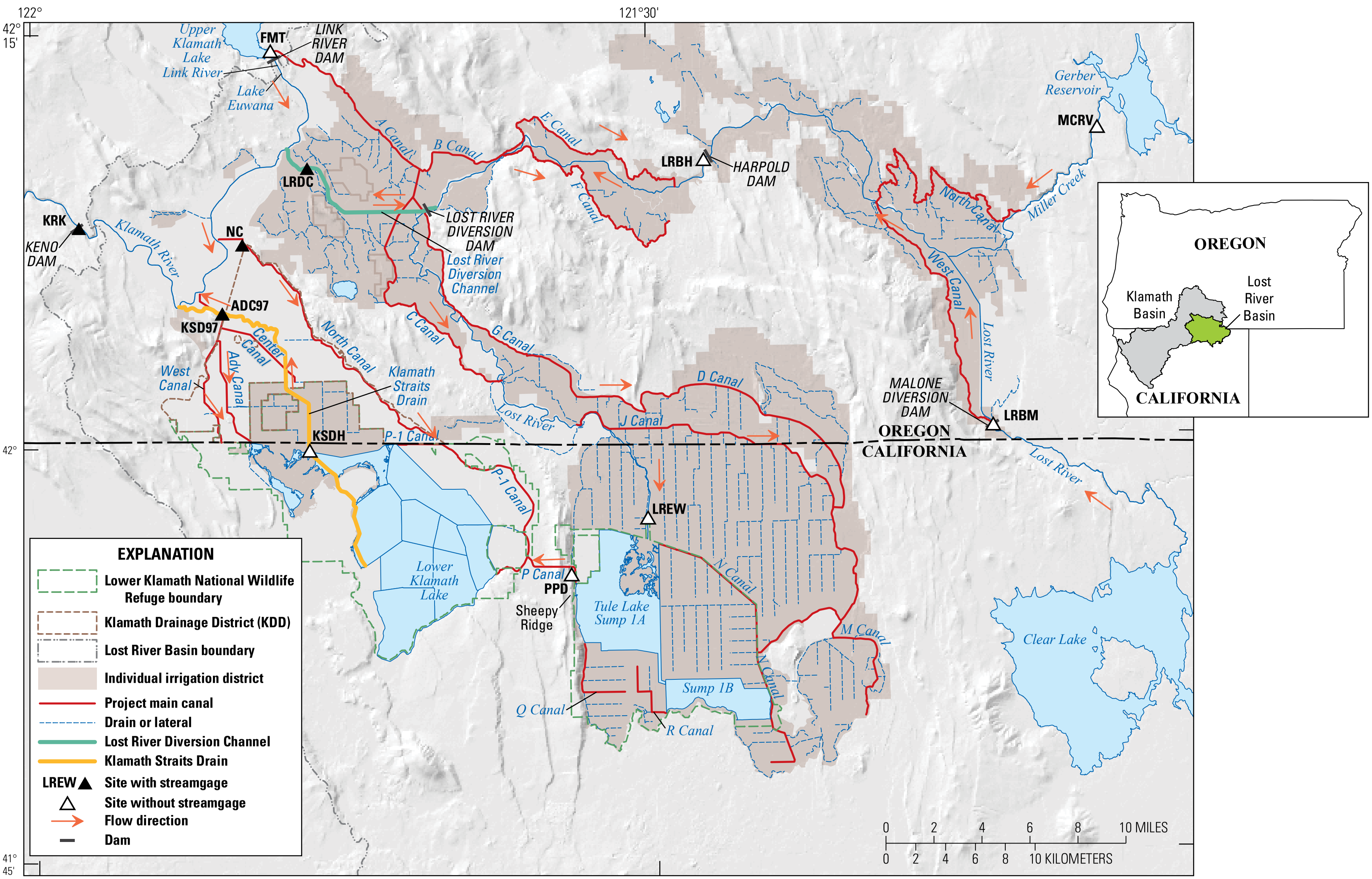
The Lost River Basin begins and terminates in a closed basin that straddles the Oregon-California border and covers parts of Klamath and Lake Counties in Oregon, and Modoc and Siskiyou Counties in California. The Basin is 7,790 km^2 (3,009 mi^2) in area, or 19.2 percent of the Upper and Lower Klamath Basins combined (Natural Resources Conservation Service, 2014). The Lost River headwaters are the tributaries to Clear Lake and the river terminates at Tule Lake. Along its course, the Lost River gains water from natural tributaries and gains and loses water by way of canals, drains, and pumps (fig. 1). The main stem of the Lost River is highly channelized and includes several impoundments to facilitate water storage and support diversion canals and return flow drains.

Water in the upper Lost River Basin generally originates in Clear Lake and the Gerber Reservoir, and is diverted from Miller Creek through North Canal and from the Lost River main stem through West Canal during irrigation season (fig. 1). Water from these diversions returns to the Lost River main stem through agricultural drains. Harpold Dam (at site LRBH) marks the farthest downstream extent of water deliveries from these two reservoirs during irrigation season, except for about 10 ft^3/s that moves past the dam to service a small area that cannot be serviced by the A Canal (Jason Cameron, Bureau of Reclamation, oral commun., August 5, 2016). This area within the project, upstream of Harpold Dam, is commonly referred to as the east side of the Klamath Project. During non-irrigation periods, water in the Lost River moves freely from the upper Lost River Basin past Harpold Dam.

During irrigation season, water is delivered from Upper Klamath Lake to multiple irrigation districts downstream of Harpold Dam. These districts are serviced by canals and laterals that originate from the A Canal, which conveys water from the southern end of Upper Klamath Lake. In the summer, Upper Klamath Lake has large blooms of cyanobacteria, which is dominated by the species *Aphanizomenon flos-aquae* (AFA) (Eldridge and others, 2012). Site FMT (fig. 1), therefore, represents water-quality conditions caused by these algal blooms in the summer because of its location at the southern end of the lake, and also represents water diverted through A Canal during irrigation season. The algal bloom in the lake also causes water-quality issues downstream in the reach of the Klamath River between the Link River Dam and Keno Dam (Sullivan and others, 2010). As a result, water delivered to the Klamath Project through the Lost River Diversion Channel, North Canal, and Ady Canal also contains high concentrations of AFA, which can affect water quality in these canals.

An intricate system of canals, laterals, pumps, and drains services irrigation districts from Harpold Dam to Tule Lake, south of the Oregon border. Water in the Lost River downstream of the Lost River Diversion Channel originates in the Klamath River (through the Diversion Channel), from the Lost River main stem, and from various drains within nearby irrigation districts. The Lost River terminates at Tule Lake, and water from Tule Lake is intermittently pumped through Sheepy Ridge from Pump Plant D, into various management units within the Lower Klamath National Wildlife Refuge (NWR), and through the P-canal and associated laterals. Water from the Lower Klamath NWR moves through the Klamath Straits Drain adjacent to site KSDH on the Oregon-California border. In addition to water from the NWR, Klamath Straits Drain also receives drainage water from irrigated lands within the Klamath Drainage District (KDD), which does not receive water from A Canal diversions, but rather through North Canal and Ady Canal, which divert water directly from the Klamath River. (Note that North Canal and West Canal within KDD irrigated lands have identical names to the east side diversions.) Klamath Straits Drain terminates in the Klamath River upstream of the Keno Dam.

During non-irrigation periods, water in the Lost River from the upper Lost River Basin is diverted to the Klamath River through the Lost River Diversion Channel, which is used for flood control during winter storms. Water in the Lost River between the Lost River Diversion Channel and Tule Lake originates from concrete box culvert drains that move stormwater from the city of Klamath Falls, and from drains from irrigation lands west and north of the Lost River Diversion Dam (Jason Cameron, Bureau of Reclamation, oral commun., August 5, 2016). The flow in the Lost River Diversion Channel is operated by gravity only, and water in the channel can flow to or from the Klamath River.



Base from U.S. Geological Survey digital dataset, 30-meter digital elevation model, and other digital data, various scales.

Canals, drains, and irrigation district data provided by Bureau of Recalamation.

Figure 1. Sample and data collection sites, Klamath River and Lost River Basins, south-central Oregon and northern California, March 2012–March 2015. Sites KSD97 and ADC97 are located on Klamath Straits Drain and Ady Canal, respectively. Site locations are proximal to each other, resulting in the appearance of overlap on the map. See table 1 for site description details.

This study was done during water years[1] (WYs) 2012–15. Considering mean annual streamflow over a 40-year period (1976–2015) at the Williamson River near Chiloquin (USGS streamgage 11502500, the closest streamgage near the project area on an unregulated river), WY 2012 was considered a normal streamflow year with a mean annual streamflow close to the 50th percentile value for the 40-year period (fig. 2). WYs 2013–15 are all considered low-flow years, with mean annual streamflows below the 25th percentile of the 40-year period. Mean annual streamflow in WY 2014 was below the 10th-percentile value. As a result, much of the data from this study were collected during abnormally low streamflow years, so interpretation of the results should be considered representative of these hydrologic conditions, and may not compare well to any future efforts that characterize normal streamflow years.

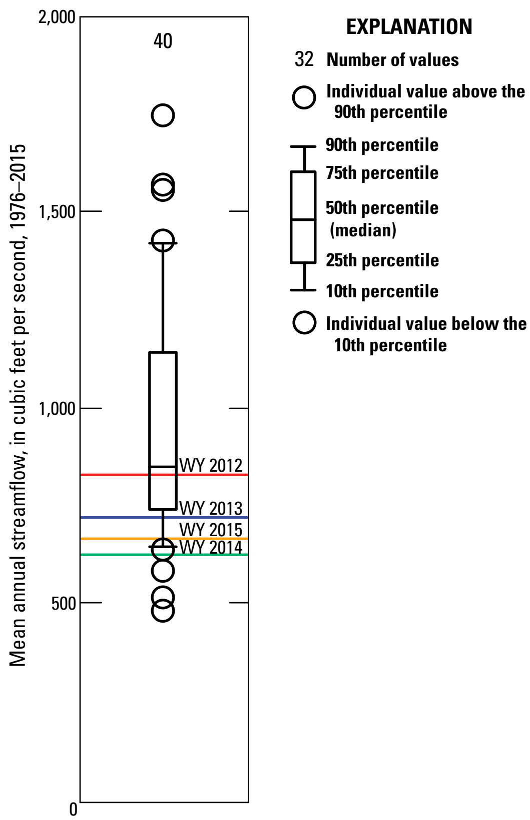


Figure 2. Mean annual streamflow at Williamson River near Chiloquin (U.S. Geological Survey streamgage 11502500), Upper Klamath Basin, south-central Oregon, water years (WYs) 1976–2015, and reference lines for WYs 2012–15.

Methods

Sampling Sites

Water-quality samples, streamflow, and field parameter data were collected at 10 sites during year 1 of the study, and at 12 sites during years 2–3 (fig. 1, table 1). Reclamation collected all water-quality and field-parameter data during year 1 (March 2012–March 2013), and the USGS collected data for years 2 and 3 (March 2013–March 2015) (table 2). Beginning in year 2, sites LREW and PPD were added by the USGS to represent water-quality conditions upstream of Tule Lake (site LREW), and at Pump Plant D (site PPD), which moves water from Tule Lake through Sheepy Ridge and into the P canal and associated laterals that eventually move water to Lower Klamath Lake, which is within the boundaries of the Lower Klamath NWR (fig. 1).

Three sites are used to represent conditions along the main Lost River Channel upstream of Tule Lake—(1) below Malone Reservoir (site LRBM), (2) below Harpold Reservoir (site LRBH), and (3) Lost River at East-West Road (site LREW). Site PPD represents water that is pumped intermittently from Tule Lake through Sheepy Ridge. Two sites represent conditions along Lower Klamath Lake and the Klamath Straits Drain—(1) KSD headworks (site KSDH), and (2) Klamath Straits Drain at Highway 97 (U.S. Route 97) (site KSD97). Five sites represent tributaries to the Lost River, A Canal, and Klamath Straits Drain systems—(1) Miller Creek at Round Valley (site MCRV), (2) UKL at Fremont Bridge (site FMT, a surrogate for A Canal water quality), (3) North Canal (site NC), (4) Ady Canal at Highway 97 (U.S. Route 97) (site ADC97), and (5) Lost River Diversion at Tingley Lane (site LRDC). The site at the Klamath River at Keno (KRK) is the lower boundary of the study area, and represents water quality on the main-stem Klamath River downstream of Upper Klamath Lake and the canals and drains managed by Reclamation that either divert or add water to the Klamath River (sites LRDC, NC, ADC97).

[1]The 12-month period from October 1, for any given year, through September 30 of the following year. The water year is designated by the calendar year in which it ends.

Table 1. Water-quality sampling sites, Lost River Basin, south-central Oregon and northern California, March 2012–March 2015.

[Site locations are shown in figure 1. **Abbreviations:** KDD, Klamath Drainage District; UKL, Upper Klamath Lake; UKR, Upper Klamath River]

Site name	Alternate site name	Site name abbreviation	USGS site identification No.	Latitude (north)	Longitude (west)	Study years sampled	Relevance	Site group designation in current report	Streamgage (yes or no)
Lost River at Bridge Crossing below Harpold Dam	Below Harpold Reservoir	LRBH	421010121271200	42°10′10″	-121°27′12″	1,2,3	Lost River main stem	Upper Lost River sites	no
Lost River below Malone Reservoir	Below Malone Reservoir	LRBM	420025121132800	42°00′25.2″	-121°13′27.6″	1,2,3	Lost River main stem	Upper Lost River sites	no
Miller Creek at Round Valley	none	MCRV	421114121080100	42° 11′14.3″	-121°08′1.3″	1,2,3	Lost River tributary inflow	Upper Lost River sites	no
Lost River near Hatfield, California	Lost River at East-West Road	LREW	11488495	41°57′14″	-121°30′12″	2,3	Lost River mainstem upstream of Tule Lake	Tule Lake sites	no
Tulelake Canal at Sheepy Ridge Pumping Station	Pump Plant D	PPD	11488510	42°55′14″	-121°33′58″	2,3	Connects Tule Lake to Lower Klamath Wildlife Refuge and Klamath Straits Drain	Tule Lake sites	no
Ady Canal at Highway 97	none	ADC97	11509200	42°04′51.3″	-121°50′44.3″	1,2,3	Canal serving KDD	KDD sites	yes
North Canal at Highway 97	North Canal	NC	11509105	42°07′19.5″	-121°49′43.5″	1,2,3	Canal serving KDD	KDD sites	yes
Lost River Diversion at Tingley Lane	none	LRDC	11486990	42°10′04″	-121°46′31″	1,2,3	Lost River tributary inflow or Klamath River tributary inflow	KDD sites	yes
Klamath Straits Drain at Highway 161 near Dorris, California	KSD headworks	KSDH	415950121463701	41°59′50″	-121°46′37″	1,2,3	Beginning of the Klamath Straits	KDD sites	no
Klamath Straits Drain at Highway 97	none	KSD97	420450121504500	42°04′50″	-121°50′45″	1,2,3	Klamath Straits Drain mainstem downstream of all KDD drains	KDD sites	yes
Fremont Bridge	UKL at Fremont Bridge	FMT	421420121481700	42°14′20″	-121°48′17.1″	1,2,3	A-canal tributary inflow during irrigation season, and Klamath River inflow at south end of UKL	End member	no
Klamath River at Keno, Oregon	UKR downstream of Keno Dam	KRK	11509500	42°08′00″	-121°57′40″	1,2,3	Klamath River mainstem	End member	yes

Table 2. Study years and responsible sampling agencies.

[**Sampling agency:** Reclamation, Bureau of Reclamation; USGS, U.S. Geological Survey]

Study year	Date range	Sampling agency	Number of sites
Year 1	03-27-12 to 03-10-13	Reclamation	10
Year 2	03-11-13 to 03-09-14	USGS	12
Year 3	03-10-14 to 03-23-15	USGS	12

Collection of Water-Quality Samples

Water samples were collected every two weeks from March 2012 to March 2015, and were analyzed for concentrations of TP, TN, dissolved ammonia as N, (hereinafter, "NH_3"), dissolved nitrate plus nitrite as N (NO_3+NO_2), dissolved orthophosphate as P (ortho-P), and chlorophyll-*a*. Samples also were collected for determination of BOD_5 and $CBOD_5$, which are the amount of dissolved oxygen needed by aerobic organoheterotrophic microorganisms to break down organic matter in the water sample during 5 days of incubation at 20 ºC. $CBOD_5$ differs from BOD_5 in that the contribution from nitrogenous bacteria is suppressed during determination of $CBOD_5$ (Delzer and McKenzie, 2003). Sites also were sampled about every 8 weeks (beginning on April 22, 2013) for dissolved organic carbon (DOC), total particulate carbon (organic plus inorganic; TPC), and total particulate nitrogen (TPN) concentrations.

As mentioned in the section, "Sampling Sites," two different agencies were responsible for collecting water-quality samples over the 3-year study period. As a result, different sampling methods and analytical laboratories were used during sampling efforts by Reclamation during year 1 compared to USGS during years 2 and 3. Reclamation collected grab samples in year 1 at all sites by using either a Van Dorn sampler or by hand-dipping a 14-L churn splitter into the stream depending on the site. The sampling devices were triple rinsed with environmental water prior to sample collection. Samples were processed on site using the churn splitter churned at a rate of 9 in/s for unfiltered samples. The 1,000-mL, high-density polyethylene (HDPE) sample bottles were filled with churned water for analysis of Total Kjelhahl Nitrogen (TKN), TP, BOD_5, and $CBOD_5$. The 1,000-mL clear HDPE bottle for TKN and TP analysis was preserved with 1 mL of sulfuric acid. A 250-mL brown HDPE bottle was filled with churned water for chlorophyll-*a* analysis. After unfiltered samples were collected and preserved, filtered samples were collected from the water remaining in the churn splitter using a peristaltic pump and 0.45-micron (µm) inline filter. The 1,000-mL clear HDPE bottles were filled with filtered water for ortho-P, NH_3, and NO_2+NO_3 analysis. The bottle for NH_3 and NO_3+NO_2 analysis was acidified with 1 mL of sulfuric acid. All water samples were chilled on-site and during transport. Nutrient and BOD_5/$CBOD_5$ samples were shipped overnight on ice to the Sierra Foothills Laboratory (no longer in operation) for analysis. Whole water for chlorophyll-*a* was shipped overnight to the Reclamation Pacific Northwest Regional Laboratory in Boise, Idaho, where it was filtered prior to analysis. Field parameters (water temperature, dissolved oxygen, pH, and specific conductance) were collected using a YSI® multi-parameter sonde after sample collection, and a secchi depth was recorded. Turbidity data also were recorded using a separate HACH® turbidimeter. Analytical methods and reporting limits for the project are shown in table 3.

Samples collected by USGS in years 2–3 of the study were collected following established USGS sampling protocols (U.S. Geological Survey, various dates) and using USGS-certified field supplies that are subject to quality-assurance procedures. When flows at the sampling sites exceeded 0.46 m/s (1.5 ft/s), samples were collected using the equal-width-increment (EWI) method as described in the USGS Field Manual (U.S. Geological Survey, 2006). The EWI method results in a composite sample that represents the streamflow-weighted concentration of analytes in the stream cross section being sampled. Samples were collected as grab samples when flows were less than 0.46 m/s (1.5 ft/s). These grab samples were collected in an open container, a DH-81 water-quality sampler, or a DH-95 water-quality sampler, without a nozzle and from a single point in the stream cross section. Where possible, grab samples were collected from several locations across the channel and combined in one sample.

Water samples collected by the USGS were composited using an 8-L churn splitter. TP and TN samples were preserved immediately after collection with the addition of 1 mL of 4.5 normal (4.5 N) sulfuric acid, and dissolved nutrient samples were filtered through a 0.45-µm capsule filter. All water samples were chilled on site and during transport. Total and dissolved nutrient samples were shipped on ice overnight within 3 days of collection and analyzed at the USGS National Water Quality Laboratory (NWQL; Denver, Colorado). Analytical methods and method reporting limits for USGS sample collection are shown in table 3. Dissolved nutrient samples were analyzed using USGS methods I-2525-89 and I-2522-90 for NH_3 concentration, method I-2545-90 for NO_2+NO_3 concentration, and methods I-2606-89 and I-2601-90 for ortho-P concentration (Fishman, 1993). TP and TN samples were analyzed using USGS method I-4650-03 (Patton and Kryskalla, 2003). Water samples collected for chlorophyll-*a* analysis were passed through 47-mm-diameter, 1.2-µm pore size, glass-fiber (Whatman™ GF/C) filters (Whatman, Inc., Piscataway, New Jersey) at the USGS Klamath Falls Field Station and immediately frozen.

Table 3. Laboratory analysis methods and method reporting limits for this study, March 2012–March 2015.

[**Abbreviations:** BOD, biochemical oxygen demand; BOR-PNRL, Bureau of Reclamation Pacific Northwest Regional Laboratory; CBOD, carbonaceous biochemical oxygen demand; Chl-*a*, chlorophyll-*a*; DOC, dissolved organic carbon; EPA, U.S. Environmental Protection Agency; MRL, method reporting limit; N, nitrogen; NWQL, National Water Quality Laboratory; P, phosphorus; TPC, total particulate carbon; TPN, total particulate nitrogen; SM, standard method; SRWQL, Sprague River Water Quality Laboratory; USGS, U.S. Geological Survey; mg/L, milligram per liter; NA, not applicable]]

Project Year 1, Bureau of Reclamation				Project Years 2–3, U.S. Geological Survey			
Analyte	Analyzing laboratory	Analytical method	MRL (mg/L)	Analyte	Analyzing laboratory	Analytical method	MRL (mg/L)
Total P as P, unfiltered	Sierra Foothills	SM 4500P-E	0.020	Total P as P, unfiltered	NWQL	USGS I-4650-03	0.010
Total Kjeldahl nitrogen as N, unfiltered	Sierra Foothills	SM 4500NH3C/351.2	0.20	Total nitrogen as N, unfiltered	NWQL	USGS I-4650-03	0.050
Orthophosphate as P, filtered	Sierra Foothills	EPA 365.3/SM 4500P E	0.050	Orthophosphate as P, filtered	NWQL	USGS I-2606-89, I-2601-90	0.004
Ammonia as N, filtered	Sierra Foothills	SM 4500NH3B,D/350.1	0.030	Ammonia as N, filtered	NWQL	USGS I-2525-89, I-2522-90	0.010
Nitrate + nitrite as N, filtered	Sierra Foothills	SM 4110B/EPA 300.0	0.050	Nitrate + nitrite as N, filtered	NWQL	USGS I-2545-90	0.050
BOD	Sierra Foothills	SM 5210B	2.0	BOD	SRWQL	SM 5210B	0.30
CBOD	Sierra Foothills	SM 5210B	2.0	CBOD	SRWQL	SM 5210B	0.30
Chl-*a*	BOR-PNRL	SM 10200H	various	Chl-*a*	BOR-PNRL	SM 10200H	various
DOC	NA	NA	NA	DOC	NWQL	USGS O-1122-92	0.23
TPC	NA	NA	NA	TPC	NWQL	EPA 440.0	0.050
TPN	NA	NA	NA	TPN	NWQL	EPA 440.0	0.030

These samples were stored and analyzed according to Standard Method 10200H (American Public Health Association, 2005) at the Bureau of Reclamation Pacific Northwest Region Laboratory in Boise, Idaho. Samples for BOD_5 and $CBOD_5$ analysis were delivered the same day they were collected to the Sprague River Water Quality Laboratory (SRWQL) in Chiloquin, Oregon. The close proximity of this laboratory to the study area allowed for minimal holding time (6–24 hours) between sample collection and the start of analysis. Samples were analyzed at the SRWQL following standard method 5210B (Clesceri and others, 2005).

Samples collected every 8 weeks for determination of DOC, TPC, and TPN concentrations were filtered at the Klamath Falls Field Station the same day they were collected using pre-combusted 25-mm-diameter, 0.7-µm pore size, glass fiber (Whatman™ GF/F) filters and following the USGS procedures for processing water samples (Wilde and others, 2004). For DOC samples, the filtrate was submitted for analysis, and for TPC/TPN samples, the filtrand was analyzed. Samples were shipped on ice overnight within 3 days of collection and analyzed at the USGS NWQL. DOC samples were analyzed following USGS method O-1122-92 (Brenton and Arnett, 1993), TPC and TPN were analyzed using U.S. Environmental Protection Agency method 440.0 (Zimmerman and others, 1997).

In year 1 of the study, water samples collected by Reclamation were analyzed for TKN, whereas, in years 2 and 3, USGS samples were analyzed for TN. These two analytes are not equivalent, as Kjeldahl nitrogen includes ammonium and organic nitrogen, whereas TN includes ammonium, NO_3+NO_2, and organic nitrogen (Patton and Kryskalla, 2003). Therefore, TN reported for year 1 of this study was calculated by adding the nitrate plus nitrite results to the TKN results and the resulting TN values were flagged as “estimated” in the USGS National Water Information System database.

Streamflow Data

Instantaneous streamflow for each sample event was determined from the continuous streamgage located at the sampling site, or, for sites without a continuous streamgage, an instantaneous streamflow measurement was collected during each sample event. At sites without a streamgage, instantaneous flow measurements were determined by two methods—(1) the mid-section method as described in Turnipseed and Sauer (2010) and (2) the moving boat method using an acoustic Doppler current profiler (Simpson, 2001, Turnipseed and Sauer, 2010). Streamflow primarily was determined using the mid-section method at sites LRBM, MCRV, LRBH, and LREW, and the moving boat method was used twice at site LRBH and once at site LREW. The moving boat method also was used for streamflow measurements at sites FMT, PPD, and KSDH.

Streamflow data were recorded continuously at sites LRDC, NC, ADC97, KSD97 and KRK. Instantaneous streamflow was computed at sites LRDC, NC, ADC97, and KSD97 using the index velocity method described in Levesque and Oberg (2012). At site KRK, the stage-streamflow method was used. The stage-streamflow method is based on the relation between channel water level (stage), as measured by an in-place sensor, and streamflow for a range of conditions. Streamflow relations were checked with instantaneous streamflow measurements every 6–8 weeks.

Site FMT is located at the southern end of Upper Klamath Lake, just upstream of the Link River Dam and the A Canal diversion. The lake is constricted at site FMT, and water is diverted through the A Canal and the Link River Dam downstream of the site, so measurable streamflow occurs at site FMT year-round. However, streamflow at site FMT often is affected by wind events and can change rapidly. The outflow from Upper Klamath Lake at site FMT was not directly measured from the start of the study in March 2012 to July 29, 2013. Instantaneous streamflow was estimated at this site using the water balance from data recorded at the USGS streamgage on the Link River, located 2.1 km downstream of Fremont Bridge (USGS streamgage 11507500, fig. 3), and flow data provided by Bureau of Reclamation for A Canal and Pacific Power for the Westside Canal (also known as “Keno Canal”). The water-balance equation was the sum of the flows out of Upper Klamath Lake through the A Canal, the Westside Canal, and the Link River. Instantaneous streamflow measured after July 29 were compared to the water-balance-calculated instantaneous streamflow, and the estimated streamflow values were determined to be reasonable (median relative percentage difference, 4.6 percent; range, 0.0–26 percent). The Eastside Canal was not included in the calculation because that streamflow was included in Link River streamflow.

Load Estimation

Constituent loads were computed at all project sites for TP, TN, BOD_5, and $CBOD_5$. Loads were computed using two methods: (1) a multivariate regression load estimation program, and (2) computation of instantaneous loads for individual samples averaged over specified time periods during the study.

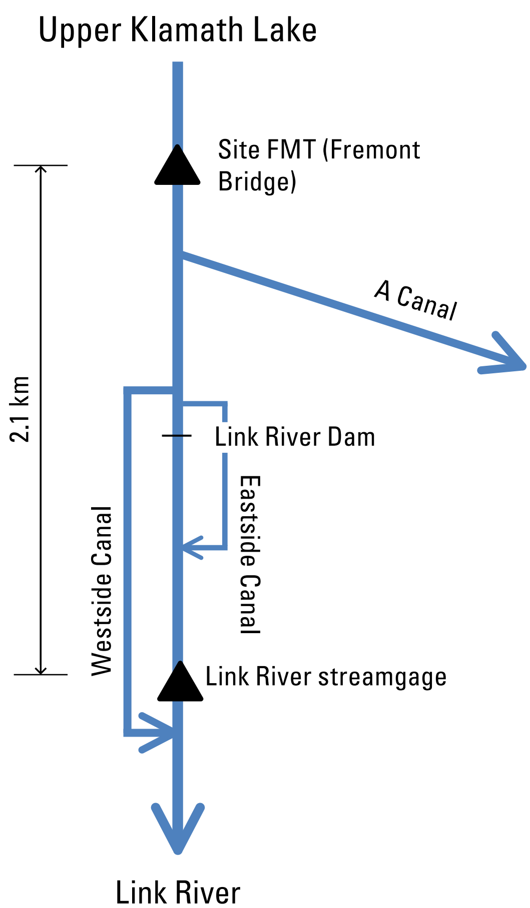


Figure 3. Schematic representation of the Link River (connecting Upper Klamath Lake to Lake Ewauna) showing flows (arrows) used to estimate instantaneous streamflow at site FMT, Upper Klamath Basin, south-central Oregon. Total flow at site FMT was determined as the sum of flows from A Canal, Westside Canal, and the Link River. Flow data from A Canal and Westside Canal were provided by the Bureau of Reclamation and Pacific Power; flow on the Link River was measured by the U.S. Geological Survey streamgage 11507500, located 2.1 kilometers downstream of Fremont Bridge. Site name and description are shown in table 1; site location is shown in figure 1.

LOADEST Models

The USGS LOAD ESTimator (LOADEST) program (Runkel and others, 2004), a USGS program for estimating constituent loads in streams and rivers, was used to estimate loads at two of the project sites that represent the upper and lower boundaries of the study—(1) the northernmost project site at Fremont Bridge (site FMT), and (2) the southernmost project site at Klamath River downstream of Keno dam (site KRK). The R-version of LOADEST (rloadest), an update from the Fortran-based model described by Runkel and others (2004), was used to run the models for this study. LOADEST uses a multiple regression approach to estimate the effects of streamflow, season, and time on water-quality concentration and loads. LOADEST models were not able to be calibrated at other sampling sites in the study area because consistent relations among flow conditions and water-quality constituent concentrations could not be identified.

LOADEST includes several predefined models that specify the form of a multivariate regression equation to estimate loads, using explanatory variables of streamflow, time, and season. The base model used in this study is shown in equation 1, with six explanatory variables plus an intercept term. The primary method used to estimate parameters in the regression equation within LOADEST is adjusted maximum likelihood estimation (AMLE), except for the special cases where the calibration data set is uncensored, in which case maximum likelihood estimation (MLE) is used (Runkel and others, 2004). The AMLE and MLE methods assume a linear model with normally distributed errors; logarithmic transformations are frequently used to satisfy the normality assumptions and to improve the fit of the regression (Helsel and Hirsch, 2002). LOADEST users can select a predefined model based on the knowledge of the system being modeled, or the program can select a best-fit model using an automated process that incorporates two statistics to select the model—the Akaike Information Criterion (AIC) and the Schwarz Posterior Probability Criterion (SPPC) (Runkel and others, 2004). The two statistics are computed for the calibrated model, and the predefined model with the lowest AIC statistic is selected as the best-fit model by the program, which contains some combination of the explanatory variables shown in equation 1. For this study, the best-fit model was evaluated, as well as additional models with the next-lowest AIC statistics:

$$\ln(L) = \beta_1 + \beta_2 \times (\ln Q) + \beta_3 (\ln Q^2) + \beta_4 \times dtime + \beta_5 \times dtime^2 + \beta_6 \sin(2\pi dtime) + \beta_7 \times \cos(2\pi dtime)\,, \quad (1)$$

where

ln	is natural logarithm;
L	is constituent load in kilograms per day;
$\beta_{1\ldots7}$	are coefficients of the explanatory variables;
Q	is streamflow, in cubic feet per second; and
$dtime$	is decimal time.

In addition to the AIC-determined model selection approach, seasonal-wave load models also were evaluated to determine if that model type resulted in a better-fit model than the model form in equation 1. A seasonal wave function has been shown to work well for pesticide models (Vecchia and others, 2008), where concentrations follow seasonal patterns unrelated to streamflow. Seasonal wave models, therefore, were evaluated given the seasonal pattern of the irrigation season, and the seasonal patterns of total nutrient concentrations in Upper Klamath Lake. The seasonal-wave model requires determining the timing of the peak of the constituent loads and values for the other parameters of the model, which comprise a loading period and decay rate (Lorenz, 2017). The form of the seasonal-wave model is shown in equation 2:

$$\ln(L) = \beta + \text{center}(\ln(Q)) + \text{seasonalWave}(dtime, p, l, d), \quad (2)$$

where

- ln is natural logarithm;
- L is constituent load in kilograms per day;
- β is Intercept term;
- Q is streamflow, in cubic feet per second;
- $dtime$ is decimal time;
- p is timing of the constituent concentration peak, in decimal time;
- l is loading period, in months; and
- d decay rate indicated by a half-life, in months.

The center (ln(Q)) term in equation 2 is referred to as a streamflow anomaly by Vecchia and others (2008), which is the deviation of concurrent daily streamflow from average conditions for the previous 30 days. The “seasonalWave” term is a function in R that describes the variation in ln (L) over the course of a year as a function of the remaining explanatory variables. Documentation for this and other USGS-specific R functions in rloadest can be found at https://github.com/USGS-R/rloadest.

Several model statistics were evaluated when selecting the final model to estimate constituent loads:

1. The coefficient of determination (R^2),
2. The probability plot correlation coefficient (PPCC),
3. The load bias in percent (Bp),
4. The partial load ratio, and
5. The Nash Sutcliffe Efficiency Index.

The PPCC value tests the normality of residuals on a normal-probability plot, and log-transformations that maximize the PPCC value (correlation coefficient values close to 1) for regression residuals optimize the normality of the residuals (Helsel and Hirsch, 2002), which satisfies the assumptions of multivariate linear regression. LOADEST includes routines to identify the best model from a suite of models based on the lowest AIC score (Runkel and others, 2004). In some cases, the model with the PPCC value closest to 1 or the lowest Bp value may not have been the model with the highest R^2 or the lowest AIC. As a result, the model that was used to estimate loads in this study may have required rejecting the best-fit model selected by LOADEST if the best-fit model was shown to have more bias or did not satisfy the assumptions of the regression as well as a different model. Seasonal wave models are not incorporated in the AIC and SPPC process of model selection within the program, so those models were run separately and the model statistics were evaluated in comparison to the multivariate regression model results. The seasonal wave model in LOADEST also does not function with left-censored data, so this model type was evaluated first for TP and TN loads, which did not contain censored results for sites FMT and KRK. BOD_5 and $CBOD_5$ models for both sites were evaluated using the multivariate models explained above. If the multivariate model for BOD and CBOD was determined to be unsatisfactory, the seasonal wave model was evaluated, and left-censored data were treated as results with concentrations that were equal to the laboratory reporting limit.

The LOADEST program was run on the current R platform as developed by the USGS, which includes updates in 2013 that provided additional diagnostic tools to evaluate bias in models estimating constituent loads. The 2013 update is available at http://water.usgs.gov/software/loadest/doc/loadest_update.pdf.

Daily constituent loads calculated using LOADEST were aggregated for irrigation and non-irrigation seasons for each year of the study by averaging the daily loads. Irrigation seasons for sites FMT and KRK were defined as the time period when water was diverted through A Canal.

Instantaneous and Daily Load Averaging

Surface water constituent loads at study sites without continuous records of streamflow, or for those sites that were located on Reclamation project canals where LOADEST was not used, were computed as instantaneous loads for each sample date when there was measurable streamflow at the site. When there was no measurable streamflow at the site, the instantaneous load was assumed to be zero and incorporated in the overall average. Instantaneous loads were computed using equation 3:

$$L_i = C \times Q \times c, \quad (3)$$

where

- L_i is instantaneous load in kilograms per day;
- C is constituent concentration in milligrams per liter;
- Q is streamflow, in cubic feet per second (ft^3/s) or cubic meters per second (m^3/s); and
- c conversion factor = 2.45 for Q in ft^3/s, and 86.4 for Q in m^3/s.

Instantaneous streamflow measurements were collected on sample days at site locations that were not located on Reclamation canals within the Klamath Project, following methods described in the section, “Streamflow Data”. The concentrations of TP, TN, BOD_5, and $CBOD_5$ were multiplied by these instantaneous streamflow measurements, and used to compute instantaneous loads using equation 3. Study sites with only instantaneous streamflow data used for load calculations include sites LRBH, LRBM, MCRV, KSDH, LREW, and PPD. Sample data collected at site MCRV in year 1 by Reclamation did not include instantaneous streamflow measurements, but instead relied on an existing rating curve operated by Reclamation for flows coming out of Gerber Reservoir, just upstream of the sampling site. As a result, instantaneous loads for year 1 at site MCRV were calculated using daily streamflow values provided by Reclamation, and loads for years 2 and 3 were calculated using the instantaneous streamflow measurements collected by USGS during sample collection. In study year 1 at site MCRV, Reclamation reported zero flows during non-irrigation periods, so the loads are assumed to be zero for that time period. For years 2 and 3, USGS recorded measurable streamflow from instantaneous measurements during non-irrigation periods, so loads are reported for those time periods.

At the canal sites (sites KSD97, NC, ADC97, and LRDC), daily values of streamflow obtained from the streamgage data were used to compute daily loads. Daily values were used at these sites because there were numerous scenarios where water-quality samples were collected at very low or very high streamflows that were the result of intermittent pump operations throughout the day. The instantaneous streamflows during sample collection often did not accurately represent the flow regime for the day, potentially resulting in non-representative daily loads. This approach requires the assumption that the samples collected at a discrete point in time also represented water-quality conditions for that day. In subsequent sections of this report, daily and instantaneous loads at the canal sites are referred to as instantaneous loads.

Loads were aggregated each study year by averaging all the calculated daily loads during irrigation and non-irrigation seasons. In subsequent sections of this report, the “load” at a site refers to this aggregated value, unless explicitly stated otherwise. For sites FMT and KRK, where LOADEST was used to compute loads, daily loads computed from the model were averaged separately for irrigation and non-irrigation seasons. This resulted in two average loads per study year per site, for a total of six time periods over the three study years.

Irrigation season lengths were different for sites on the western side of the project receiving water from A Canal diversions compared to sites on the eastern side of the project receiving water from Clear Lake and Gerber Reservoir. As a result, the length of the irrigation season for the western sites was defined as the time period when water was diverted through A Canal—typically mid-April to early October. The length of the irrigation season for the eastern sites also typically was mid-April to early October, and was defined as the time period when water was diverted from Gerber Reservoir (for sites MCRV and LRBH), and when water was diverted through the West Canal (for site LRBM) (fig. 1).

Quality Assurance

Because two agencies collected water-quality samples that were analyzed at different laboratories, reporting of quality assurance (QA) results is separated by the collecting agency.

Bureau of Reclamation Quality Assurance

QA samples were collected at various sites by Reclamation during the first year of the study. Sample QA followed standard operating procedures specific to the Klamath Basin Area Office of the Bureau of Reclamation. In summary, these samples included blanks and field duplicate samples. Blank samples were collected as laboratory blanks or rinsate blanks as denoted by Reclamation standard operating procedures. Laboratory blanks were prepared in the laboratory or office to avoid field contamination for the purpose of testing the cleanliness of the sampling equipment. Laboratory blank sample bottles were rinsed three times with reagent grade deionized (DI) water and corresponding preservatives were added. A rinsate blank is designed to check sampling equipment and field crew techniques for contamination. After the sampling equipment had been cleaned with DI water at the last sampling site of the day, the rinsate blank was collected. Rinsate blanks were prepared by pouring reagent grade DI water into the sample collection equipment (Van Dorn, etc.), ensuring that all internal surfaces are wetted. The rinsate water was then collected in a churn splitter. Following field procedures, the sample bottles were rinsed three times with the rinsate water and then filled with rinsate water. For filtered constituents, the rinsate water was filtered using a peristaltic pump or filter syringe using the same techniques that were used for the regular sample. Preservation techniques are the same as those used for the regular samples. Duplicate samples were subsamples of the total sample, had a water matrix identical to that of the regular sample, and were used to determine analytical precision within an analyzing laboratory.

U.S. Geological Survey Quality Assurance

QA samples were collected at various sites by USGS during the second and third years of the study. These samples included the following:

1. Field equipment blanks (the first samples collected each sample day in the field) for total (TP, TN) and dissolved nutrients (NH_3, NO_3+NO_2, ortho-P), BOD_5, $CBOD_5$, and DOC,

2. Laboratory equipment blanks (collected at the Klamath Falls Field Station prior to field sampling on days with inclement weather—three times for total and dissolved nutrients and once for BOD_5, $CBOD_5$, and DOC during the study period,

3. Laboratory filtration blanks (collected after samples were filtered at the Klamath Falls Field Station for TPC, TPN, and chlorophyll-*a*), and

4. Either a sequential replicate sample (hereinafter, “replicate” sample) or a split replicate sample (hereinafter, “split” sample) for all constituents.

The laboratory filtration blank described in item number 3 is a process to test the efficiency of cleaning procedures between environmental samples that are filtered for particulate carbon and nitrogen, and chlorophyll-*a*.

Replicate environmental samples were collected twice in rapid succession from the same location (the entire sample collection procedure was completed twice), and analyzed to determine variability associated with sample collection procedures and analytical methods. Split samples were environmental samples collected once and divided into two or more samples (analysis bottles were filled sequentially from the same churn splitter) to determine the variability in sample splitting and in the analytical methods. Split samples were collected in addition to replicates to determine how much variability measured in replicate samples was due to sampling compared to laboratory analysis. Blank spike and sample matrix spike samples also were prepared for total and dissolved nutrient analyses to measure potential bias in laboratory analytical procedures. Spike samples were prepared at the USGS Klamath Falls Field Station by adding target compounds (a field-matrix spike mixture) to American Chemical Society reagent-grade inorganic blank water and to split-replicate environmental samples. Methods for collecting and evaluating quality-control samples are described in Eldridge and others (2012).

Quality Assurance Results

Bureau of Reclamation Quality Assurance Results

Blank sample results from Reclamation in year 1 of the study (March 2012–February 2013) showed no occurrences exceeding the minimum reporting level (MRL) for TP, TKN, ortho-P, NH_3, and NO_3+NO_2 (table 4a). The MRL for TKN changed from 0.20 to 0.05 mg/L on January 15, 2013, and blank sample concentrations beyond that date also were less than the new MRL. All chlorophyll-*a* filter apparatus blanks and BOD_5/$CBOD_5$ field blank concentrations also were less than the laboratory reporting limits for all blank samples.

Table 4. Quality-control data for Bureau of Reclamation water-quality samples, Klamath River and Lost River drainages, south-central Oregon and northern California. (a) blank samples, March 2012–March 2015; (b) replicate samples, March 2013–March 2014.

[Table 4a and 4b are Microsoft® Excel files and are available for download at https://doi.org/10.3133/sir20185075]

The mean relative percent difference (RPD) for all duplicate samples was less than 10 percent for TP, ortho-P, NH_3, NO_3+NO_2, and BOD_5/$CBOD_5$ (table 4b). The mean RPDs for chlorophyll-*a* and TKN duplicates were 14.8 and 14.9 percent, respectively.

U.S. Geological Survey Quality Assurance Results

Less than 5 percent of all blank samples for total nutrients (TP and TN, n=106), dissolved nutrients (ortho-P, NH_3, NO_3+NO_2, n=106), chlorophyll-*a* (n=105), and DOC (n=24) contained concentrations more than the minimum reporting level (table 5a). Laboratory filtration blank samples for TPC and TPN analyses exceeded the MRL in 17 and 9 percent of samples, respectively. However, concentrations of TPC and TPN in environmental samples were much greater than the concentrations detected in the blank samples. Mean concentrations in laboratory filtration blank samples were 0.20 and 0.04 mg/L for TPC and TPN, respectively, whereas the fifth-percentile values of environmental samples collected at all sites exceeding the MRL were 0.51 and 0.06 mg/L for TPC and TPN, respectively (table 5a). Therefore, low-level contamination indicated by the blanks did not limit the use of these data.

Table 5. Quality-control data for U.S. Geological Survey water-quality samples, Klamath River and Lost River drainages, south-central Oregon and northern California. (a) blank samples, March 2012–March 2015; (b) split samples, March 2012–March 2015; (c) replicate samples, March 2013–March 2014; (d) spikes, March 2013–March 2014.

[Tables 5a, 5b, 5c, and 5d are Microsoft® Excel files and are available for download at https://doi.org/10.3133/sir20185075]

Fifty-three percent of BOD_5 and 58 percent of $CBOD_5$ equipment field blank samples and the single laboratory equipment blank sample for BOD_5 and $CBOD_5$ exceeded the MRL. Contamination in these blank samples was primarily an artifact of the process used to initiate the blank water incubation for the assay, and, therefore, an overestimate of contamination in the environmental samples. Laboratory personnel informed USGS that the initial dissolved oxygen readings of submitted blank water samples typically were supersaturated and that the initial agitation of the sample was ineffective at bringing the concentration to saturation. As a result, over a 5-day analysis, the blank water would equilibrate to laboratory conditions and lose a portion of its dissolved oxygen, resulting in the sample analysis at 5 days showing depletion of dissolved oxygen and a value greater than the reporting limit. Once the problem was rectified, the concentration in the blank samples decreased (table 5a).

BOD_5 and $CBOD_5$ concentrations measured in environmental samples generally were much larger than the concentrations detected in the blanks. The mean concentration of BOD_5 and $CBOD_5$, measured in equipment blank samples with concentrations greater than the MRL, was 0.61 mg/L (range 0.30–2.69 mg/L) and 0.62 mg/L (range 0.30–2.40 mg/L), respectively, for equipment field blanks, and 1.20 and 1.22 mg/L, respectively, for laboratory equipment blanks (only one laboratory equipment blank was collected). The 5th-percentile values of environmental samples (collected from the same sites as the field equipment blanks) for BOD_5 and $CBOD_5$ were 1.21 and 0.90 mg/L, respectively (table 5a). Therefore, low-level contamination indicated by the blanks did not limit the use of these data.

Split and replicate samples collected during March 2013–March 2015 had mean RPDs of less than 11 percent for all dissolved nutrients and DOC (tables 5b and 5c), with greater RPD values for replicate samples than for split samples, indicating the greater variability associated with sequential sampling. The RPD of split samples of analytes with suspended material generally was higher than the RPD of replicates sampled for the same analytes, suggesting that the sample splitting (using a churn splitter) did not provide much uniformity in samples with regard to suspended material. The highest RPDs for split samples of suspended material were reported for BOD_5 and $CBOD_5$ (11.2 and 15.1 percent, respectively), the next highest for chlorophyll-*a* (11.1 percent), and the third highest for TPN (10.5 percent).

Bias measured by analysis of spike samples is known as "recovery," which is a measure of a spike analyte added to a sample, expressed as the percentage of the spiked amount (U.S. Geological Survey, 2006). The recovery in a sample without loss or gain of the measured analyte (due to degradation or matrix character) should be 100 percent. Spiked nutrient samples for this study were prepared and analyzed on July 17, 2013, December 3, 2013, and July 17, 2014. The results showed mean nutrient spike recoveries between 92 and 103 percent for the July and December 2013 spikes (table 5d), and 75 to 164 percent for the July 2014 spike. With the exception of the 2014 spiked samples, all recoveries were greater than 90 percent and most were greater than 96 percent. The maximum (164 percent) and minimum (75 percent) recoveries for the July 2014 spiked samples all occurred in the mid-level spiked blank water and spiked sample matrix water, respectively, for NO_3+NO_2. These low and high recoveries likely originated from a pipet error during spike sample preparation because mean recovery for low-level and high-level spiked blank water was 101 and 97 percent, respectively.

Results

Streamflow

As mentioned in the section, "Background," streamflow in the Upper Klamath Basin was below average for most of the study period, particularly during WYs 2014 and 2015 (fig. 2). The sites with the highest streamflow for all three study years during both irrigation and non-irrigation seasons were the end member sites FMT and KRK (fig. 4). Average streamflow ranged from 1,440 to 2,200 ft^3/s at FMT during irrigation season, and 653 to 715 ft^3/s during non-irrigation season. By comparison, all the other study sites except for KRK had mean streamflows of less than 200 ft^3/s for both irrigation and non-irrigation seasons. Streamflow data during irrigation and non-irrigation seasons in year 1 were not recorded for sites LREW and PPD, and were not available for site KSDH. In non-irrigation year 2 and all of study year 3, streamflow at site KSDH was determined to be zero, which also resulted in zero values for constituent loads. (Note that mean streamflow data for sites LREW and PPD during irrigation seasons 2 and 3, and site MCRV during non-irrigation seasons do not appear in figure 4 because the values are too small to appear on the scale of the bar chart, which is scaled to the same value on the y-axis to allow for comparison between sites.) Among the upper Lost River Basin sites, site MCRV had the highest mean streamflow during irrigation season, a result of dam releases from Gerber Reservoir for irrigation. During non-irrigation periods, site LRBH had the highest streamflow among those sites, a result of the management of streamflow that allows water to pass through the small regulating structure during non-irrigation periods.

Water-Quality Concentrations

For purposes of this report, only those water-quality samples collected while there was measurable streamflow at the sampling site are reported. At site LRDC, where water flows in two directions depending on water management operations and season, a positive flow direction [LRDC(+)] indicates water flowing from the Klamath River onto the Klamath Project, and a negative flow direction [LRDC(-)] indicates water flowing from the project toward the Klamath River. This designation is consistent with water velocity directional data recorded at the streamgage where samples were collected as mentioned above. Eleven sample concentrations are reported for site KSDH over the 3-year study; however, only two of these samples were used to compute instantaneous loads. The additional nine samples are from year 1 of the study when Reclamation collected samples and the site was flowing, and during irrigation year 2.

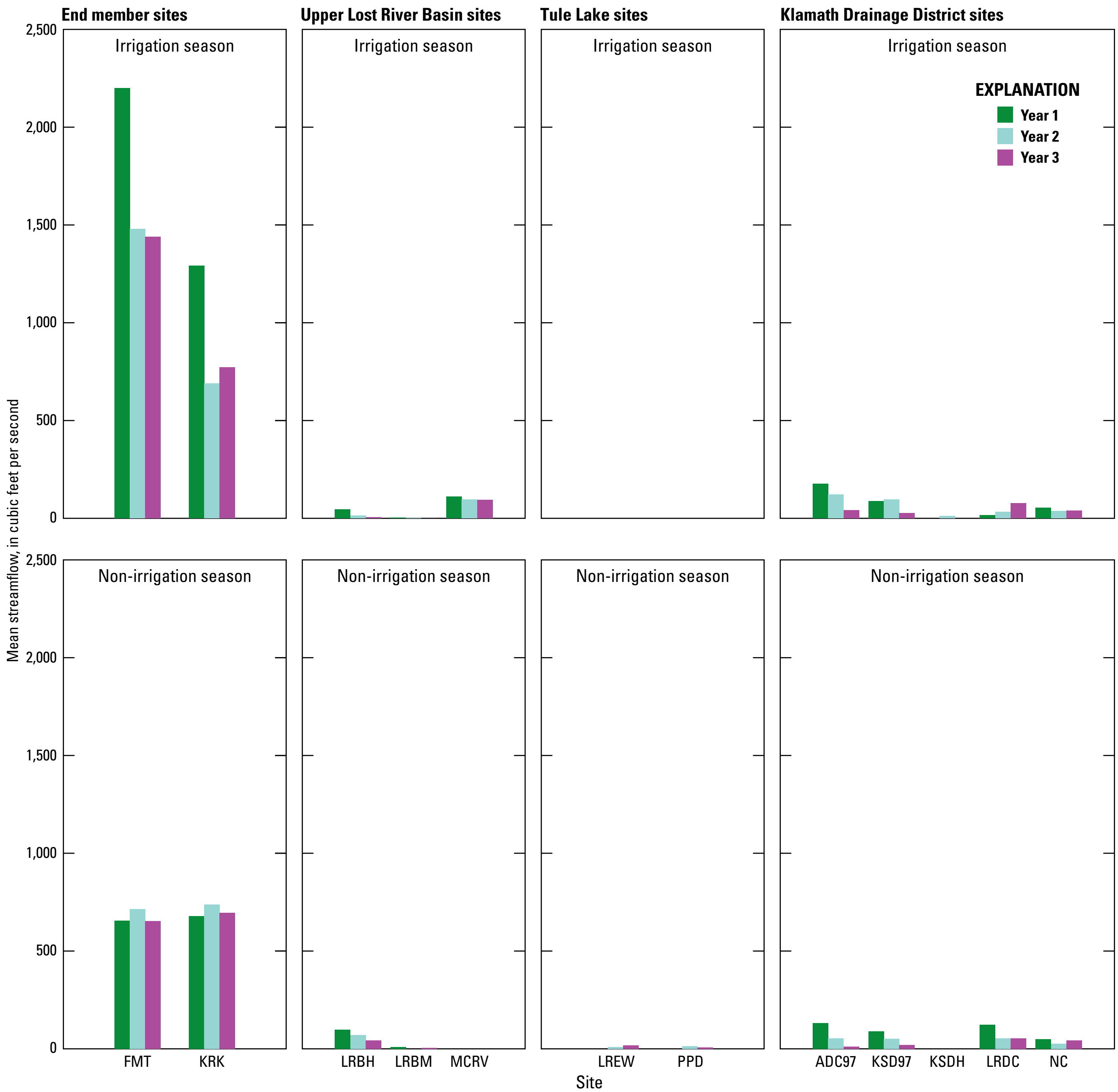


Figure 4. Mean streamflow at study sites during irrigation and non-irrigation seasons, Klamath River and Lost River Basins, Oregon and California, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

Streamflow values during these periods could not be verified to compute instantaneous loads, so those values were not included in the load computations.

A Mann-Whitney U test was done on the sample concentration results to determine if mean concentrations of constituents were distinguishable between sites ($p<0.05$). In tables 6 and 7, the "MWU" column contains results of these analyses in the form of lowercase letters. Sites that share a letter have sample concentrations that are statistically the same, and sites that do not share a letter have sample concentrations that are not statistically the same. This test was not used on DOC, TPC, and TPN results because the small sample sizes ($n<13$) did not allow for robust statistical analysis.

Total Nutrients

The highest median concentrations of TP from the three study years at all sites were at site KSDH (0.430 mg/L), which occurred in year 1 of the study (table 6). However, site KSDH had the second smallest number of samples collected at any of the study sites, so the water-quality conditions were not well characterized there, and most of the samples were collected early in the study period. Among all the sites, median TP concentrations were lowest at the end member sites, and highest at Tule Lake site LREW and KDD site KSDH, with median concentrations of 0.407 and 0.430 mg/L, respectively. The two highest maximum TP values were 0.950 mg/L at site KSDH, and 0.776 mg/L at site LREW. The lowest minimum TP value was 0.025 mg/L at site FMT, one of the end member sites. The median TP concentrations at canal sites within the KDD site group typically were higher than the upper basin and end member sites, with the exception of site LRBM. Concentrations of TP at site LRDC when water was flowing onto the project were slightly lower than concentrations when water was flowing towards the Klamath River (0.149 versus 0.171 mg/L, respectively), although concentrations for the two flow directions were not statistically different when evaluated with a Mann-Whitney U test ($p<0.05$). Within the upper Lost River Basin sites, site LRBM had the highest median TP concentration of 0.183 mg/L, and site MCRV had the highest maximum TP concentration of 0.573 mg/L.

TN values followed a similar pattern, except that median concentrations were lowest in the upper Lost River Basin sites, and second to lowest in the end member sites. Median TN concentration was highest at site PPD (4.08 mg/L), and lowest at site MCRV (0.764 mg/L), which suggests that the upper Lost River Basin might not be a significant source of TN compared to areas within the project near Tule Lake. For site LRDC, TN concentrations were statistically similar for both flow directions (table 6).

At the end member sites, TP concentrations were statistically higher at site KRK than at site FMT when combining data from all three study years, and TN concentrations were not statistically different (table 6). Median TP and TN concentrations were higher at site KRK than at site FMT during irrigation season, and similar at the two sites during non-irrigation periods (fig. 5). Median concentrations of TN and TP at the upper basin sites in years 1 and 2 were variable at sites LRBH and LRBM, but site MCRV showed a smaller range of values in those years, particularly during irrigation seasons in years 1 and 2, suggesting that Gerber Reservoir does not contribute high concentrations of nutrients to the Lost River during irrigation season (fig. 6). In year 3, median concentrations of TN and TP were higher at site MCRV than at the other sites during the non-irrigation season (fig. 6). Water-quality samples at the Tule Lake sites were not collected in year 1, so only 2 years of data are available for analysis. More samples were collected at site LREW than site PPD because of lack of streamflow at site PPD (fig. 7). Because of the limited data at site PPD, more samples would provide for a more robust comparison if future studies are undertaken. Within the KDD group, site KSDH, which represents water moving from the Lower Klamath Wildlife Refuge into the Klamath Straits Drain, had higher concentrations of TP than the other sites during year 1 of the study and the irrigation season of year 2, and similar concentrations in non-irrigation year 2 (samples were not collected at site KSDH in year 3 because the canal was not flowing on sample collection days) (fig. 8). Concentrations of TP were statistically higher ($p<0.05$) at site KSDH when compared to the rest of the KDD sites after combining data from all 3 years (table 6), although these results are based on much fewer samples collected at site KSDH compared to the rest of the sites. The site with the second-highest concentrations of TP and TN in years 1 and 2 was site KSD97, which represents drainage water from irrigated lands in the KDD before entering the Klamath River. In year 3 of the study, site KSD97 had the highest median concentrations of TN and TP in both irrigation and non-irrigation seasons (fig. 8), and concentrations were statistically higher at that site for all three study years compared to canal sites NC and ADC97, which bring water from the Klamath River into the KDD for irrigation (table 6).

Table 6. Summary statistics of total and dissolved nutrient sample results, Klamath River and Lost River Basins, south-central Oregon and northern California, March 2012–March 2015.

[Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Site name abbreviation:** LRDC (+) indicates samples that were collected when the flow direction was towards the Lost River; LRDC (-) indicates samples that were collected when the flow direction was toward the Klamath River. **MWU (Mann-Whitney U statistical test):** Sites that share a letter under the MWU column have sample concentrations that are the same statistically. Sites that do not share a letter have sample concentrations that are statistically different. **Abbreviations**: n, number of samples; N, nitrogen; mg/L, milligram per liter; ND, no data; <, less than]

Site name abbreviation	Total phosphorus (mg/L)					Total nitrogen (mg/L)					Orthophosphate (mg/L)				
	n	Median	Maximum	Minimum	MWU	n	Median	Maximum	Minimum	MWU	n	Median	Maximum	Minimum	MWU
Upper Lost River Basin															
LRBM	46	0.183	0.469	0.028	a	46	0.874	2.56	0.413	a	46	<0.050	0.227	0.011	b
MCRV	51	0.093	0.573	0.053	a	51	0.764	6.27	0.349	a	51	0.031	0.136	0.011	c
LRBH	71	0.130	0.384	0.035	a	71	0.787	3.02	0.250	a	71	0.096	0.322	0.039	a
Tule Lake sites															
LREW	40	0.407	0.776	0.207	ND	40	1.77	3.37	0.758	ND	40	0.274	0.602	0.146	ND
PPD	4	0.306	0.372	0.174	ND	4	4.08	5.08	3.52	ND	4	0.009	0.010	0.007	ND
Klamath Drainage District sites															
KSDH	11	0.430	0.950	0.232	c	11	3.26	4.13	2.65	c	11	0.196	0.723	0.018	b,c
ADC97	54	0.160	0.370	0.078	a	54	1.46	3.85	0.754	a	54	0.063	0.245	0.010	a
NC	66	0.131	0.620	0.074	a	66	1.31	3.69	0.686	a,d	66	0.063	0.526	0.014	a
LRDC (+)	36	0.149	0.445	0.074	a	36	1.32	4.35	0.517	a,d	36	0.064	0.271	0.025	a,c
LRDC (-)	43	0.171	0.48	0.096	a	43	1.22	3.15	0.479	d	43	0.095	0.301	0.008	c
KSD97	52	0.320	0.545	0.121	b	52	2.73	5.02	1.36	b	52	0.151	0.390	0.008	b
End member sites															
FMT	75	0.080	0.404	0.025	a	75	1.19	3.83	0.343	a	75	0.024	0.195	0.005	a
KRK	77	0.116	0.416	0.416	b	77	1.30	3.32	0.626	a	77	0.048	0.310	0.010	b

Site	Nitrate + nitrite as N (mg/L)					Ammonia as N (mg/L)				
	n	Median	Maximum	Minimum	MWU	n	Median	Maximum	Minimum	MWU
Upper Lost River Basin										
LRBM	46	<0.050	0.271	<0.01	b	46	0.032	0.120	<0.01	a,b
MCRV	51	0.067	1.80	<0.01	c	51	0.019	0.100	<0.01	b
LRBH	71	0.296	2.19	<0.01	a	70	0.041	0.371	<0.01	a
Tule Lake sites										
LREW	40	0.163	1.60	<0.01	ND	40	0.114	1.34	<0.01	ND
PPD	4	<0.010	0.024	<0.01	ND	4	0.022	0.338	0.02	ND
Klamath Drainage District sites										
KSDH	11	<0.050	0.779	0.02	a,b,d	11	0.300	0.780	0.02	a,b
ADC97	54	0.108	0.580	<0.01	a,b	54	0.094	0.990	<0.00	a
NC	66	0.063	0.530	<0.01	a,d	66	0.101	1.46	0.01	a
LRDC (+)	36	<0.050	0.461	<0.01	d	36	<0.100	1.39	<0.01	a
LRDC (-)	43	0.246	1.56	<0.01	b,c	43	0.116	0.817	<0.01	a
KSD97	52	0.182	1.60	0.01	c	52	0.410	1.03	0.01	b
End member sites										
FMT	75	0.136	0.469	<0.01	a	75	0.056	0.380	<0.01	a
KRK	77	0.117	0.670	<0.01	a	77	0.087	1.30	0.01	a

Table 7. Summary statistics of 5-day biochemical oxygen demand, 5-day carbonaceous biochemical oxygen demand, and chlorophyll-*a* sample results, Klamath River and Lost River Basins, south-central Oregon and northern California, March 2012–March 2015.

[Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Site name abbreviation:** LRDC (+) indicates samples that were collected when the flow direction was towards the Lost River; LRDC (-) indicates samples that were collected when the flow was toward the Klamath River. **MWU (Mann-Whitney U statistical test):** Sites that share a letter under the MWU column have sample concentrations that are the same statistically. Sites that do not share a letter have sample concentrations that are statistically different. **Abbreviations:** DOC, dissolved organic carbon; n, number of samples; TPC, total particulate carbon; TPN, total particulate nitrogen; µg/L, microgram per liter; mg/L, milligram per liter; ND, no data ; <, less than]

Site name abbreviation	BOD_5 (mg/L)					$CBOD_5$ (mg/L)					Chlorophyll-*a* (µg/L)				
	n	Median	Maximum	Minimum	MWU	n	Median	Maximum	Minimum	MWU	n	Median	Maximum	Minimum	MWU
Upper Lost River Basin															
LRBM	46	<2.00	5.10	0.970	a	46	0.874	2.56	0.413	a	32	2.70	2.70	2.70	a
MCRV	50	1.42	7.50	0.490	b	51	0.764	6.27	0.349	a	50	5.00	28.0	1.00	a
LRBH	68	<2.00	4.41	0.650	a	71	0.787	3.02	0.250	a	55	4.50	25.4	2.80	a
Tule Lake sites															
LREW	39	3.76	17.2	1.02	ND	38	3.00	17.1	0.680	ND	39	11.0	161	3.20	ND
PPD	4	12.2	17.7	5.61	ND	4	11.0	17.0	4.78	ND	4	99.2	150	27.3	ND
Klamath Drainage District sites															
KSDH	9	6.60	12.0	2.90	a	9	4.70	9.00	2.20	a	12	51.7	167	4.20	a
ADC97	51	3.38	14.5	<2.00	a,b	50	2.62	12.0	1.50	a	54	22.4	115	7.30	a
NC	64	3.10	13.9	1.98	b	63	2.63	15.8	0.660	a	65	13.6	89.9	4.30	b,c
LRDC (+)	36	4.26	39.0	1.17	a,b	35	3.80	26.5	1.24	a	23	15.4	291	3.80	a,b,c
LRDC (-)	41	2.49	9.93	1.14	c	41	2.03	10.2	0.870	b	40	11.2	120	4.20	c
KSD97	50	4.47	13.2	1.63	a	49	3.35	15.3	1.28	a	52	22.2	174	4.20	a,b,c
End member sites															
FMT	72	2.32	25.0	1.41	a	71	<2.00	23.9	0.600	a	59	11.2	330	4.10	a
KRK	74	2.70	10.2	1.07	a	73	2.10	7.54	0.910	a	77	16.0	69.2	3.50	a

Dissolved Nutrients

Over the course of the 3-year study, two different agencies collected samples and sent them to different laboratories, resulting in multiple MRLs for most of the constituents analyzed. The differences in MRLs are most noticeable in the dissolved nutrient results because non-detection was common for NO_3+NO_2 and NH_3 results. The MDL for NO_3+NO_2 was 0.05 mg/L in year 1, and 0.01 mg/L in years 2 and 3. As a result, the median value at two sites, LRBM and KSDH, is reported as less than (<) 0.05 mg/L and, at site PPD, as <0.01 mg/L (table 6). The MRL for NH_3 during year 1 changed once, from 0.10 to 0.03 mg/L, and then a second time for years 2–3 to 0.01 mg/L. As a result, median NH_3 values at site LRDC(+) are reported as <0.10 mg/L in table 6. The MRL for ortho-P also changed from year 1 (0.05 mg/L) to years 2 and 3 (0.004 mg/L), resulting in a median value reported as <0.05 mg/L at site LRBM and minimum value of 0.011 mg/L. All results with censored values are shown in table 8**.**

Table 8. Sample concentration results from all sites.

[Table 8 is a comma delimited file (.csv) and is available for download at https://doi.org/10.3133/sir20185075]

The highest median ortho-P concentration occurred at site LREW (0.274 mg/L), and the second-highest median concentration occurred at site KSDH (0.196 mg/L) (table 6). Concentrations of NO_3+NO_2 at all sites reported minimum concentrations that were less than the MRL of 0.01 mg/L, with the exception of sites KSDH and KSD97, which reported minimums of 0.0146 and 0.0108 mg/L, respectively, The highest median concentrations of NO_3+NO_2 occurred at site LRBH (0.296 mg/L) in the upper Lost River Basin and LRDC(-) (0.246 mg/L), when water was flowing from the project to the Klamath River. Overall, the lowest NO_3+NO_2 median concentrations occurred at sites LRBM, KSDH, and LRDC(+) (<0.05 mg/L), and PPD (<0.01 mg/L), with moderate concentrations at end member sites FMT and KRK, and sites ADC97 and KSD97. Median NH_3 concentrations were highest at sites KSD97 (0.410 mg/L), with the next highest median concentration occurring at LRDC(-) (0.116 mg/L). The lowest median concentration occurred at site MCRV (0.0191 mg/L). Minimum NH_3 concentrations at all sites were at or slightly above the MRL of 0.01 mg/L from the laboratory in study years 2 and 3. Site LRDC(+) reported median NH_3 concentrations less than the MRL of 0.1 mg/L from study year 1.

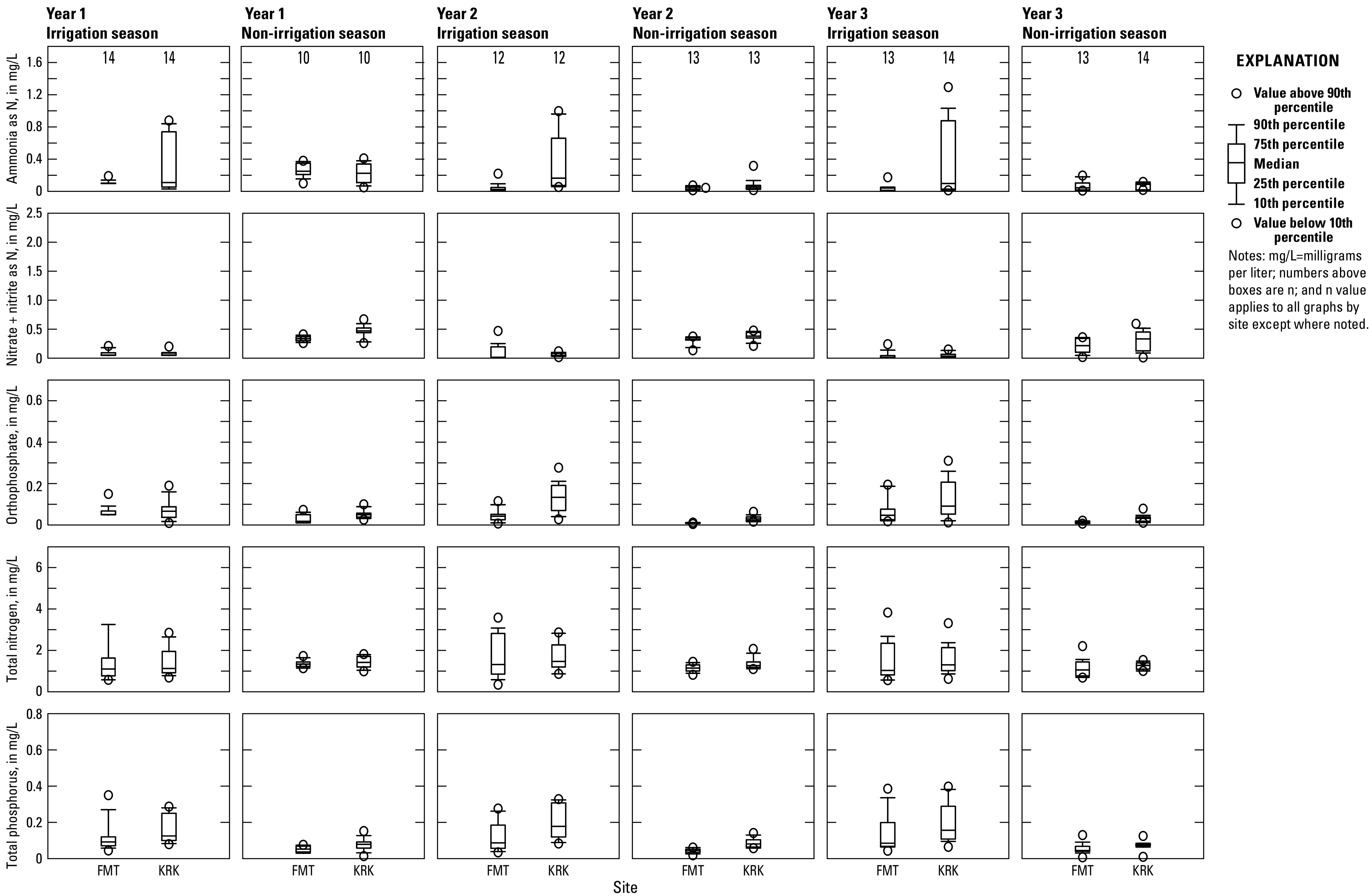


Figure 5. Nutrient concentrations at end member sites, south-central Oregon, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

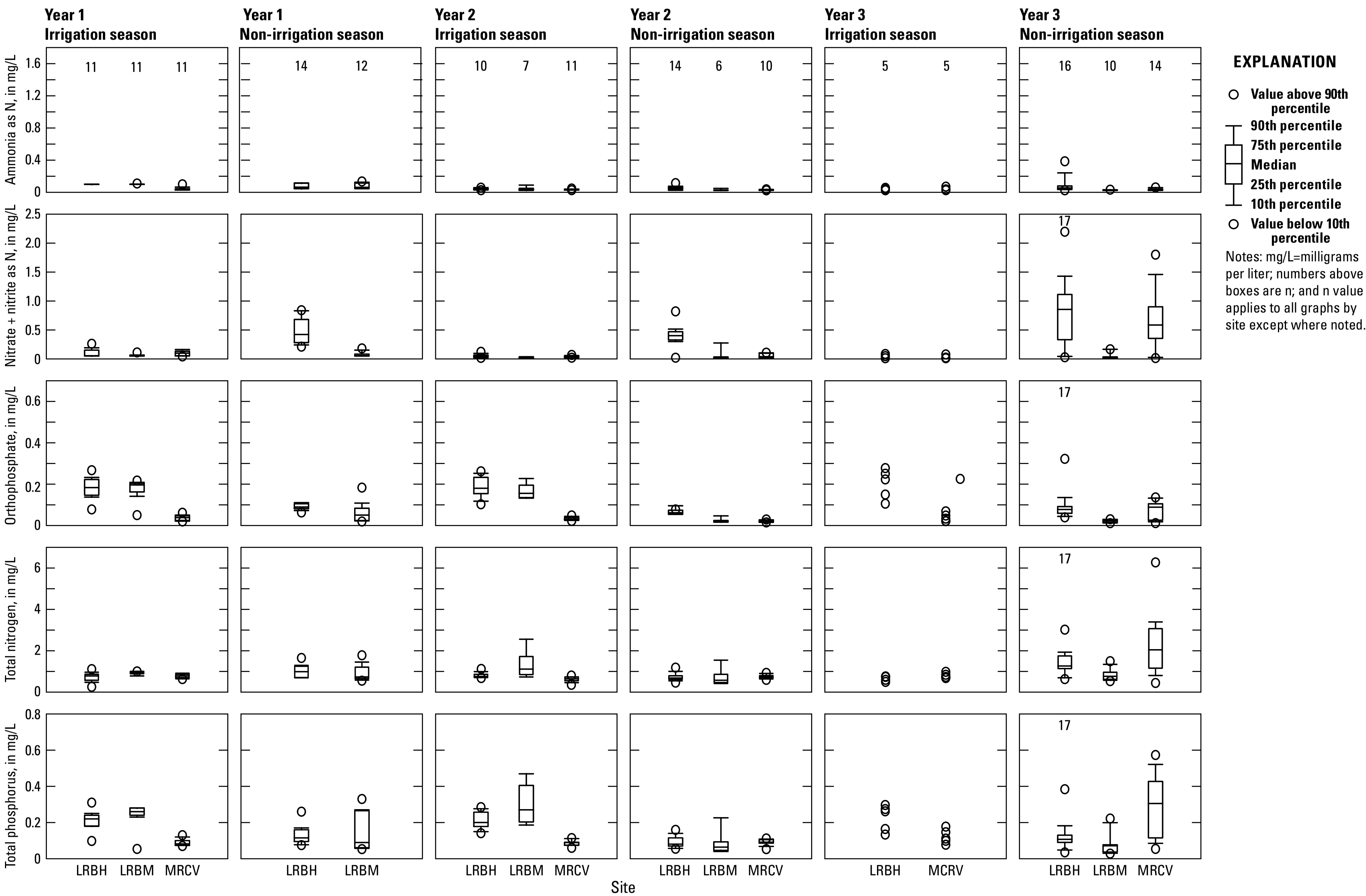


Figure 6. Nutrient concentrations at upper Lost River Basin sites, south-central Oregon, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

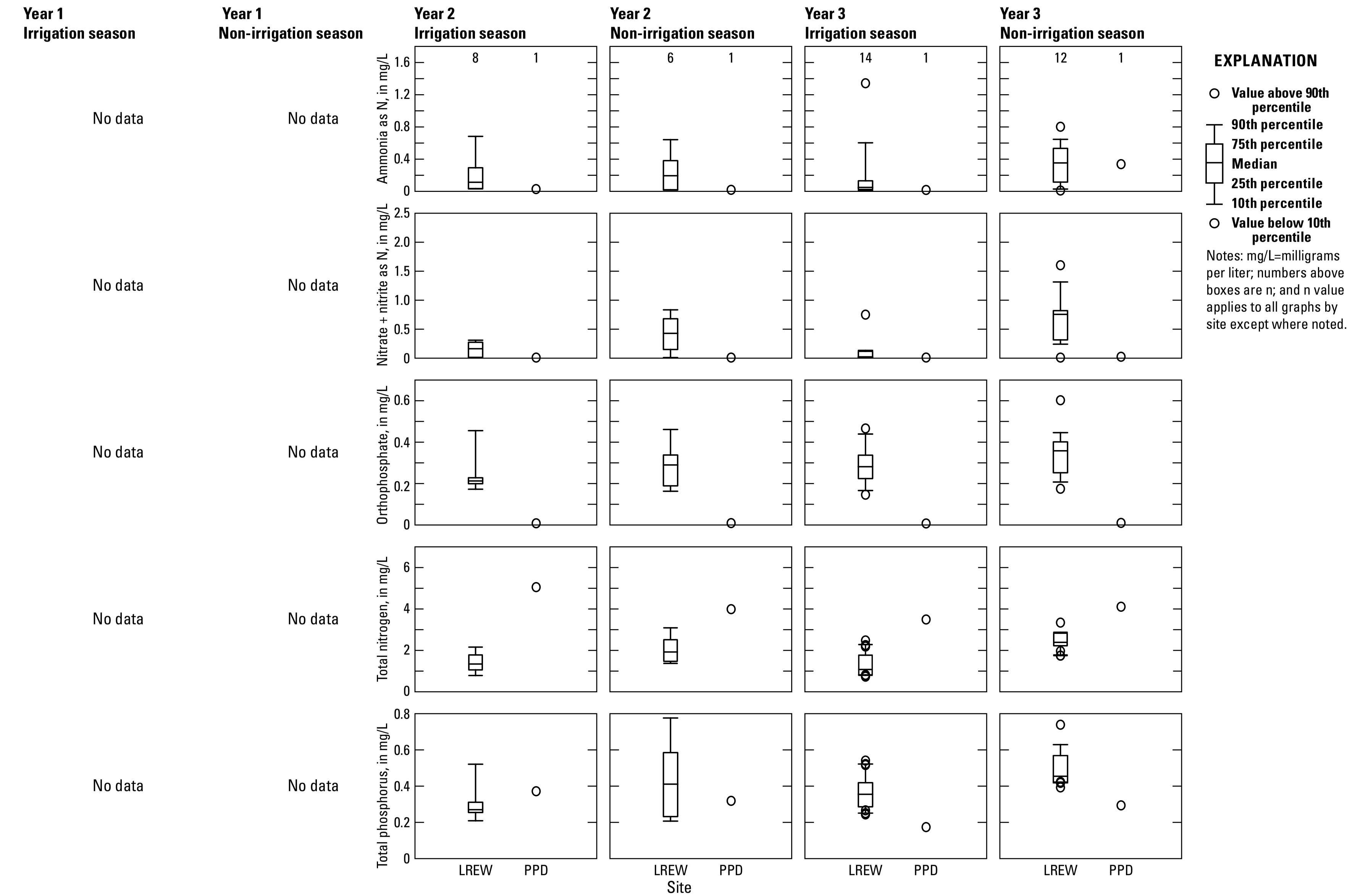


Figure 7. Nutrient concentrations at Tule Lake sites, northern California, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

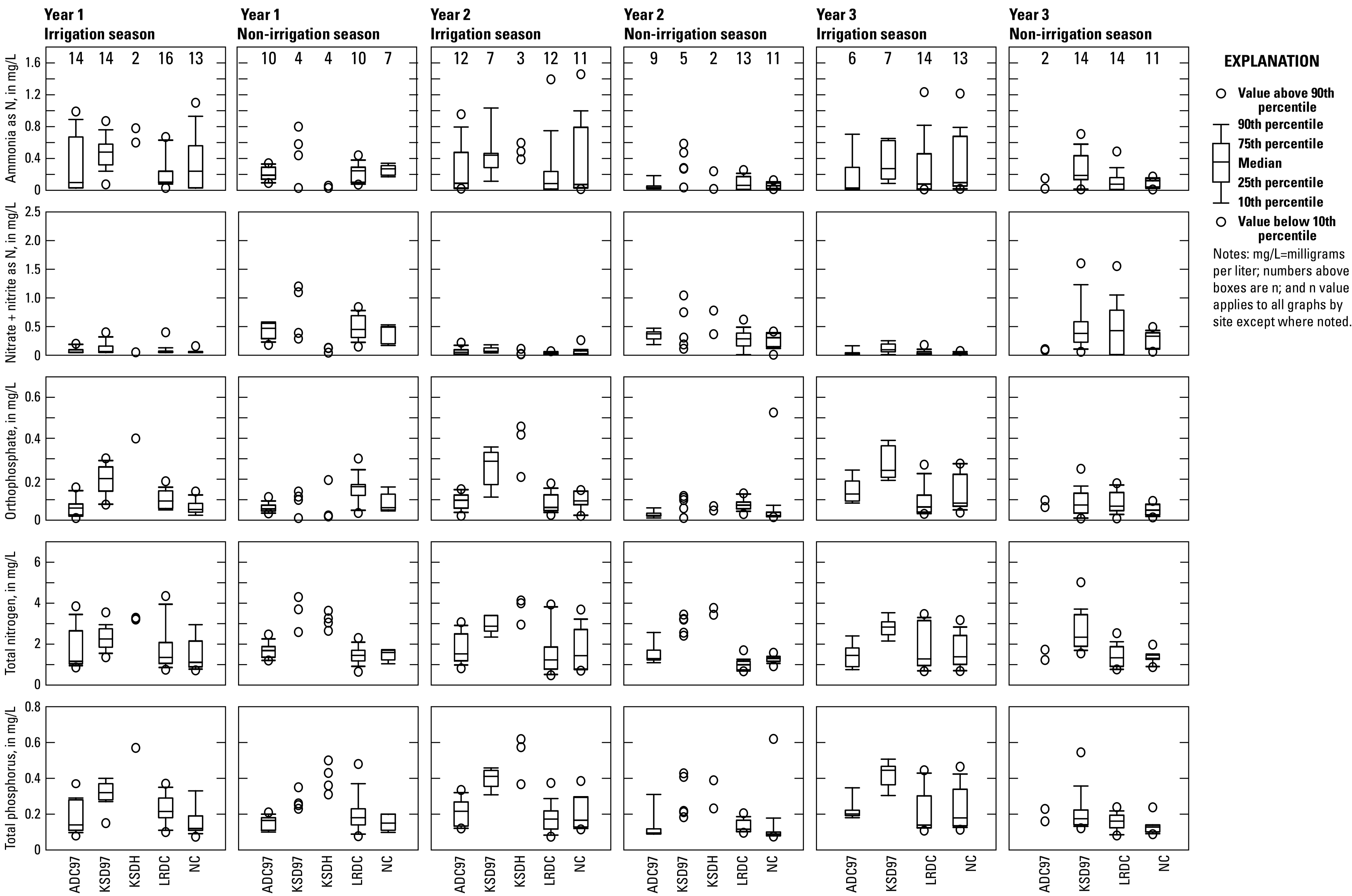


Figure 8. Nutrient concentrations at Klamath Drainage District sites, south-central Oregon, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

At the end member sites, ortho-P concentrations were statistically higher at site KRK than at site FMT for all three years of the study, and NO_3+NO_2 and NH_3 were not statistically different (table 6). During irrigation seasons, ortho-P and NH_3 concentrations had a wider range of values, higher median concentrations, and higher peak concentrations at site KRK compared to site FMT (fig. 5). Among the upper Lost River Basin sites, median ortho-P concentrations were highest at site LRBH in both irrigation and non-irrigation seasons, with the exception of non-irrigation year 3 (fig. 6). Median NH_3 concentrations were similar at the upper Lost River Basin sites for all 3 years regardless of irrigation season, and maximum values of NH_3 at site LRBH were highest in year 3 (fig. 6).

Concentrations of dissolved nutrients at site LREW were of similar ranges regardless of irrigation or non-irrigation season (fig. 7). Median ortho-P concentrations at the KDD sites followed patterns similar to patterns for TP, with sites KSDH and KSD97 having the highest concentrations in years 2 and 3, and site KSD97 having the highest median concentration in year three. Overall, site KSD97 had the highest median ortho-P concentrations during the irrigation seasons among the KDD sites (fig. 8). NO_3+NO_2 median concentrations typically were elevated at the KDD sites during non-irrigation seasons, and NH_3 median concentrations varied at all KDD sites in both irrigation and non-irrigation seasons (fig. 8).

Five-Day Biochemical Oxygen Demand (BOD_5), 5-Day Carbonaceous Biochemical Oxygen Demand ($CBOD_5$), and Chlorophyll-*a*

Because of the change in analyzing laboratories between years 1 and 2 of the study, MRLs for BOD_5 and $CBOD_5$ were different for year 1 and years 2 and 3 of the project. The MRL in year 1 was 2.00 mg/L, and 0.300 mg/L for years 2 and 3. As a result, median values for these constituents are reported as less than the year-1 MRL of 2.00 mg/L for some of the study sites (table 7).

Median concentrations of BOD_5 and $CBOD_5$ were lowest among the upper Lost River Basin sites and highest at site PPD (12.2 and 11.0 mg/L, respectively, albeit this comparison is based on only four samples collected at site PPD over the 3-year study period), and elevated at sites KSDH (6.60 and 4.70 mg/L, respectively) and KSD97 (4.47 and 3.35 mg/L, respectively). The highest maximum BOD_5 and $CBOD_5$ concentrations were reported at sites LRDC(+) (39.0 and 26.5 mg/L, respectively) and FMT (25.0 and 23.9 mg/L, respectively; table 7), likely representing the seasonal AFA blooms in Upper Klamath Lake. Median concentrations of chlorophyll-*a* were lowest at the upper Lost River Basin sites, moderate at sites FMT, KRK, LREW, LRDC, and NC, and elevated at sites KSDH and KSD97. The median concentration of chlorophyll-*a* was highest at site PPD (99.2 µg/L), and the maximum concentration of chlorophyll-*a* was highest at site FMT (330 µg/L).

At the end member sites, BOD_5 and $CBOD_5$ concentrations were not statistically different when data from all 3 years were evaluated with the Mann-Whitney U test. However, site FMT showed a wider range of values with higher maximum concentrations than site KRK during irrigation seasons (fig. 9), likely due to the content of AFA present in the samples during the summer algal bloom as represented by the elevated chlorophyll-*a* concentrations. The relation of chlorophyll-*a* and BOD_5/$CBOD_5$ concentrations has been shown by Sullivan and others (2010) in the Klamath River downstream of site FMT, and might suggest that chlorophyll-*a* is a predictor of BOD_5/$CBOD_5$ at some of the study sites. At the upper Lost River Basin sites, BOD_5 and $CBOD_5$ median concentrations were low compared to all the study sites, with multiple concentrations less than the MRL of 2.0 mg/L (fig. 10, table 7). Concentrations of BOD_5, $CBOD_5$, and chlorophyll-*a* were similar at all three upper Lost River Basin sites regardless of irrigation or non-irrigation season (fig. 10).

At site LREW, BOD_5 and $CBOD_5$ concentrations were similar regardless of irrigation or non-irrigation season, and chlorophyll-*a* concentrations had a higher range of values and higher maximum concentrations in non-irrigation seasons compared to irrigation seasons (fig. 11). Among the KDD sites, BOD_5, $CBOD_5$, and chlorophyll-*a* median concentrations varied at all sites, and site LRDC showed the widest range of values and highest maximum concentrations during the irrigations seasons, although concentrations for all three constituents were not statistically different at most of the sites when combining results from all 3 years (fig. 12, table 7).

Dissolved Organic Carbon, Total Particulate Carbon, and Total Particulate Nitrogen

The highest median concentration of DOC occurred at site KSDH in year 2 of the study (28.5 mg/L), when only two samples were collected. The second highest median DOC concentration was at site PPD (21.9 mg/L), also a site in which only two samples were collected. The highest maximum concentration among all sites also was collected at site KSDH (36.7 mg/L), the second highest maximum concentration was at site KSD97 (22.7 mg/L), followed by site PPD (22.0 mg/L). TPC and TPN median concentrations were highest at site PPD (10.9 and 1.77 mg/L, respectively), again with only two samples collected when the site was flowing (table 9).

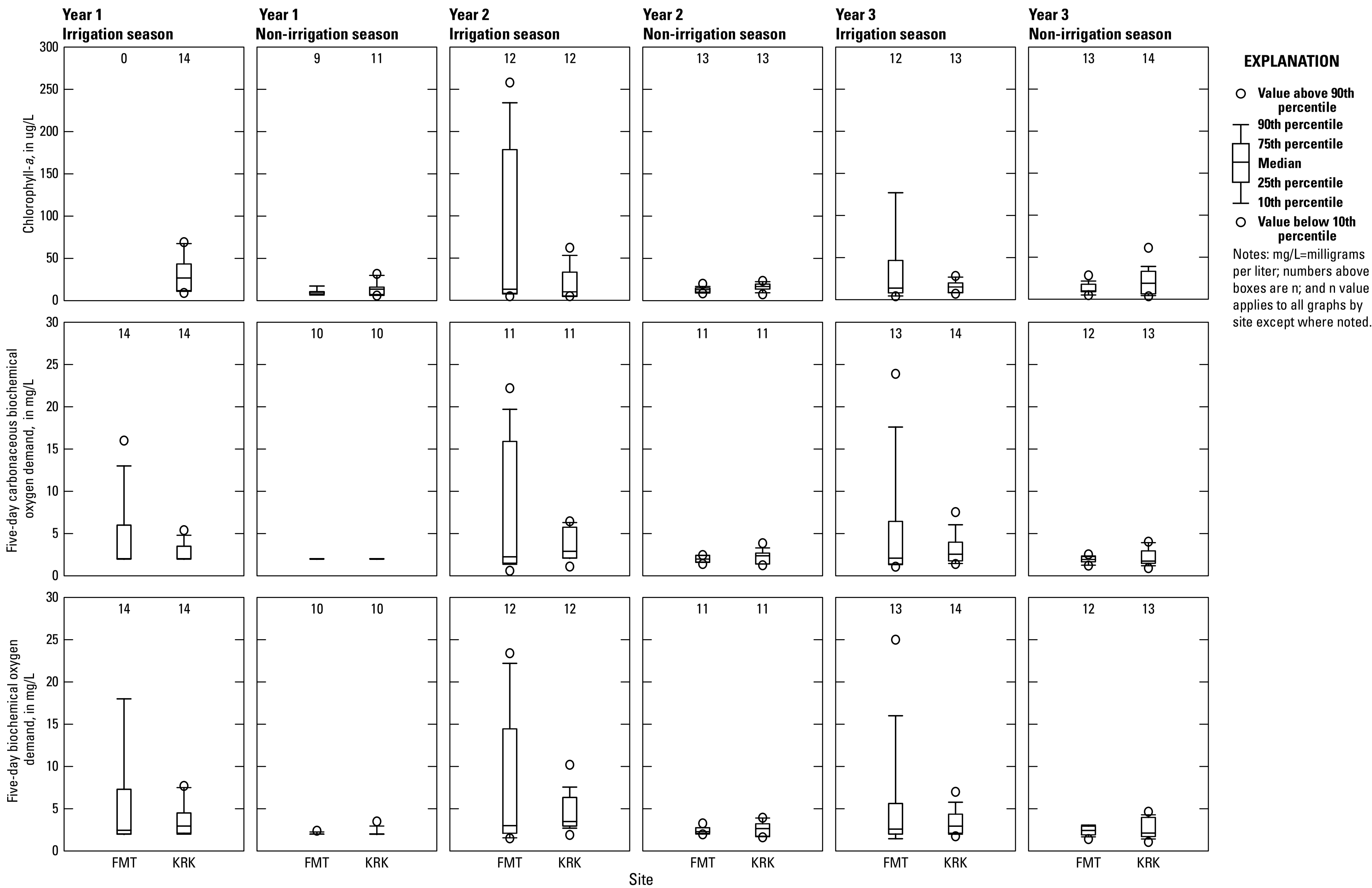


Figure 9. Five-day biochemical oxygen demand, 5-day carbonaceous biochemical oxygen demand, and chlorophyll-*a* sample results at end member sites, south-central Oregon, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

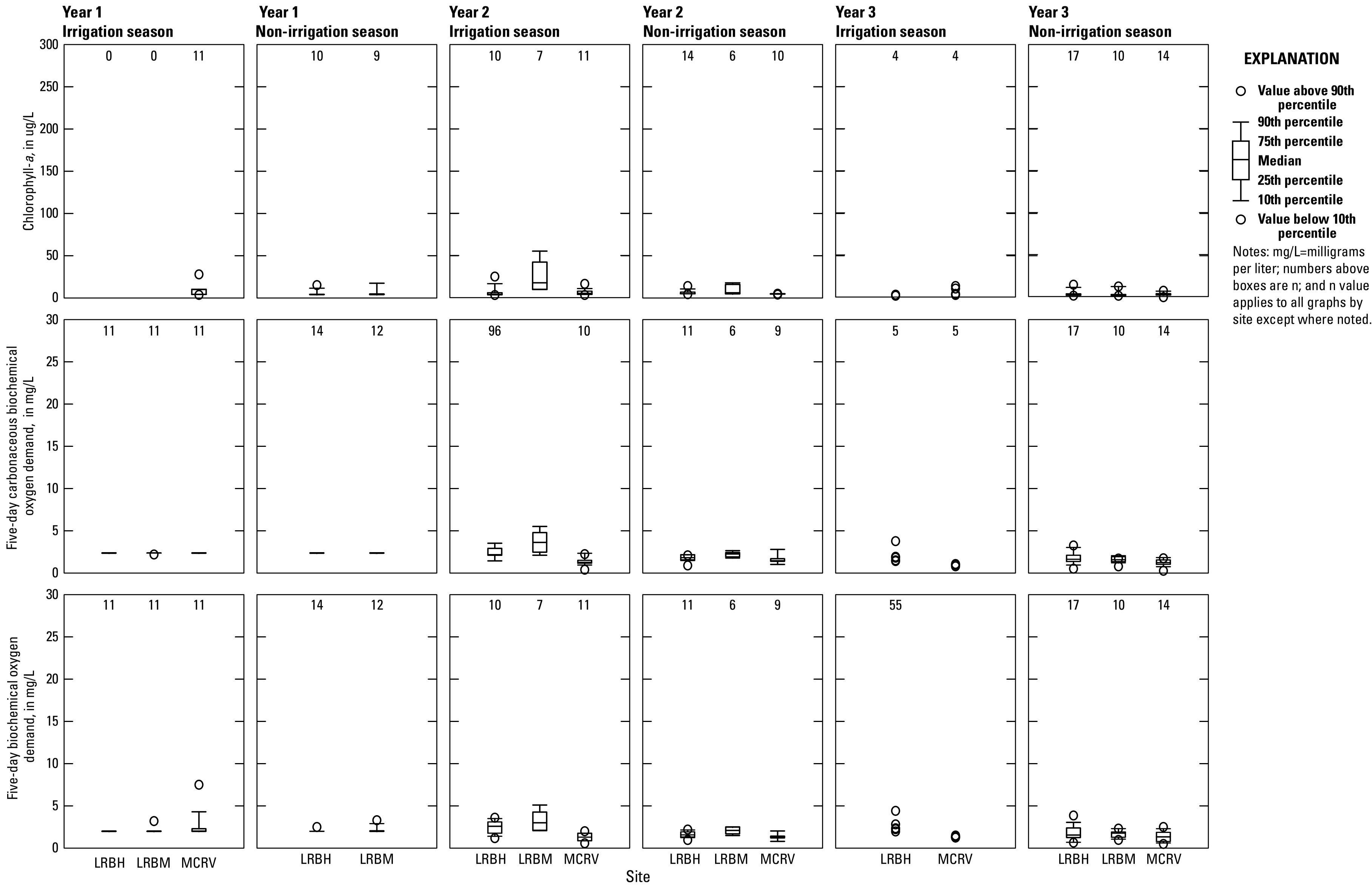


Figure 10. Five-day biochemical oxygen demand, 5-day carbonaceous biochemical oxygen demand, and chlorophyll-*a* sample results at upper Lost River Basin sites, south-central Oregon, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

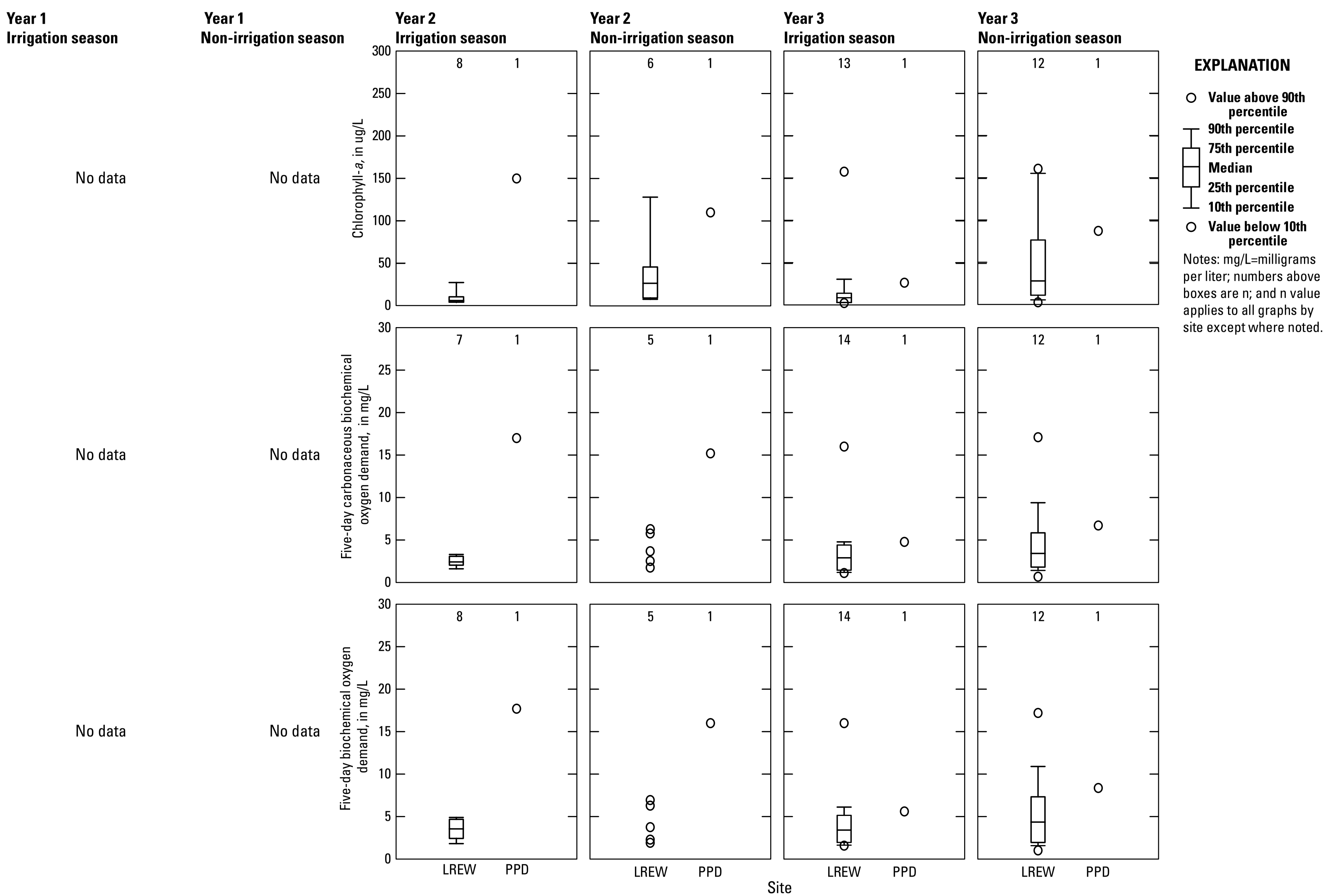


Figure 11. Five-day biochemical oxygen demand, 5-day carbonaceous biochemical oxygen demand, and chlorophyll-*a* sample results at Tule Lake sites, northern California, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

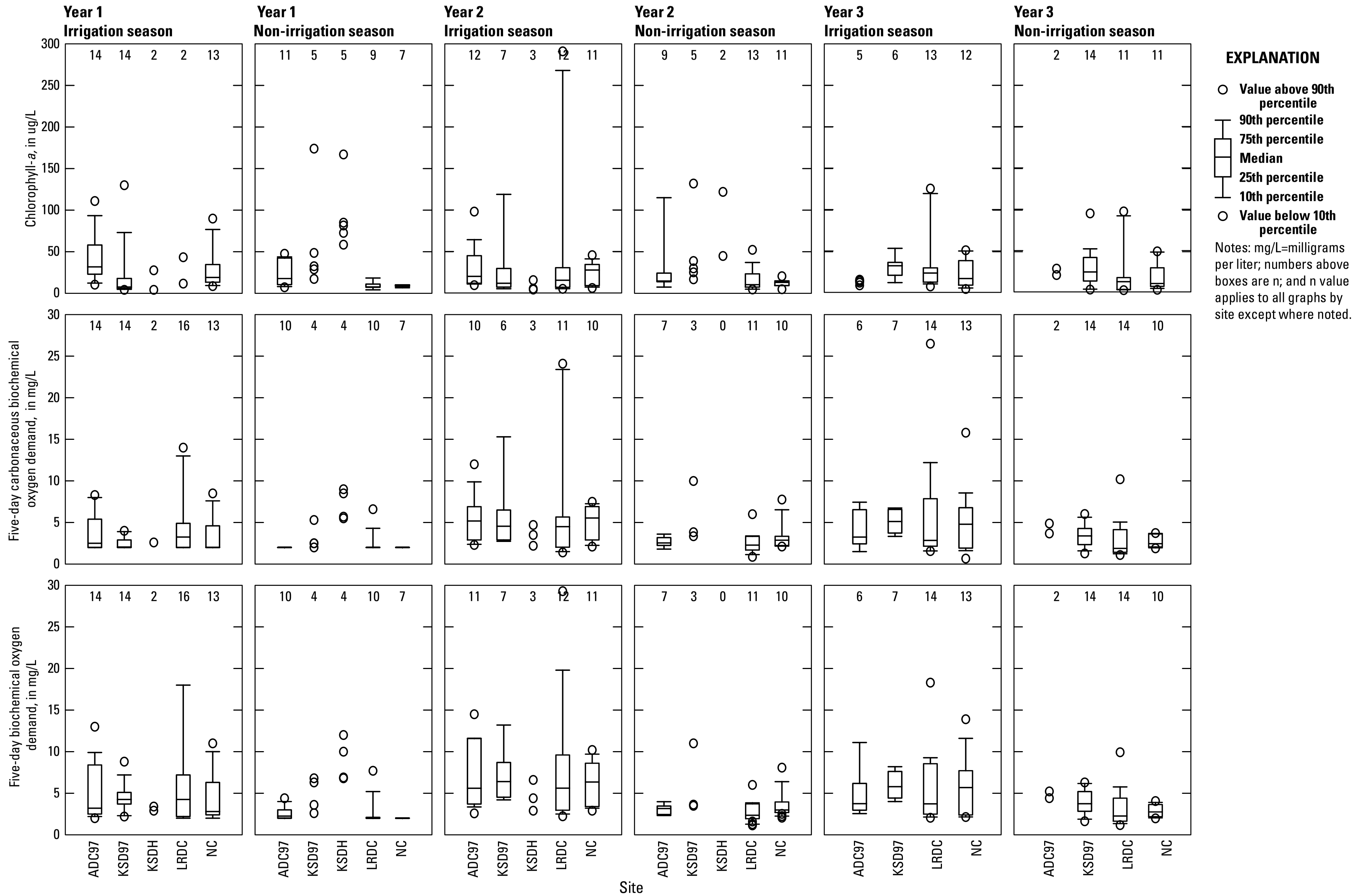


Figure 12. Five-day biochemical oxygen demand, 5-day carbonaceous biochemical oxygen demand, and chlorophyll-*a* sample results at Klamath Drainage District sites, south-central Oregon, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

Table 9. Summary statistics of dissolved organic carbon, total particulate carbon, and total particulate nitrogen sample results, Klamath River and Lost River Basins, south-central Oregon and northern California, March 2012–March 2015.

[Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Site name abbreviation:** LRDC (+) indicates samples that were collected when the flow direction was towards the Lost River; LRDC (-) indicates samples that were collected when the flow direction was toward the Klamath River. **Abbreviations**: DOC, dissolved organic carbon; n, number of samples; TPC, total particulate carbon; TPN, total particulate nitrogen; µg/L, microgram per liter; mg/L, milligram per liter; ND, no data ; <, less than]

Site name abbreviation	DOC (mg/L)				TPC (mg/L)				TPN (ug/L)			
	n	Median	Maximum	Minimum	n	Median	Maximum	Minimum	n	Median	Maximum	Minimum
Upper Lost River Basin												
LRBM	7	9.20	11.3	5.83	7	1.24	10.8	0.506	7	0.155	1.39	0.082
MCRV	11	5.84	8.64	4.96	11	0.915	8.40	0.463	11	0.122	1.36	<0.030
LRBH	12	6.63	9.45	1.61	12	0.665	2.61	0.368	12	0.074	0.418	<0.030
Tule Lake sites												
LREW	9	6.32	9.71	4.61	9	1.81	10.7	0.351	9	0.288	1.85	0.067
PPD	2	21.9	22.0	21.8	2	10.9	12.7	9.24	2	1.77	2.04	1.50
KDD sites												
KSDH	2	28.5	36.7	20.4	2	2.61	3.95	1.27	2	0.360	0.541	0.178
ADC97	9	6.45	9.24	4.06	9	2.15	4.13	1.75	9	0.357	0.830	0.278
NC	11	5.49	7.58	4.15	11	1.66	5.97	0.923	11	0.274	0.919	0.147
LRDC (+)	6	5.20	7.25	4.33	6	2.7	5.84	0.687	6	0.458	1.26	0.084
LRDC (-)	7	4.66	6.69	2.73	7	1.35	3.10	0.673	7	0.235	0.624	0.087
KSD97	10	18.3	22.7	9.09	10	2.11	8.10	0.901	10	0.315	1.10	0.114
End member sites												
FMT	11	4.11	6.45	3.00	11	1.79	8.22	1.10	11	0.308	1.59	0.063
KRK	13	6.12	8.67	3.98	13	1.68	6.08	1.03	13	0.255	1.11	0.125

DOC concentrations were highest overall at site KSDH when it was sampled, and also were elevated at sites PPD and KSD97. Sites PPD and KSD97 also showed the highest median TPC concentrations. Median DOC concentrations at sites other than sites KSDH and KSD97 were much lower, with concentrations less than 10 mg/L. Median DOC concentrations increased from site LREW(6.32 mg/L) upstream of Tule Lake to site PPD (21.9 mg/L) and then to site KSDH (28.5 mg/L), but were lower at site KSD97 (18.3 mg/L). TPC did not follow this trend, in that TPC concentrations increased from sites LREW (1.81 mg/L) to PPD (10.9 mg/L), again resulting in increased concentrations from Tule Lake, but were lower at site KSDH (2.61 mg/L), and lower still at site KSD97 (2.11 mg/L) (table 9). However, with only two samples collected at sites PPD and KSDH over the 3-year study period, compared to 10 samples collected at KSD97, these relations are not well defined by the available data. Additionally, during the dry years of this study, the flowpath from sites LREW to KSD97 was largely discontinuous, and sample concentrations at site KSD97 were more influenced by Ady and North Canals than site KSDH during those years.

The median TPN concentration was highest at site PPD, based on two samples, and the median TPN concentration was lowest at site LRBH in the upper Lost River Basin. The second highest concentration occurred at site LRDC(+) when water was flowing from the Klamath River to the Reclamation project. Overall, median TPN concentrations were highest at site PPD, and sites within the KDD that divert water from the Klamath River, as well as at site FMT (which represents Klamath Lake water). The concentrations were lowest in the upper Lost River Basin at sites LRBM, MCRV, and LRBH (table 9).

Load Estimates

TP, TN, BOD_5, and $CBOD_5$ loads are presented in tables for each site during the irrigation and non-irrigation seasons for the 3 years of the study. Loads at two of the sites (sites FMT and KRK) were computed using the LOADEST model. All other sites are reported as the average of computed instantaneous loads during the irrigation or non-irrigation seasons.

Klamath River at Keno (Site KRK) LOADEST Model Results

As explained in the section, "Methods," multivariate and seasonal wave regression models were evaluated to compute loads of TP, TN, BOD_5, and $CBOD_5$. Seasonal wave models best described loads of TN and TP, and a four-parameter regression model best described loads of BOD_5 and $CBOD_5$ (table 10). For TN and TP, the seasonal wave models were a better fit because the regulated flows downstream of Keno Dam had little effect on the concentrations of those constituents. Instead, the data fluctuate seasonally, with concentration peaks occurring during the summer (fig. 13). A time series of computed daily TP and TN loads using the seasonal wave, plus 95-percent prediction intervals, is shown in figure 14. Daily TP loads modeled (computed) with LOADEST ranged from 50 to 930 kg/d for the 3 years of the study. The minimum instantaneous TP load used in the calibration dataset was 48 kg/d, and the maximum load was 856 kg/d. Daily TN loads computed with LOADEST ranged from 730 to 8,711 kg/d for the three study years. The minimum instantaneous TN load used in the calibration dataset was 625 kg/d, and the maximum was 7,000 kg/d. Statistics and model summaries for rejected models are shown in appendix 1.

The LOADEST-selected best fit model for BOD_5 was a four parameter model with components of streamflow and seasonality as explanatory variables (table 10). The LOADEST-selected best fit $CBOD_5$ model was a five parameter model with components of streamflow, seasonality, and decimal time. The next-lowest AIC-scored model for $CBOD_5$ was the four parameter model, an identical model form to the best-fit BOD_5 model. The model results of the four and five parameter CBOD model showed a similar R^2 between the two models, and similar bias percentages, but the five-parameter model included two non-significant ($p>0.05$) explanatory variables compared to one non-significant explanatory variable for the four-parameter model.

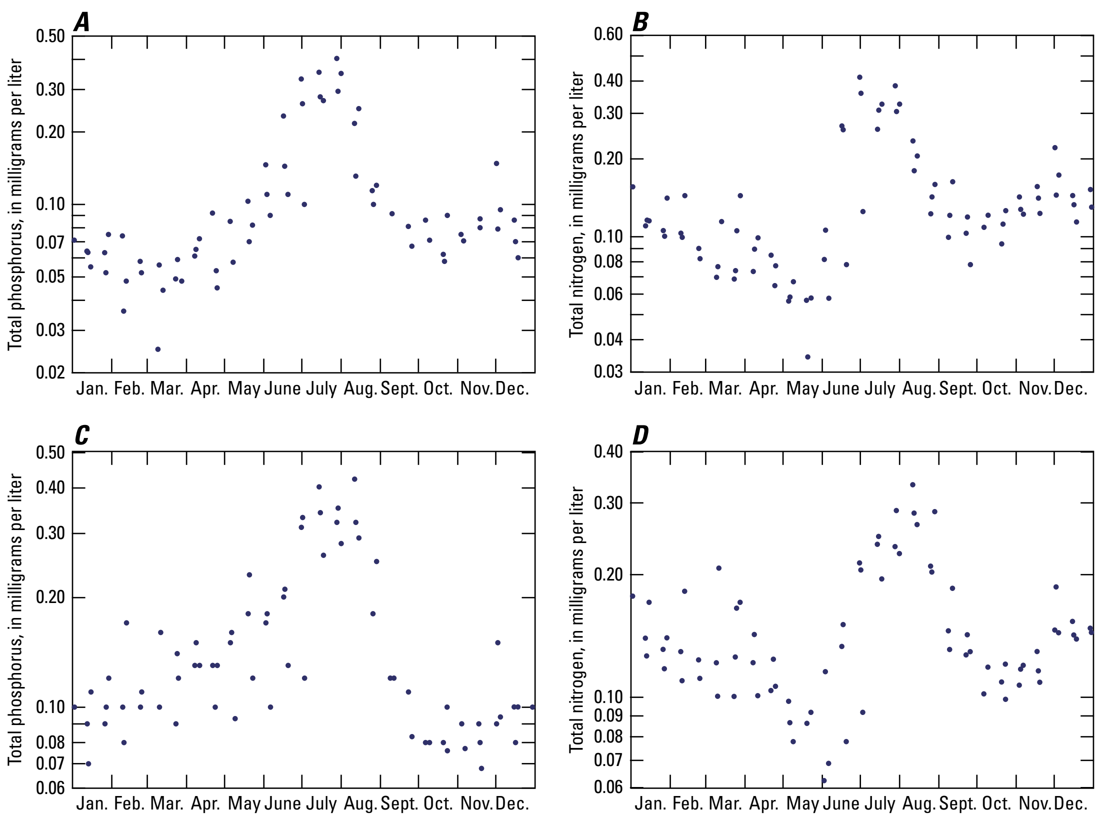


Figure 13. Seasonal peak concentrations of (*A*) total phosphorus at site FMT, (*B*) total nitrogen at site FMT, (*C*) total phosphorus at site KRK, and (*D*) total nitrogen at site KRK, south-central Oregon, March 2012–March 2015. Site names and descriptions are shown in table 1; site locations are shown in figure 1.

Table 10. Model statistics for LOADEST results at Klamath River at sites KRK and FMT, south-central Oregon.

[Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Abbreviations:** 5-day BOD_5, biochemical oxygen demand; 5-day $CBOD_5$, carbonaceous biochemical oxygen demand; dtime, decimal time; ln, natural logarithm; PPCC, probability plot correlation coefficient; Q, streamflow; TN, total nitrogen; TP, total phosphorus; >, greater than; < less than]

Constituent	Model type	Number of observations in calibration dataset	Number of uncensored observations in calibration dataset	Model equation	Coefficient of determination (R^2)	PPCC	Load bias percentage (Bp)
				Klamath River at Keno (site KRK)			
TP	Seasonal wave	72	72	ln(TP) = 5.9 + 1.06center(ln(Q)) + 1.10seasonalWave(dtime,0.60,3,1)	0.82	0.99	0.23
TN	Seasonal wave	77	77	ln(TN) = 8.2 + 0.90center(ln(Q)) + 0.82seasonalWave(dtime,0.62,2,1)	0.76	0.99	0.15
BOD_5	Four parameter	74	63	ln(BOD) = 8.60 + 0.59 ln(Q) + 0.084sin(2πdtime) – 0.45cos(2πdtime)	0.53	0.99	3.31
$CBOD_5$	Four parameter	73	56	ln(CBOD) = 8.40 + 0.48ln(Q) + 0.081sin(2πdtime) – 0.45cos(2πdtime)	0.46	0.98	4.50
				Fremont Bridge (site FMT)			
TP	Seasonal wave	77	77	ln(TP) = 5.76 + 0.99center(ln(Q)) + 1.62(seasonalWave(dtime,0.57,2,1)	0.91	0.97	0.170
TN	Seasonal wave	77	77	ln(TN) = 8.16 + 0.83center(ln(Q)) + 1.44(seasonalWave(dtime,0.50,1,4)	0.84	0.99	-1.95
BOD_5	Seasonal wave	74	74	ln(BOD) = 9.286 + 0.815center(lnQ) – 1.943seasonalWave(dtime,0.34,9,1)	0.84	0.99	-11.01
$CBOD_5$	Seasonal wave	73	73	ln(CBOD) = 9.17 + 0.785center(lnQ) – 2.06seasonalWave(dtime,0.35,9,1)	0.83	0.98	-13.1

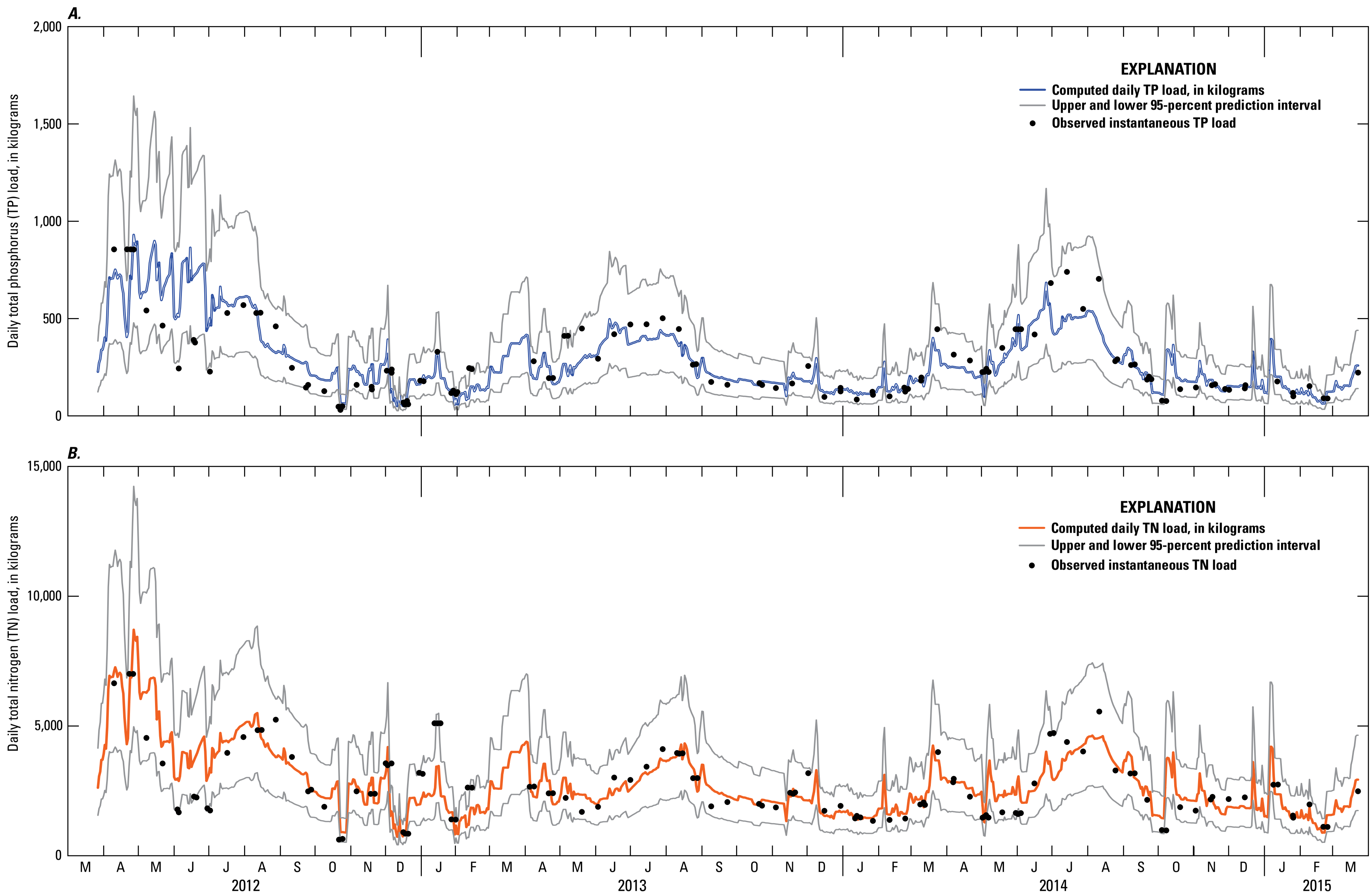


Figure 14. Time series of computed daily loads, associated 95-percent prediction intervals, and observed instantaneous loads of total phosphorus (*A*), and total nitrogen (*B*) at site KRK, south-central Oregon, March 2012–March 2015. Site name and description are shown in table 1; site location is shown in figure 1.

Because model statistics were similar between the two models, the four-parameter model was selected to compute loads to reduce bias in the load predictions by reducing the number of non-significant explanatory variables. A time series of computed daily BOD_5 and $CBOD_5$ loads plus 95-percent prediction intervals is shown in figure 15. A number of the BOD_5 and $CBOD_5$ analytical results were reported as “less than” the reporting limit of the analyzing laboratory, so the LOADEST models for these two parameters contained censored values in the calibration dataset. Coefficients of determination were lower for BOD_5 (R^2=0.53) and $CBOD_5$ (R^2=0.46) than the seasonal wave models for TP and TN, but load bias percentages (Bp) were still less than 5 percent for both models (table 10).

Comparison of modeled daily loads from LOADEST and measured loads from instantaneous discrete samples and streamflow shows better agreement for the TP and TN models compared to the BOD_5 and $CBOD_5$ models at site KRK (fig. 16). The BOD_5 and $CBOD_5$ models tend to have the highest percent difference when the models were underestimating the measured loads in July and August, and when the models were overestimating the loads in May and June. This trend suggests that the LOADEST model does not accurately characterize the peak loads of BOD_5 and $CBOD_5$ in mid-to-late summer when the AFA biomass is reaching seasonal peak levels in the Klamath River, and that the parameters available in the model are not adequately describing a process that causes the peak loads to occur.

Fremont Bridge (site FMT) LOADEST Model Results

The model-selection process at site FMT followed the same process used at site KRK. TP and TN concentrations showed strong seasonal patterns (fig. 13), and, thus, seasonal wave models were selected for both of these constituents (table 10). The strong seasonal patterns for TP and TN at this site on the south end of Upper Klamath Lake likely represent the summer peak concentrations of these constituents, which are coincident with the persistent algal bloom in the lake. A time series of computed daily TP and TN loads using the seasonal wave, plus 95-percent prediction intervals, is shown in figure 17. Daily TP loads computed with LOADEST ranged from 32 to 1,872 kg/d for the 3 years of the study. The minimum instantaneous TP load used in the calibration data set was 33 kg/d, and the maximum was 1707 kg/d. Daily TN loads computed with LOADEST ranged from 570 to 16,467 kg/d for the three study years. The minimum instantaneous TN load used in the calibration data set was 672, and the maximum load was 16,431. Statistics and model summaries for rejected models are shown in appendix 1.

BOD_5 and $CBOD_5$ loads at site FMT initially were best described by a four-parameter model with streamflow and seasonality terms as explanatory variables. After the modeled daily loads, prediction intervals, and measured instantaneous loads were plotted, these models were shown to underestimate the measured instantaneous loads. Seasonal wave models better explained the measured loads for both BOD_5 and $CBOD_5$, although uncertainty around both of these estimates was high, particularly during the summer when algal biomass is high in the lake (fig. 18). Coefficients of determination were slightly lower for BOD_5 (R^2=0.84) and $CBOD_5$ (R^2=0.83) (table 10) than for the seasonal wave models for TP and TN. Load bias percentages (Bp) were greater for BOD_5 (-11.01 percent) and $CBOD_5$ (-13.1 percent) compared to results at site KRK, where Bp values for both BOD_5 and $CBOD_5$ were less than 5 percent.

Comparison of modeled loads from LOADEST and measured loads from instantaneous discrete samples and streamflow shows better agreement for the TP and TN models compared to the BOD_5 and $CBOD_5$ models at site FMT (fig. 19). As with site KRK, the BOD_5 and $CBOD_5$ models at site FMT tended to have the highest percent difference when the models were underestimating the measured loads, except that the models at site FMT resulted in underestimation in June and July. Model overestimation occurred in April and May at site FMT, compared to May and June at site KRK. This trend suggests that the LOADEST model does not accurately characterize the peak loads of BOD_5 and $CBOD_5$ in mid-to-late summer when the AFA biomass is reaching seasonal peak levels in Upper Klamath Lake, and that the parameters available in the model also are not adequately describing a process that causes the peak loads to occur at this site.

The computation of loads at sites KRK and FMT allows for direct comparison of the upper and lower boundaries for this study during irrigation and non-irrigation seasons. Loads at site FMT generally were higher than loads at site KRK during irrigation seasons for all constituents, and lower than loads at site KRK during non-irrigation seasons, but well within the 95-percent prediction intervals for those models (table 11). Most notable are the BOD_5 and $CBOD_5$ loads at site FMT, which were an order of magnitude higher than loads at site KRK during all irrigation seasons. Because irrigation season coincides with the seasonal algal blooms in Upper Klamath Lake, the large load values for BOD_5 and $CBOD_5$ likely represent the oxygen demand of AFA in the samples collected from site FMT. At both sites, constituent loads were higher during irrigation season compared to non-irrigation seasons, although the magnitude of differences was different depending on the constituent.

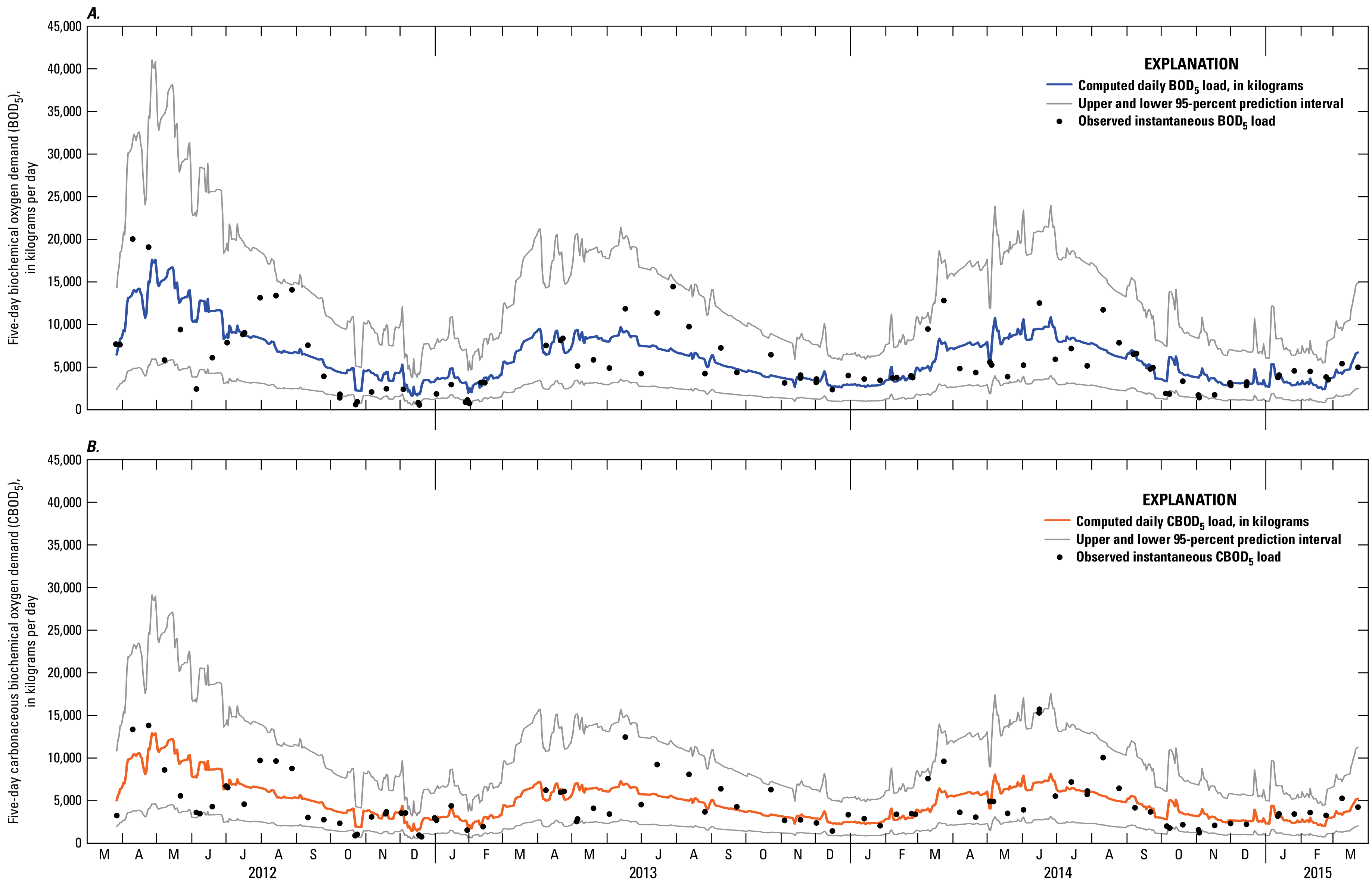


Figure 15. Time series of computed daily loads, associated 95-percent prediction intervals, and observed instantaneous loads of 5-day biochemical oxygen demand (*A*), and 5-day carbonaceous biochemical oxygen demand (*B*) at site KRK, south-central Oregon, March 2012–March 2015. Site name and description are shown in table 1; site location are shown in figure 1.

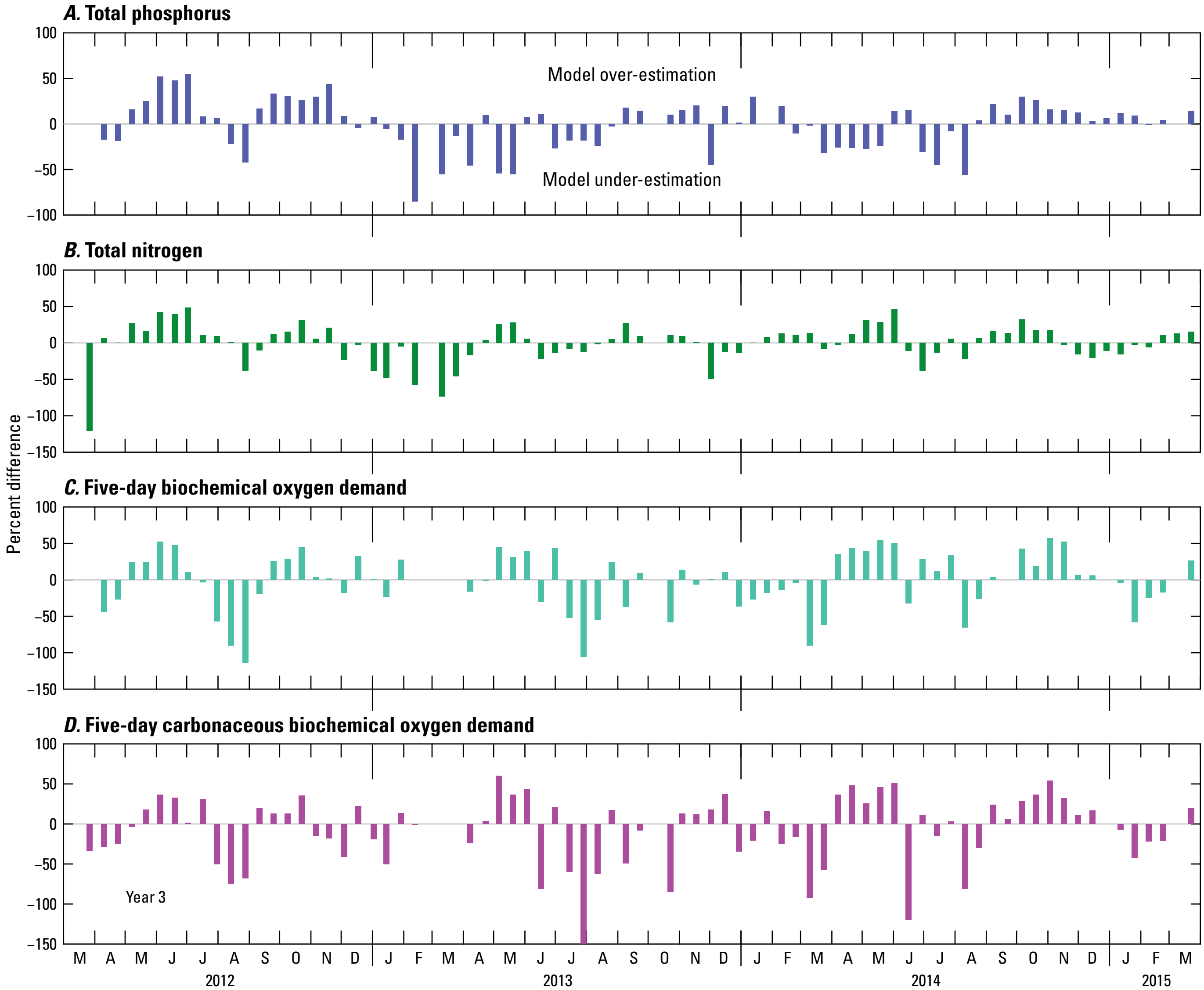


Figure 16. Percent difference between modeled (LOADEST) and measured loads for total phosphorus (*A*), total nitrogen (*B*), 5-day biochemical oxygen demand (*C*), and 5-day carbonaceous biochemical oxygen demand at site KRK (*D*), south-central Oregon, March 2012–March 2015. Site name and description are shown in table 1; site location is shown in figure 1.

Instantaneous and Daily Load Averaging Results

Nutrient loads at the remaining study sites, not including sites FMT and KRK, were calculated by averaging instantaneous loads for irrigation and non-irrigation seasons as described in the section, "Methods." The sites are evaluated based on their geographic location within the project by separating them into three distinct groups—(1) Upper Lost River Basin (sites LRBM, MCRV, and LRBH); (2) Tule Lake sites (LREW and PPD), and (3) Klamath Drainage District (KDD) sites (KSDH, ADC97, NC, LRDC, KSD97). The KDD sites were selected because they are either managed for water delivery within the KDD, or because irrigation and return flows from irrigation areas within KDD have the potential to affect water quality at a study site. Site LRDC was included in this group because of its spatial location and so it could be grouped with the other canal sites, but site LRDC does not supply water to the KDD. Water flowing in site LRDC is delivered either to the Tulelake Irrigation District lands, or the Klamath Irrigation District lands. Loads at site LRDC are represented as either negative (flowing to the Klamath River) or positive (flowing towards the Lost River), consistent with the flow direction data reported at the streamgage.

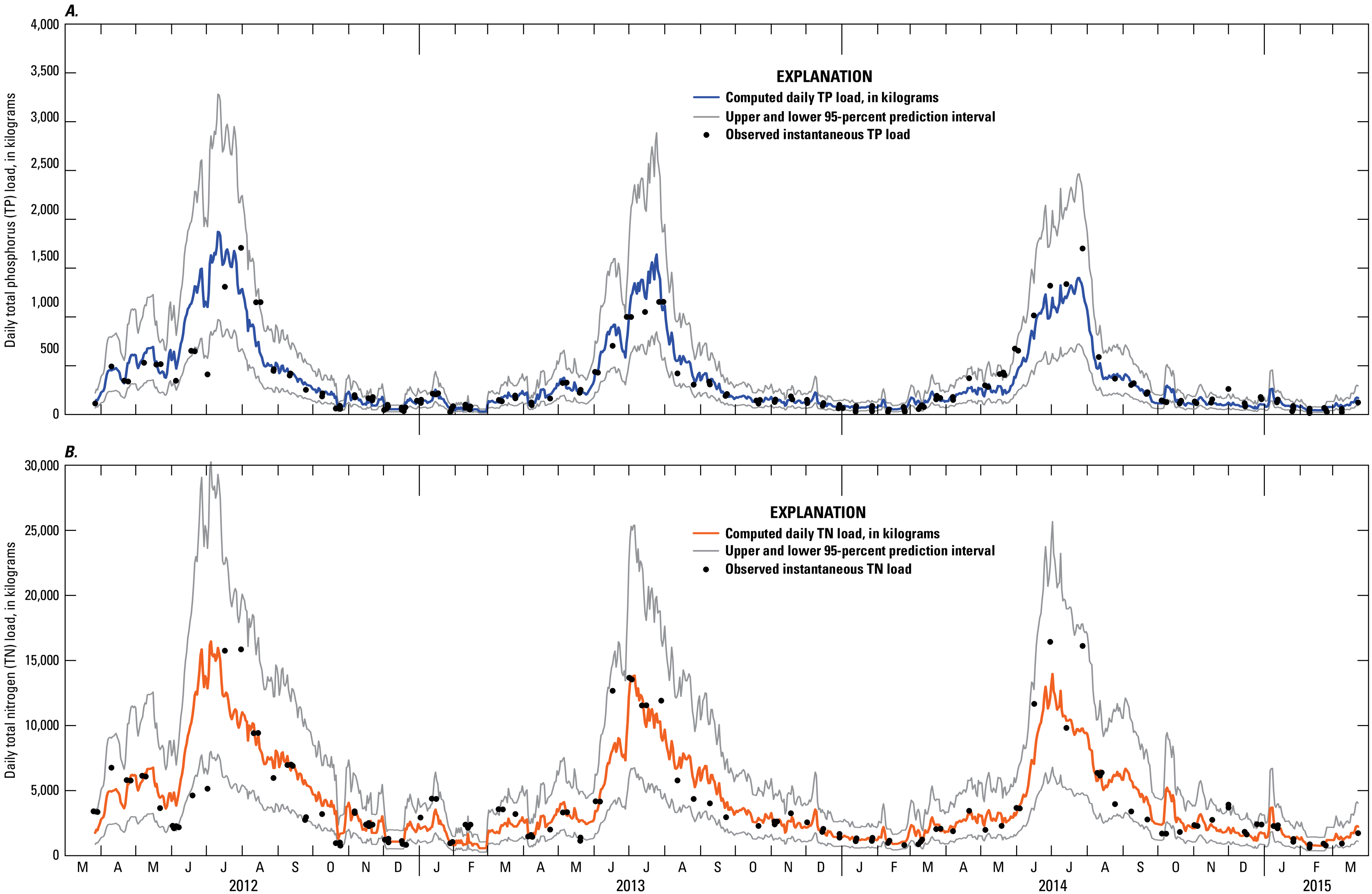


Figure 17. Time series of computed daily loads, associated 95-percent prediction intervals, and observed instantaneous loads of total phosphorus (*A*), and total nitrogen (*B*) at site FMT, south-central Oregon, March 2012–March 2015. Site name and description are shown in table 1; site location is shown in figure 1.

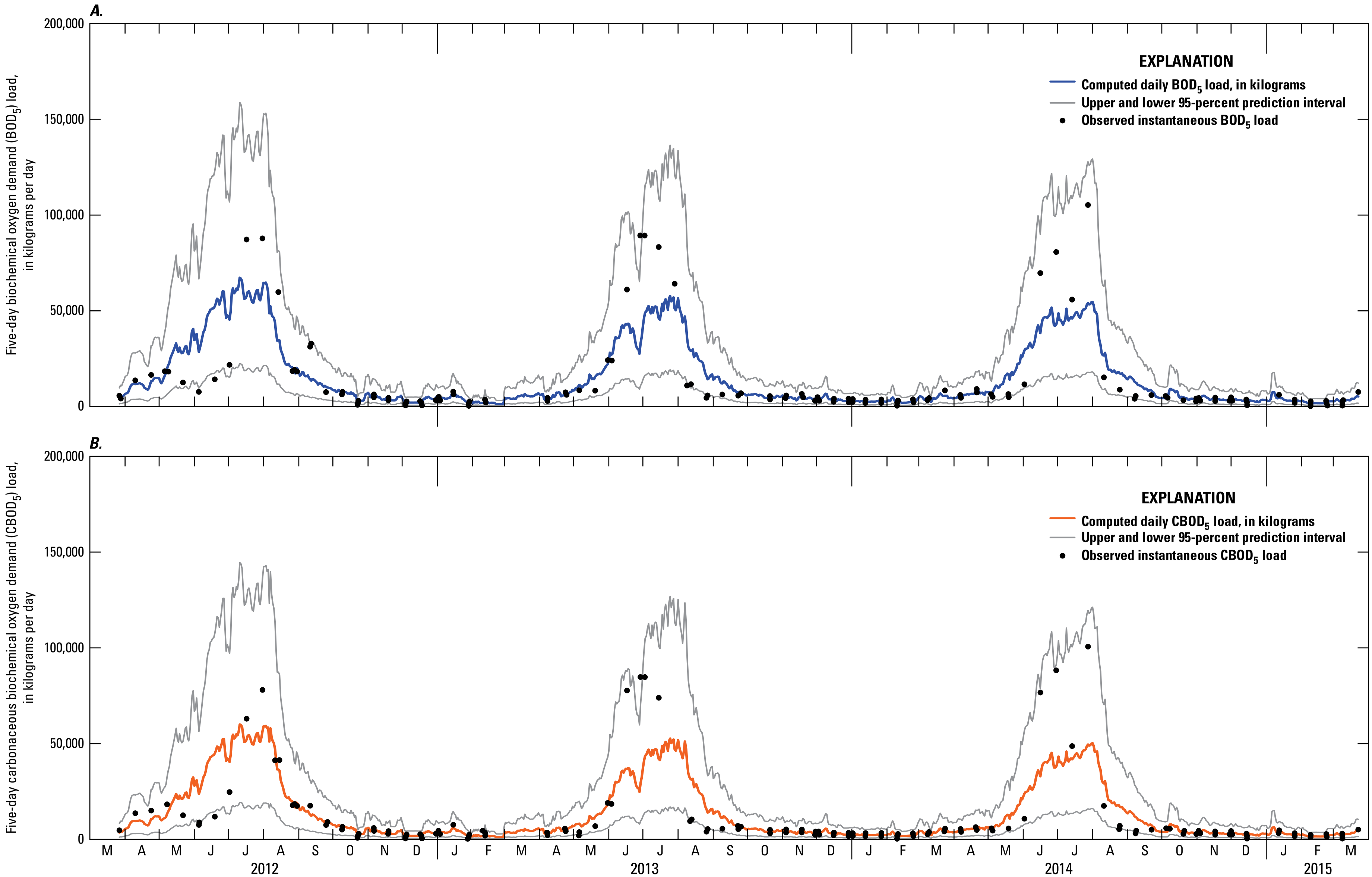


Figure 18. Time series of computed daily loads, associated 95-percent prediction intervals, and observed instantaneous loads of 5-day biochemical oxygen demand (*A*), and 5-day carbonaceous biochemical oxygen demand (*B*) at site FMT, south-central Oregon, March 2012–March 2015. Site name and description are shown in table 1; site location is shown in figure 1.

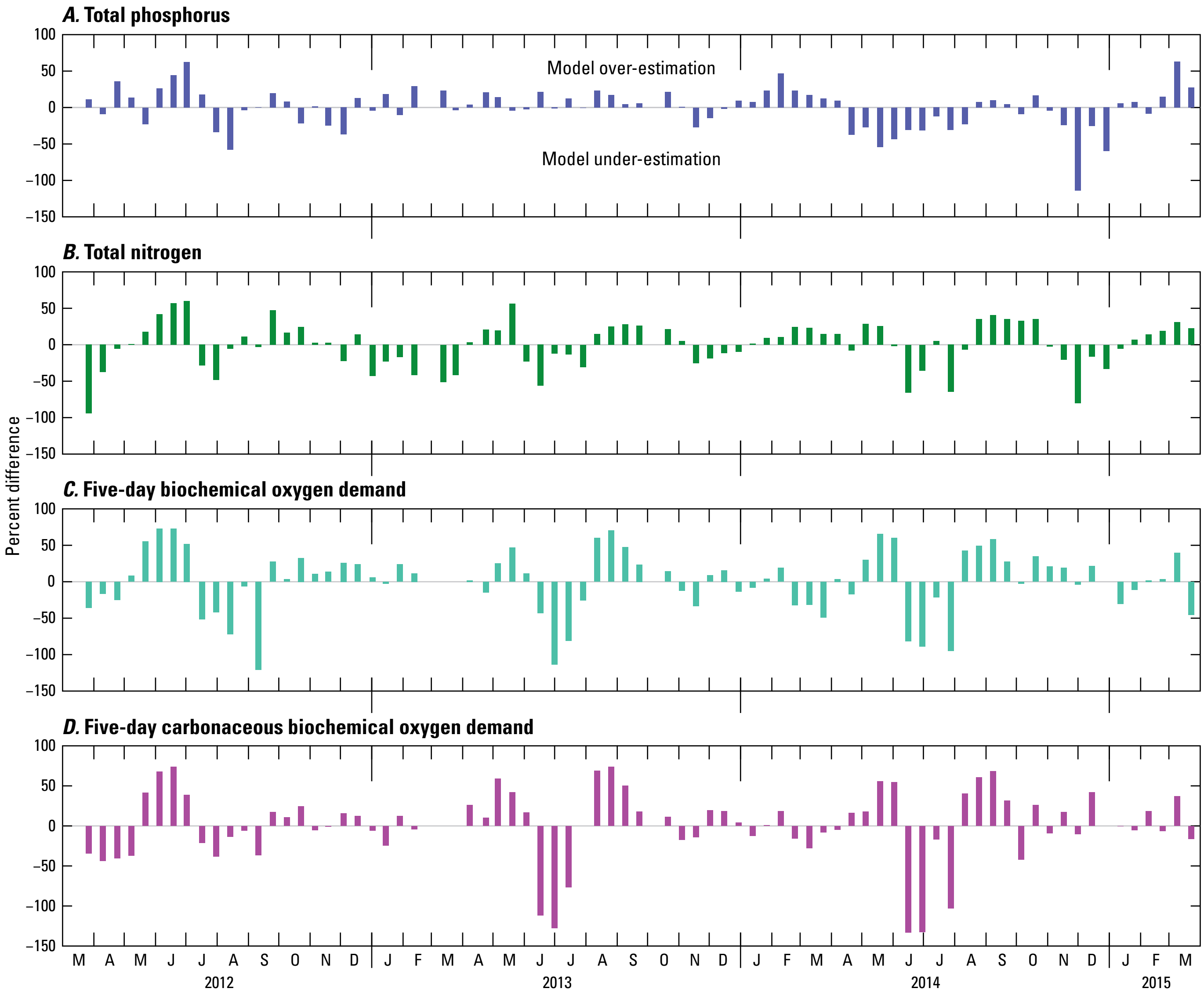


Figure 19. Percent difference between modeled (LOADEST) and measured loads for total phosphorus (*A*), total nitrogen (*B*), 5-day biochemical oxygen demand (*C*), and 5-day carbonaceous biochemical oxygen demand (*D*) at site FMT, March 2012–March 2015, south-central Oregon. Site name and description are shown in table 1; site location is shown in figure 1.

Upper Lost River Basin Sites

Average loads of TP and TN were lower at site LRBM (the farthest upstream site in the study) during irrigation and non-irrigation seasons compared to sites MCRV and LRBH (table 12). TP and TN loads at site LRBM were lower during irrigation season compared to non-irrigation season for all three study years, which was atypical compared to other monitoring sites. No samples were collected during irrigation year 3 because of the lack of streamflow at that site, so loads are represented as zero. Average TP and TN loads at site LRBH were higher during the non-irrigation season compared to irrigation season. Streamflows are higher at that site during non-irrigation seasons because much of the water in Lost River is diverted upstream of the sampling location during irrigation season. Fewer samples were collected at all sites during irrigation season year 3 (summer 2014) owing to lack of water from the eastern side of the Reclamation project because of drought conditions. No samples were collected at site LRBM because of lack of streamflow, and only five samples were collected at sites MCRV and LRBH.

Table 11. Average modeled (LOADEST) mean daily loads of total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand at sites FMT and KRK during irrigation and non-irrigation seasons, south-central Oregon, March 2012–March 2015.

[Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Abbreviations:** ft^3/s, cubic foot per second; kg/d, kilogram per day]

Site name abbreviation	Total phosphorus (kg/d)	Total nitrogen (kg/d)	Biological oxygen demand (kg/d)		Average streamflow (ft^3/s)
			5-day	5-day carbonaceous	
Irrigation year 1 (201 days)					
FMT	726	7,590	29,700	26,300	2,200
KRK	527	4,450	9,750	7,410	1,291
Non-irrigation year 1 (145 days)					
FMT	111	1,870	3,700	3,150	655
KRK	172	2,060	3,670	3,040	678
Irrigation year 2 (189 days)					
FMT	555	5,990	24,200	21,800	1,480
KRK	302	2,760	6,980	5,410	689
Non-irrigation year 2 (168 days)					
FMT	120	1,950	3,990	3,390	715
KRK	188	2,220	4,270	3,470	739
Irrigation year 3 (195 days)					
FMT	529	5,750	23,200	20,800	1,440
KRK	344	3,070	7,430	5,740	772
Non-irrigation year 3 (200 days)					
FMT	110	1,780	3,690	3,150	653
KRK	176	2,100	4,110	3,350	695

In contrast to sites LRBM and LRBH, TP and TN loads at site MCRV were higher during irrigation season compared to non-irrigation season in years 2 and 3. Instantaneous loads at site MCRV during the non-irrigation period in year 1 were calculated at zero because of zero flows reported by Reclamation for that time period. (Reclamation reported zero flow at site MCRV outside the irrigation seasons, and USGS did not begin streamflow measurements until year 2 of the study). Overall, TN and TP loads were highest at site MCRV for irrigation periods for all 3 years of the study, likely owing to higher streamflow during irrigation season at that site.

BOD_5 and $CBOD_5$ loads were lowest at site LRBM during irrigation periods for years 1 and 2 (no data were collected in year 3), and BOD_5 and $CBOD_5$ loads were highest at site MCRV during irrigation periods for all 3 years, owing to the higher streamflows at that site (table 12). The converse relation occurred during non-irrigation periods for years 2 and 3, when BOD_5 and $CBOD_5$ loads were lowest at site MCRV compared to the other two sites and highest at site LRBH. Overall, BOD_5 and $CBOD_5$ loads were highest at site LRBH for all non-irrigation periods.

Table 12. Averaged instantaneous loads of total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand, during irrigation and non-irrigation seasons, at upper Lost River Basin sites LRBM, MCRV, and LRBH, Lost River and Klamath River Basins, south-central Oregon, March 2012–March 2015.

[Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Abbreviations:** n, number of instantaneous loads used in the averaging calculation; sd, standard deviation; ft^3/s, cubic foot per second; kg/d, kilogram per day]

Site name abbreviation	Total phosphorus (TP)			Total nitrogen (TN)			5-day biochemical oxygen demand (BOD_5)			5-day carbonaceous biochemical oxygen demand ($CBOD_5$)			Average streamflow (ft^3/s)
	TP (kg/d)	n	sd	TN (kg/d)	n	sd	BOD_5 (kg/d)	n	sd	$CBOD_5$ (kg/d)	n	sd	
Irrigation year 1 (129 days LRBM, 147 days MCRV and LRBH)													
LRBM	1.69	9	0.657	6.13	9	2.33	13.8	9	5.53	13	9	4.64	2.63
MCRV	24.8	11	10.6	210	11	72.8	771	11	636	540	11	180	110
LRBH	24.6	11	19.2	86.2	11	66.9	225	11	143	225	11	143	45.9
Non-irrigation year 1 (236 days LRBM, 198 days MCRV and LRBH)													
LRBM	3.55	16	7.4	22.8	16	44.2	50.3	16	92.4	49.7	16	92.4	9.89
MCRV	0	13	0	0	13	0	0	13	0	0	13	0	0
LRBH	38.6	14	53.3	273	14	329	501	14	413	484	14	386	98.2
Irrigation year 2 (106 days LRBM, 152 days MCRV and LRBH)													
LRBM	0.076	8	0.107	0.317	8	0.442	1.12	7	1.43	0.924	6	1.56	0.132
MCRV	20	11	2.97	144	11	33.5	317	11	127	253	10	131	95.3
LRBH	5.97	11	6.63	31.2	11	54.8	76.6	11	88.6	68.5	10	87.5	13.8
Non-irrigation year 2 (259 days LRBM, 212 days MCRV and LRBH)													
LRBM	0.704	14	0.863	3.69	14	3.76	10.7	12	8.63	10	12	8.42	1.46
MCRV	0.252	11	0.118	2.07	11	0.908	3.89	10	2.49	3.46	10	2.22	1.16
LRBH	18.2	14	25.1	129	14	134	303	11	439	262	11	355	70.7
Irrigation year 3 (0 days LRBM, 77 days MCRV and LRBH)													
LRBM	0	4	0	0	4	0	0	4	0	0	4	0	0
MCRV	27.8	5	6.68	181	5	14.8	309	5	30.8	229	5	42	94.6
LRBH	2.37	5	2.24	7.95	5	8.73	53.5	5	87.5	44	5	75.9	5.86
Non-irrigation year 3 (288 days LRBM,MCRV, and LRBH)													
LRBM	0.88	22	2.16	9.07	22	21.2	22.7	22	60	16.3	22	41.6	5.01
MCRV	0.58	21	0.653	4.15	21	4.28	2.52	21	2.55	1.74	21	1.76	0.807
LRBH	13.2	17	17.7	163	17	161	203	17	288	174	17	274	43.4

Tule Lake Sites

Sites LREW and PPD were added to the project in year 2 of the study when USGS began collecting samples and streamflow measurements. Site PPD, which pumps water from Tule Lake west towards the Lower Klamath Wildlife Refuge, pumped water infrequently in years 2 and 3 of the study, because of ongoing drought conditions. As a result, only two samples were collected in each year, one during irrigation season and one during non-irrigation season, and all other loads were reported as zero when the site was not flowing and incorporated in the averages. As a result, more samples were collected at site LREW than at site PPD. (table 13). TP loads were similar at both sites in year 2, but were an order of magnitude higher at site LREW in year 3. TN loads were higher at site PPD compared to site LREW in all 3 years, with the exception of the non-irrigation period in year 3. BOD_5 and $CBOD_5$ loads were higher at site PPD compared to site LREW in year 2 than in year 3. Overall, loads of all constituents at the Tule Lake sites were higher during irrigation and non-irrigation periods than at the upper Lost River Basin sites, which is likely a function of the higher concentrations at sites LREW and PPD rather than differences in streamflow between these two project groups.

Klamath Drainage District Sites and Site LRDC

Site KSDH is located at the headworks of the Klamath Straits Drain, which is the outlet of the Lower Klamath Wildlife Refuge. During the study period, water rarely flowed from the refuge into the canal, resulting in very few instantaneous load calculations. Only two samples during years 2 and 3 of the study were collected when water was flowing. All other loads were reported as zero when the site was not flowing and were used in the calculations of average loads. Samples were collected by Reclamation during year 1 of the study when the canal was flowing, but streamflow could not be verified independently by USGS, so no loads were reported in year 1. During the irrigation season of year 2, loads of all constituents were lower at the headworks of the Klamath Straits Drain (site KSDH) than at the Klamath Straits Drain before it enters the Klamath River, near site KSD97 (table 14). In non-irrigation year 2 and all of year 3, loads were zero at KSDH, so loads of all constituents were higher at KSD97 during those periods.

For each of the constituents (TP, TN, BOD_5, and $CBOD_5$), the sum of the loads at sites ADC97, NC, and KSDH (which represents irrigation water coming into the KDD and water from the Lower Klamath Wildlife Refuge) can be either higher or lower than the load at site KSD97 (near the terminus of Klamath Straits Drain before it enters the Klamath River) depending on flow conditions. For the non-irrigation period in study year 2, TP and TN loads were higher at site KSD97 than the sum of the loads at sites ADC97, NC, and KSDH (table 14), and TP loads were higher during the non-irrigation period in year 3. For all other periods, the sum of the TP and TN canal loads was higher than the load at site KSD97. This suggests that the KDD area can export either more or less nutrients into Klamath Straits Drain than it receives depending on the hydrologic regime, and that the ability of site KSDH to transport constituent loads is poorly characterized in this study because the canal was not flowing most of the time.

At site LRDC, water generally flows from the Klamath River onto the Klamath Project during irrigation periods, and from the project to the Klamath River during the non-irrigation periods. However, in all years of the study, water flowed in both directions during irrigation periods, so the average instantaneous loads include flows in both positive and negative directions. Streamflow during non-irrigation periods consistently flowed toward the Klamath River. In years 1 and 2, loads of TP and TN flowing toward the Klamath River were higher during the non-irrigation period, compared to the irrigation period when loads were flowing onto the Klamath Project, likely due to the large difference in average streamflow (124 and 53.3 ft^3/s during non-irrigation periods in years 1 and 2, respectively, compared to 15 and 32.4 ft^3/s during irrigation periods in years 1 and 2, respectively). In year three, TP and TN loads were higher during the irrigation season compared to loads during the non-irrigation season (table 14).

At site LRDC, BOD_5 loads were higher during the irrigation season than during the non-irrigation season in all 3 years because of the high concentrations of oxygen-demanding cyanobacterial biomass from the seasonal blooms of AFA in the Klamath River and Upper Klamath Lake (table 14). The difference between the two seasons was particularly large in years 2 and 3, when the low flows of these two drought years resulted in smaller non-irrigation period loads than in year 1. $CBOD_5$ loads also were higher during the irrigation season than during the non-irrigation season in years 2 and 3, indicating that the largest oxygen demand was coming from senescence of AFA cells that are present in the Klamath River during the summer. However, lower $CBOD_5$ loads during the irrigation season than during the non-irrigation season in year 1 may indicate that at times, high concentrations of ammonia or cellular organic nitrogen leaving Upper Klamath Lake contribute a large nitrogenous oxygen demand, as well.

Table 13. Averaged instantaneous loads at the Tule Lake sites of total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand during irrigation and non-irrigation seasons at sites LREW and PDD, Lost River and Klamath River Basins, northern California, March 2012–March 2015.

[Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Abbreviations:** n, number of instantaneous loads used in the averaging calculation; ND, no data, sd, standard deviation; ft^3/s, cubic foot per second; kg/d, kilogram per day]

Site name abbreviation	Total phosphorus (TP)			Total nitrogen (TN)			5-day biochemical oxygen demand (BOD_5)			5-day carbonaceous biochemical oxygen demand ($CBOD_5$)			Average streamflow (ft^3/s)
	TP (kg/d)	n	sd	TN (kg/d)	n	sd	BOD_5 (kg/d)	n	sd	$CBOD_5$ (kg/d)	n	sd	
Irrigation year 1 (201 days)													
LREW	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PPD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Non-irrigation year 1 (145 days)													
LREW	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PPD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Irrigation year 2 (189 days)													
LREW	22.2	12	20.5	108	12	103	268	12	266	169	11	161	29.9
PPD	18.1	8	51.1	247	8	699	860	8	2,430	944	7	2,500	19.9
Non-irrigation year 2 (168 days)													
LREW	10.4	9	11.8	50.1	9	53.2	94.5	7	97.0	89.6	7	88.8	9.34
PPD	11.0	11	37.5	139	11	472	622	10	1,970	591	10	1,870	14.2
Irrigation year 3 (195 days)													
LREW	23.9	14	25.7	87.3	14	110	241	14	283	193	14	235	25.4
PPD	4.74	13	17.1	95.9	13	346	153	13	551	130	13	470	11.1
Non-irrigation year 3 (200 days)													
LREW	20.7	14	36.2	106	14	191	201	14	635	160	14	564	17.5
PPD	5.84	10	18.5	82.2	10	260	166	10	526	133	10	422	8.12

Table 14. Averaged instantaneous loads of total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand during irrigation and non-irrigation seasons at Klamath Drainage District sites (KSDH, ADC97, NC, LRDC, and KSD97) and site LRDC, Lost River and Klamath River Basins, south-central Oregon, March 2012–March 2015.

[Positive loads at site LRDC indicate loading to the Lost River, and negative loads indicate loading to the Klamath River. Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Abbreviations:** n, number of instantaneous loads used in the averaging calculation; NA, not applicable; ND, not data; sd, standard deviation; ft^3/s, cubic foot per second; kg/d, kilogram per day]

Site name abbreviation	Total phosphorus (TP)			Total nitrogen (TN)			5-day biochemical oxygen demand (BOD_5)			5-day carbonaceous biochemical oxygen demand ($CBOD_5$)			Average streamflow (ft^3/s)
	TP (kg/d)	n	sd	TN (kg/d)	n	sd	BOD_5 (kg/d)	n	sd	$CBOD_5$ (kg/d)	n	sd	
Irrigation year 1 (201 days)													
KSDH	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ADC97	70.1	13	37.7	709	13	403	2,100	13	1,360	1,510	13	887	177
NC	24.1	14	20.0	221	14	196	720	14	762	535	14	579	54.8
LRDC	3.78	16	84.2	173	16	726	1,400	16	3,920	845	16	2,290	15
KSD97	65.6	14	24.5	466	14	179	1,000	14	584	538	14	278	87
(ADC97+NC+KSDH) - KSD97	28.6	NA	NA	464	NA	NA	1,820	NA	NA	1,507	NA	NA	NA
Non-irrigation year 1 (145 days)													
KSDH	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	NA
ADC97	51.2	10	39.7	559	10	410	907	10	793	696	10	498	131
NC	20.6	10	21.4	197	10	183	271	10	220	267	10	224	49.3
LRDC	-93.7	10	138	-536	10	676	-1,130	10	1,940	-1,010	10	1,680	-124
KSD97	42.5	10	53.0	565	10	663	700	10	928	390	10	377	90.2
(ADC97+NC+KSDH) - KSD97	29.3	NA	NA	191	NA	NA	478	NA	NA	573	NA	NA	NA
Irrigation year 2 (189 days)													
KSDH	16.4	9	44.2	107	9	285	113	9	315	101	8	265	10.9
ADC97	63.0	12	37.3	556	12	324	2,280	11	1,750	1,790	10	1,460	121
NC	20.2	12	19.8	182	12	189	631	12	591	451	11	411	36.7
LRDC	14.8	12	56.6	172	12	582	1,300	12	2,850	1,300	11	3,300	32.4
KSD97	90.7	12	63.6	656	12	455	1,660	12	1,460	1,360	11	1,710	95.5
(ADC97+NC+KSDH) - KSD97	8.90	NA	NA	189	NA	NA	1,364	NA	NA	982	NA	NA	NA
Non-irrigation year 2 (168 days)													
KSDH	0	11	0	0	11	0	0	11	0	0	11	0	0
ADC97	13.9	12	12.1	191	12	183	389	10	394	347	10	351	54.7
NC	7.01	13	5.43	85.6	13	80.1	193	11	146	191	11	157	26.9
LRDC	-18.0	13	14.9	-131	13	125	-271	11	262	-232	11	239	-53.3
KSD97	44.2	12	88.8	389	12	673	340	10	494	320	10	452	52.4
(ADC97+NC+KSDH)– KSD97	-23.3	NA	NA	-112	NA	NA	242	NA	NA	218	NA	NA	NA

Table 14. Averaged instantaneous loads of total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand during irrigation and non-irrigation seasons at Klamath Drainage District sites (KSDH, ADC97, NC, LRDC, and KSD97) and site LRDC, Lost River and Klamath River Basins, south-central Oregon, March 2012–March 2015.—Continued

Site name abbreviation	Total phosphorus (TP)			Total nitrogen (TN)			5-day biochemical oxygen demand (BOD_5)			5-day carbonaceous biochemical oxygen demand ($CBOD_5$)			Average streamflow (ft^3/s)
	TP (kg/d)	n	sd	TN (kg/d)	n	sd	BOD_5 (kg/d)	n	sd	$CBOD_5$ (kg/d)	n	sd	
Irrigation year 3 (195 days)													
KSDH	0	12	0	0	12	0	0	12	0	0	12	0	0
ADC97	22.4	14	36.1	146	14	247	531	14	942	439	14	776	40.1
NC	27.2	14	35.2	200	14	242	736	14	971	674	14	949	38.6
LRDC	49.8	14	64.9	439	14	609	1,510	14	2,660	1,930	14	3,920	78.1
KSD97	26.9	14	36.4	204	14	278	398	14	586	335	14	512	26.9
(ADC97+NC+KSDH)– KSD97	22.7	NA	NA	142	NA	NA	869	NA	NA	778	NA	NA	NA
Non-irrigation year 3 (200 days)													
KSDH	0	13	0	0	13	0	0	13	0	0	13	0	0
ADC97	3.63	14	13.2	27.8	14	101	117	14	430	109	14	402	12.1
NC	12.6	14	11.6	146	14	143	259	13	251	228	13	203	43.1
LRDC	-24.3	14	23.8	-223	14	224	-459	14	469	-419	14	470	-53.5
KSD97	16.8	14	38.6	172	14	354	239	14	415	208	14	346	19.7
(ADC97+NC+KSDH)– KSD97	-0.570	NA	NA	1.80	NA	NA	137	NA	NA	129	NA	NA	NA

Discussion

Nutrient, 5-Day Biochemical Oxygen Demand, and 5-Day Carbonaceous Biochemical Oxygen Demand Loading within the Klamath Project

In all years, regardless of irrigation season, upper Lost River Basin sites represented the smallest constituent loads to the Klamath Project, and site FMT represented the largest loads coming into the project. Median concentrations of nutrients were similar at the upper Lost River Basin sites and site FMT (tables 6–7), but streamflow was much higher at site FMT, so the higher loads at FMT primarily are owing to higher streamflows. Median concentrations of BOD_5 and $CBOD_5$ also were similar at the upper Lost River Basin sites and site FMT, but peak concentrations of BOD_5 and $CBOD_5$ were higher at site FMT during the summer, so the increased loads of these constituents are influenced by a combination of higher streamflow at site FMT and seasonally high peak concentrations of BOD_5 and $CBOD_5$. This suggests that Clear Lake and Gerber Reservoir did not contribute significant amounts of nutrients and BOD_5/$CBOD_5$ loads to the project during the study period owing to low flows, and that Upper Klamath Lake, by contrast, contributes large loads, especially during irrigation season when flows are high at site FMT (1,440–2,200 ft^3/s, table 11), the seasonal algal bloom persists in Upper Klamath Lake, and water is being diverted through A Canal.

Without directly measuring TP, TN, and BOD_5/$CBOD_5$ in A Canal, a true representation of the load partitioning at site FMT cannot be achieved, although some approximations can be made based on available streamflow data. During irrigation season, streamflow reported by Reclamation was compared to streamflow calculated at site FMT, resulting in about 38 percent of the streamflow at site FMT being diverted through A Canal during each study year; for purposes of this report, we assume that about 38 percent of the nutrient and BOD_5/$CBOD_5$ loads also are diverted through A Canal, with the remainder flowing down the Link River, into Lake Euwana, and to the study site downstream of the Keno Dam (site KRK). Along this flowpath, point and nonpoint sources of nutrients are sourced from two wastewater treatment plants, private industrial timber manufacturing companies, stormwater runoff, internal loading from the Klamath River, and Klamath Straits Drain and Lost River Diversion Channel during non-irrigation periods (Oregon Department of Environmental Quality, 2017). The industrial and wastewater point sources and stormwater and internal loading contribute less TP loads compared to Klamath Straits Drain (Oregon Department of Environmental Quality, 2017). If 38 percent of TP loads that flow through A Canal are subtracted from the site FMT loads, then the resulting reduced TP loads at site FMT are slightly smaller during irrigation season in years 1 and 3, and larger in year 2, compared to site KRK, suggesting a slight increase in TP loads from site FMT to site KRK years 1 and 3 (table 15). In contrast, if 38 percent of TN, BOD_5, and $CBOD_5$ loads are subtracted from the site FMT loads, the remaining loads are still higher at site FMT compared to site KRK during irrigation season (with the exception of non-irrigation year 3), indicating that the Klamath Project is not a large source of TN or oxygen-demanding material and that much of the oxygen demand in the river at site FMT has been expressed by the time the same water passes through site KRK.

Table 15. Average of modeled mean daily loads (using LOADEST) of total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand during irrigation seasons to account for A Canal diversions at sites KRK and FMT, including a 38-percent reduction in loads at site FMT, south-central Oregon, March 2012–March 2015.

[Loads at site FMT during irrigation season include a 3-percent reduction to account for A Canal diversions. Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Abbreviation:** kg/d, kilogram per day]

Site name abbreviation	Total phosphorus (kg/d)	Total nitrogen (kg/d)	Biochemical oxygen demand (kg/d)	
			5-day	5-day carbonaceous
Irrigation year 1				
FMT	450	4,706	18,414	16,306
KRK	527	4,450	9,750	7,410
Non-irrigation year 1				
FMT	111	1,870	3,700	3,150
KRK	172	2,060	3,670	3,040
Irrigation year 2				
FMT	344	3,714	15,004	13,516
KRK	302	2,760	6,980	5,410
Non-irrigation year 2				
FMT	120	1,950	3,990	3,390
KRK	188	2,220	4,270	3,470
Irrigation year 3				
FMT	328	3,565	14,384	12,896
KRK	344	3,070	7,430	5,740
Non-irrigation year 3				
FMT	110	1,780	3,690	3,150
KRK	176	2,100	4,110	3,350

In most years during non-irrigation periods, TP and TN loads computed with LOADEST at the end-members sites consistently showed a small increase in TP and TN loads along the flowpath from sites FMT to KRK (table 11). Because there are no diversions of water from site FMT through A Canal during non-irrigation periods, the only nutrient inputs that could be causing this increase in nutrient loads are the point and nonpoint sources described in the previous paragraph and internal loading from sediments, with the addition of inputs from the Klamath Straits Drain and the Lost River Diversion Channel. The Lost River Diversion Channel represents nonpoint sources of nutrients from the Klamath Project, natural runoff from the upper Lost River Basin, and stormwater runoff from the city of Klamath Falls.

Data on loads entering and leaving Tule Lake during study years 2 and 3 show similar loads of TP, TN, BOD_5, and $CBOD_5$ along the flowpath from the lower Lost River to Pump Plant D (site PPD), regardless of irrigation or non-irrigation seasons. The water-quality dynamics in this area of the project are not adequately characterized because of the low volume of samples collected at site PPD. However, for the few samples that were collected, sample concentrations can be discussed. Increases in BOD_5/$CBOD_5$ concentrations from Tule Lake to site PPD in year 2 of the study are likely attributed to the high DOC concentrations also observed at site PPD (table 9). This form of organic carbon is different than the particulate algal carbon observed at site FMT, which represents biomass from Upper Klamath Lake that has an oxygen demand when the algae decompose. The organic carbon composition observed at site PPD suggests a fresh, slightly decomposed carbon that could originate from sources such as animal manure or algal exudates based on low humification index values, which show the relative contribution of terrestrial or microbial sources of organic matter (Goldman and Sullivan, 2017). Higher humification index values typically indicate an increasing rate of carbon decomposition. Additionally, the high DOC concentrations present at sites downstream of the inundated wetlands of Tule Lake and the Lower Klamath Wildlife Refuge also could be owing to molecular diffusion of DOC resulting from the inundation of peat soils (Aguilar and Thibodeaux, 2005).

Nutrient Budget for Klamath River from Link River Dam to Keno Dam

Considering nutrient, BOD_5, and $CBOD_5$ loads at the two boundary sites (sites FMT and KRK), all canal diversions from the Klamath River (NC, ADY, and LRDC during irrigation season) and drains into the Klamath River (KSD97 year-round and LRDC during non-irrigation season) between the boundary sites, a nutrient balance can be calculated to examine the change in loads from sites FMT to KRK. Loads either entering or leaving the Klamath River main stem between the boundary sites, and mean loads at the boundary sites for irrigation and non-irrigation periods for all 3 years of the study, are shown in figures 20–22 and table 16. The loads shown at site FMT in figures 20–22 include a 38-percent reduction to account for A Canal loads entering the Klamath Project during irrigation season, and the “NET” value is calculated as the site FMT reduced load subtracting the canal diversions (shown as negative loads in figures 20–22 to represent a load reduction from the Klamath River) and adding the drains (shown as positive loads to represent load additions to the river). The “NET” value, therefore, represents the mean load in the Klamath River downstream of where the Klamath Straits Drain enters the river. Site LRDC is shown as a negative load relative to the Klamath River during irrigation years, when water is flowing from the river to the Klamath Project, and as a positive load during non-irrigation seasons, when water is flowing from the project to the Klamath River.

A noticeable consistent pattern in the load balance shows that, during irrigation season in all 3 years of the study, the NET load for all constituents downstream of Klamath Straits Drain is lower than the load at site FMT before all the diversions, drains, and point sources along the Klamath River (figs. 20–22). The average percent differences during the three irrigation seasons comparing the site FMT load to the NET load for TP and TN were -10 and -12 percent, respectively, and the corresponding average percent differences for BOD_5 and $CBOD_5$ were both -17 percent (table 16). During non-irrigation periods, the NET loads were higher compared to site FMT, and the differences were larger for TP and TN than BOD_5 and $CBOD_5$. Between sites FMT and KRK during non-irrigation periods, TP loads increased by an average of 38 percent, TN loads increased by an average of 14 percent, BOD_5 loads increased by an average of 9 percent, and $CBOD_5$ loads increased by an average of 8 percent, respectively (table 16). These load differences suggest that, during irrigation season in the 3 years of the study period, more loads are being diverted from the Klamath River than are being added to the Klamath River from the combination of Klamath Straits Drain, regulated point sources along the Klamath River, and internal loading from the bottom sediments in the river. By contrast, during non-irrigation seasons, more loads are being added to the Klamath River than are being diverted through Ady and North Canals, and this difference primarily is owing to additional loads to the River from the Lost River Diversion Channel.

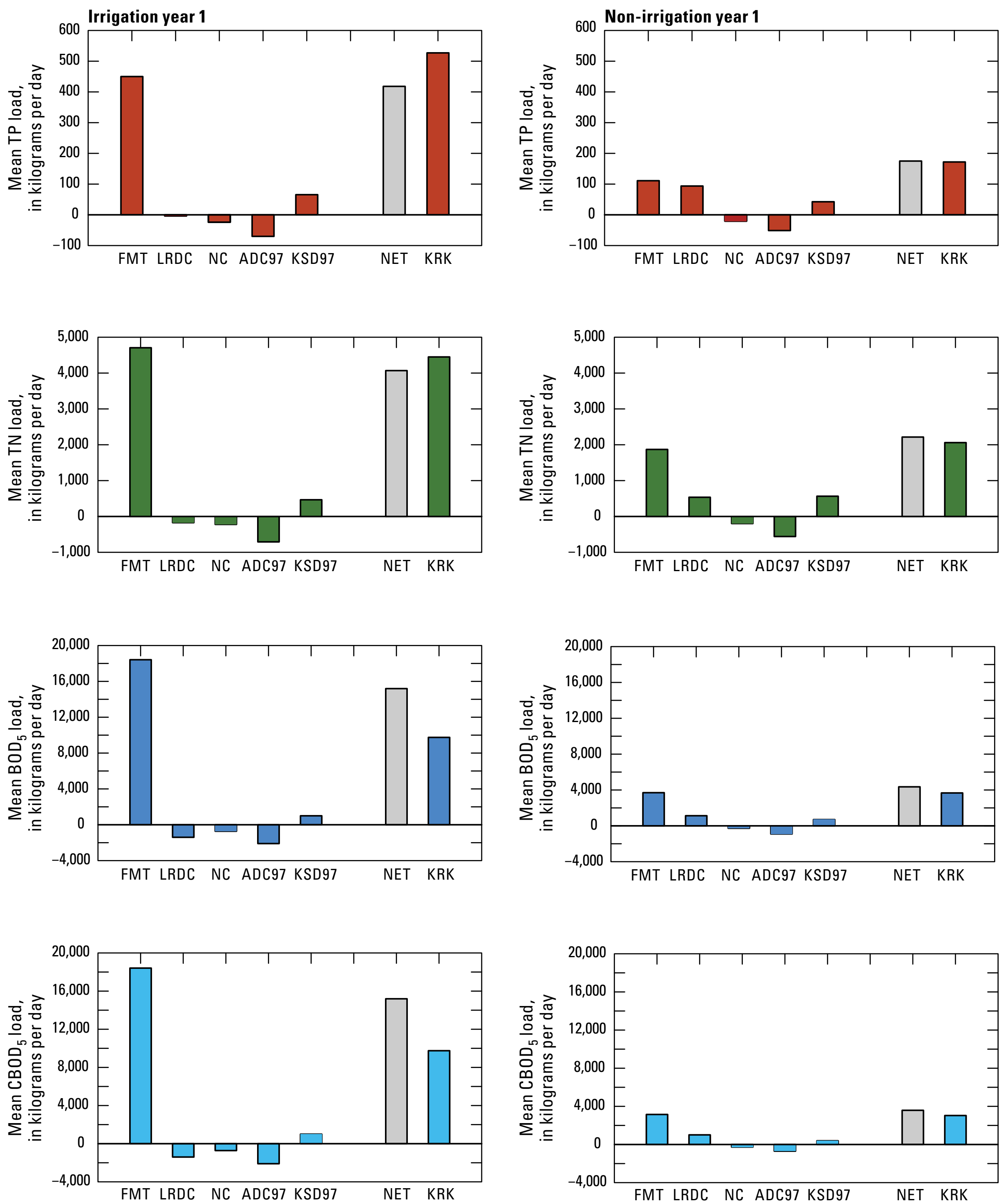


Figure 20. Total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand loads along the Klamath River flowpath from sites FMT to KRK, south-central Oregon, March 2012–13 (study year 1). Site names and descriptions are shown in table 1; site locations are shown in figure 1. “NET” refers to reduced site FMT load calculated by subtracting the canal diversions (negative loads in figure) and adding the drains (positive loads in figure excluding site KRK).

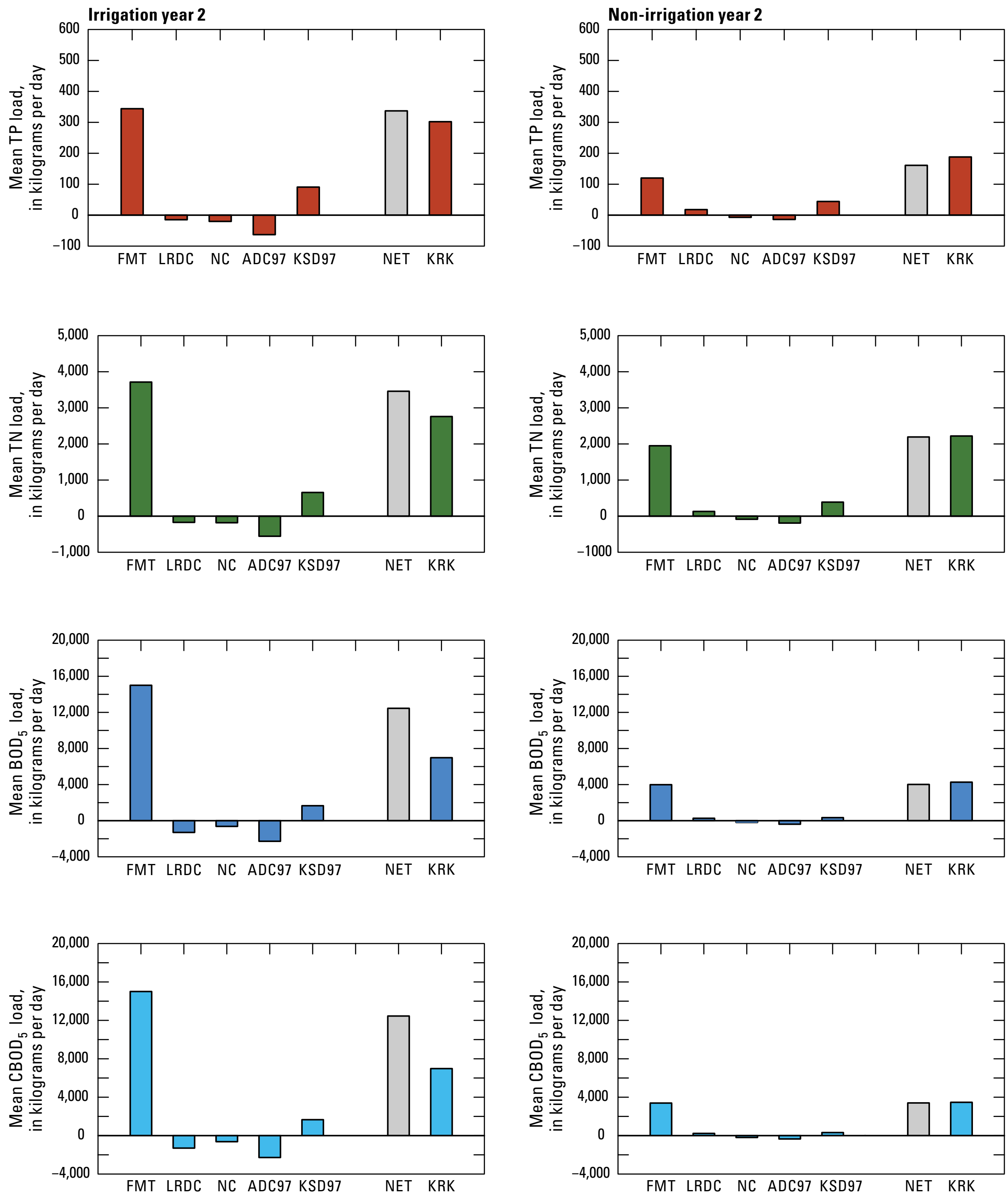


Figure 21. Total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand loads along the Klamath River flowpath from sites FMT to KRK, south-central Oregon, March 2013–14 (study year 2). Site names and descriptions are shown in table 1; site locations are shown in figure 1. "NET" refers to reduced site FMT load calculated by subtracting the canal diversions (negative loads in figure) and adding the drains (positive loads in figure excluding site KRK).

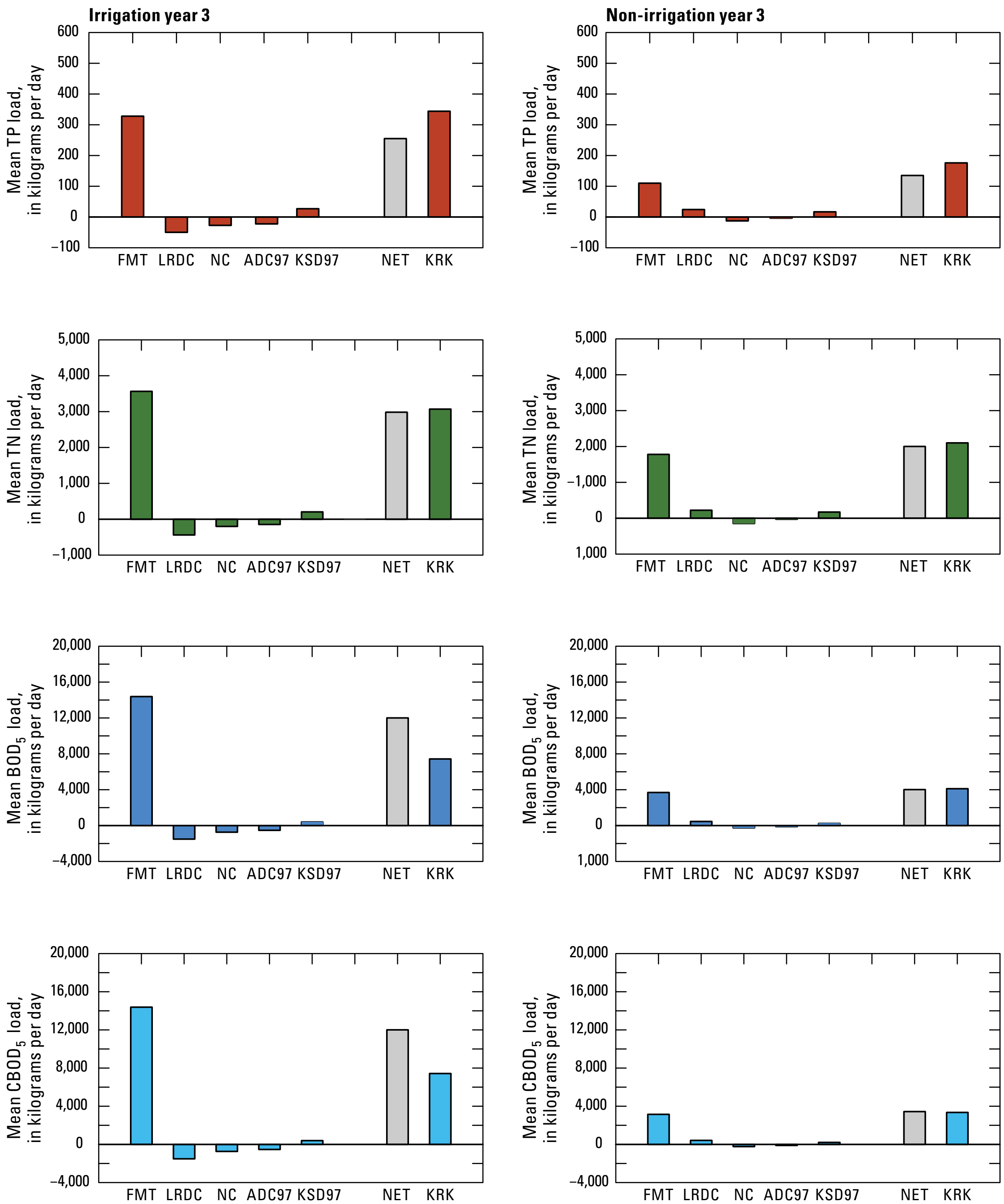


Figure 22. Total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand loads along the Klamath River flowpath from sites FMT to KRK, south-central Oregon, March 2014–15 (study year 3). Site names and descriptions are shown in table 1; site locations are shown in figure 1. “NET” refers to reduced site FMT load calculated by subtracting the canal diversions (negative loads in figure) and adding the drains (positive loads in figure excluding site KRK).

Table 16. Nutrient load and streamflow balance using average of modeled mean daily loads (using LOADEST) total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand at sites KRK and FMT, and average of daily loads at sites LRDC, NC, ADC97, and KSD97, south-central Oregon, March 2012–March 2015.

[Loads and streamflow at site FMT during irrigation season include a 38-percent reduction to account for A Canal diversions as noted. Positive loads at site LRDC indicate loading to the Lost River, and negative loads indicate loading to the Klamath River. Positive numbers in the "Balance" row indicate more nutrients or streamflow at site KRK compared to the net nutrient load and streamflow of all project diversions from, and inputs to, the Klamath River. Site names and descriptions are shown in table 1; site locations are shown in figure 1. **Abbreviations:** ft^3/s, cubic feet per second ; kg/d, kilogram per day, %, percent]

Site name abbreviation	Total phosphorus (kg/d)	Total nitrogen (kg/d)	Biochemical oxygen demand (kg/d)		Average daily streamflow (ft^3/s)
			5-day	5-day carbonaceous	
Irrigation year 1					
FMT with A Canal reduction	450	4,706	18,414	16,306	1,364
LRDC	3.78	173	1,400	845	15
NC	24.1	221	720	535	54.8
ADC97	70.1	709	2,100	1,510	177
KSD97	65.6	466	1,000	538	87
NET [FMT-sum(LRDC, NC, ADC97)+KSD97]	418	4,069	15,194	13,954	1,204
Percent difference NET-FMT	-7%	-14%	-17%	-14%	-12%
KRK	527	4,450	9,750	7,410	1,291
Balance	109	381	-5,444	-6,544	87
Percent difference NET-KRK	26%	9%	-36%	-47%	7%
Non-irrigation year 1					
FMT with A Canal reduction	111	1,870	3,700	3,150	406
LRDC	-93.7	-536	-1,130	-1,010	-124
NC	20.6	197	271	267	49.3
ADC97	51.2	559	907	696	131
KSD97	42.5	565	700	390	90.2
NET [FMT-sum(LRDC, NC, ADC97)+KSD97]	175	2,215	4,352	3,587	440
Percent difference NET-FMT	58%	18%	18%	14%	8%
KRK	172	2,060	3,670	3,040	678
Balance	-3	-155	-682	-547	238
Percent difference NET-KRK	-2%	-7%	-16%	-15%	54%
Irrigation year 2					
FMT with A Canal reduction	344	3,714	15,004	13,516	918
LRDC	14.8	172	1,300	1,300	32.4
NC	20.2	182	631	451	36.7
ADC97	63	556	2,280	1,790	121
KSD97	90.7	656	1,660	1,360	95.5
NET [FMT-sum(LRDC, NC, ADC97)+KSD97]	337	3,460	12,453	11,335	823
Percent difference NET-FMT	-2%	-7%	-17%	-16%	-10%
KRK	302	2,760	6,980	5,410	689
Balance	-35	-700	-5,473	-5,925	-134
Percent difference NET-KRK	-10%	-20%	-44%	-52%	-16%
Non-irrigation year 2					
FMT with A Canal reduction	120	1,950	3,990	3,390	443
LRDC	-18	-131	-271	-232	-53.3
NC	7.01	85.6	193	191	26.9
ADC97	13.9	191	389	347	54.7
KSD97	44.2	389	340	320	52.4
NET [FMT-sum(LRDC, NC, ADC97)+KSD97]	161	2,193	4,019	3,404	467
Percent difference NET-FMT	34%	12%	1%	0%	5%
KRK	188	2,220	4,270	3,470	739
Balance	27	27	251	66	272
Percent difference NET-KRK	17%	1%	6%	2%	58%

Table 16. Nutrient load and streamflow balance using average of modeled mean daily loads (using LOADEST) total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and 5-day carbonaceous biochemical oxygen demand at sites KRK and FMT, and average of daily loads at sites LRDC, NC, ADC97, and KSD97, south-central Oregon, March 2012–March 2015. —Continued

Site name abbreviation	Total phosphorus (kg/d)	Total nitrogen (kg/d)	Biochemical oxygen demand (kg/d)		Average daily streamflow (ft^3/s)
			5-day	5-day carbonaceous	
		Irrigation year 3			
FMT with A Canal reduction	328	3,565	14,384	12,896	893
LRDC	49.8	439	1,510	1,930	78.1
NC	27.2	200	736	674	38.6
ADC97	22.4	146	531	439	40.1
KSD97	26.9	204	398	335	26.9
NET [FMT-sum(LRDC, NC, ADC97)+KSD97]	255	2,984	12,005	10,188	763
Percent difference NET-FMT	-22%	-16%	-17%	-21%	-15%
KRK	344	3,070	7,430	5,740	772
Balance	89	86	-4,575	-4,448	9
Percent difference NET-KRK	35%	3%	-38%	-44%	1%
		Non-irrigation year 3			
FMT with A Canal reduction	110	1,780	3,690	3,150	405
LRDC	-24.3	-223	-459	-419	-53.5
NC	12.6	146	259	228	43.1
ADC97	3.63	27.8	117	109	12.1
KSD97	16.8	172	239	208	19.7
NET [FMT-sum(LRDC, NC, ADC97)+KSD97]	135	2,001	4,012	3,440	423
Percent difference NET-FMT	23%	12%	9%	9%	4%
KRK	176	2,100	4,110	3,350	695
Balance	41	99	98	-90	272
Percent difference NET-KRK	30%	5%	2%	-3%	64%
Average percent difference NET-FMT, irrigation season	-10%	-12%	-17%	-17%	-12%
Average percent difference NET-FMT, non-irrigation season	38%	14%	9%	8%	6%

In some years, the differences between loads at the Link River Dam (represented as the loads at site FMT with a 38-percent reduction to account for A Canal diversions) and the NET load downstream of Klamath Straits Drain were small. This is particularly noticeable in BOD_5 and $CBOD_5$ loads during non-irrigation season in years 2 and 3 of the study, where percent differences were 0 and 1 percent in non-irrigation year 2 and 9 percent for non-irrigation year 3. Percent differences in BOD_5 and $CBOD_5$ loads in the year 1 non-irrigation season were higher (18 and 14 percent, respectively) than in years 2 and 3, likely owing to the higher streamflows at site LRDC when it was flowing toward the Klamath River in year 1 compared to years 2 and 3.

Closing the loop on the nutrient balance for the Klamath River requires a comparison of the loads at site KRK, the lower boundary of the study, to the NET load after all measured loads to the canals and from drains are accounted for. The differences between site KRK and the NET value are shown as “Balance” in table 16, and can be assessed graphically by comparing the “NET” and “KRK” load bars in figures 20–22. Positive numbers in the “Balance” row in table 16 indicate more loads measured at site KRK than the calculated NET load, and negative numbers indicate less loads measured at site KRK than the calculated NET load. Positive balance numbers suggest that there is additional loading in the system, such as internal cycling from river bottom sediments and point sources, which is not accounted for in the large canals supplying nutrient loads to the Klamath River. A positive or negative balance also can be an indication of the error in the load estimates, particularly in the canals. Numerous individual diversions from the Klamath River along this flowpath were not characterized by this study, and also could be reducing loads in the river. The occurrence and magnitude of differences between site KRK and the NET loads were variable and showed few consistent patterns for load constituents and the irrigation/non-irrigation season. One consistent pattern was that BOD_5 and $CBOD_5$ loads were consistently lower at KRK than the calculated NET value during irrigation season in all 3 study years. This discrepancy likely is the result of the oxygen demand being expressed within the water column from the decay of the AFA biomass along this flowpath during summer in the irrigation season. It also is possible that the loads diverted from the Klamath River were underestimated because of individual diversions that were not assessed for this study, or that the loads coming into the Klamath River from site KSD97 were overestimated during irrigation season. However, these individual load values are small compared to the overall loads measured at site FMT with the 38 percent A Canal reduction, so these differences also could be owing to uncertainty in the load estimates at site FMT from the LOADEST model.

The LOADEST models used to calculate BOD_5 and $CBOD_5$ loads at site FMT greatly underestimated the peak loads that occurred during June–August in the 3 study years (fig. 18), so the loads for site FMT reported in table 16 for the irrigation periods are assumed to be biased low. If we assume that the loads are higher than reported from the LOADEST model, the conclusions of the nutrient balance do not change, but the magnitude of the differences would change, making the "NET" value reported in table 16 and figures 20–22 larger than shown. For the BOD_5 and $CBOD_5$ loads, this means that there would be a larger difference in the NET value compared to KRK during irrigation season, which could mean that more oxygen demand is expressed in the reach between Link River and Keno Dams than is shown in these figures. For the TP and TN loads, the NET value would be closer to the value reported at site KRK, which means that the canal diversions and nutrient input from Klamath Straits Drain explain most of the change in nutrient loads along this stream reach.

Organic Carbon and Nitrogen

Changes in the concentration of DOC and TPC along the Lost River-Tule Lake-Klamath Straits Drain flow path have been measured in this study for the few samples collected when the flowpath was hydrologically connected, and especially notable are changes between the inflow and outflow of Tule Lake, where concentrations of DOC, TPC, and TPN all increased from sites LREW to PPD. These relations are not well characterized because of the small volume of samples collected at site PPD. For purposes of this report, TPC is assumed to be primarily composed of organic carbon at KSD97 based on previous work that has shown non-detectable levels of particulate inorganic carbon for the Klamath Straits Drain and other sites on the Klamath River between the Link River and Keno Dams (Sullivan and others, 2010).

The highest concentrations of TPN occurred at sites that divert water directly from the Klamath River (sites FMT, ADC97, LRDC(+)), which likely is owing to particulate algae at those sites from seasonal blooms of AFA. However, only site ADC97 showed a positive correlation of chlorophyll-*a,* the biomass surrogate for AFA, with TPN (R^2=0.76, $p<0.05$). High concentrations of chlorophyll-*a* present at site FMT (the south end of Upper Klamath Lake) often were not concurrently sampled for TPN because of the infrequent nature (every 6 weeks) of constituent sampling for organic carbon and nitrogen during the study.

Nutrient Loads and Total Maximum Daily Loads

The Oregon Department of Environmental Quality sets nonpoint source load allocations of pollutants that can contribute to a stream without exceeding State water-quality standards. TP, TN, and BOD_5 loads have been identified as causing non-compliance of water quality standards for pH, dissolved oxygen, ammonia toxicity and chlorophyll-*a* in the Klamath River (Oregon Department of Environmental Quality, 2017). The two primary sources of water to the Klamath River from the Klamath Project are the Klamath Straits Drain and Lost River Diversion Channel. Klamath Straits Drain exceeded TMDL load allocations for TP and TN in all 3 study years (March 2012–March 2015; table 2), but only exceeded TMDL load allocations for BOD_5 in years 1 and 2, as indicated by averages of instantaneous daily loads during the study period (fig. 23). At site LRDC, TP loads exceeded TMDL load allocations in all three study years, TN loads exceeded TMDL load allocations in year 1 only, and BOD_5 loads were less than the TMDL load allocations for all three study years (fig. 24).

Suggestions for Future Studies

The persistent drought conditions during all years of the study resulted in many sample events when sites did not have measurable streamflow. As a result, the number of data points used to estimate loads at some sites was unacceptably small—for example, sites KSDH and PPD. Therefore, this study was unable to assess contributions of nutrients to the Klamath River under typical conditions, so some of the study conclusions may not be reproducible in out years beyond this study that have normal flow regimes. Long-term data collection efforts would allow for better representation of a range of flow regimes, and hydrologic and meteorological conditions. Additionally, biweekly, scheduled sampling events often can miss important runoff events, especially in the upper Lost River Basin, where some sites have substantial unregulated drainage and thus respond to precipitation events. A combination of scheduled and storm-event sampling would better characterize the range of constituent concentrations, loads, and streamflow at the sample sites. Additionally, close coordination with Reclamation to plan sampling events when water at sites KSDH and PPD is flowing would allow for better characterization of water quality from these sites.

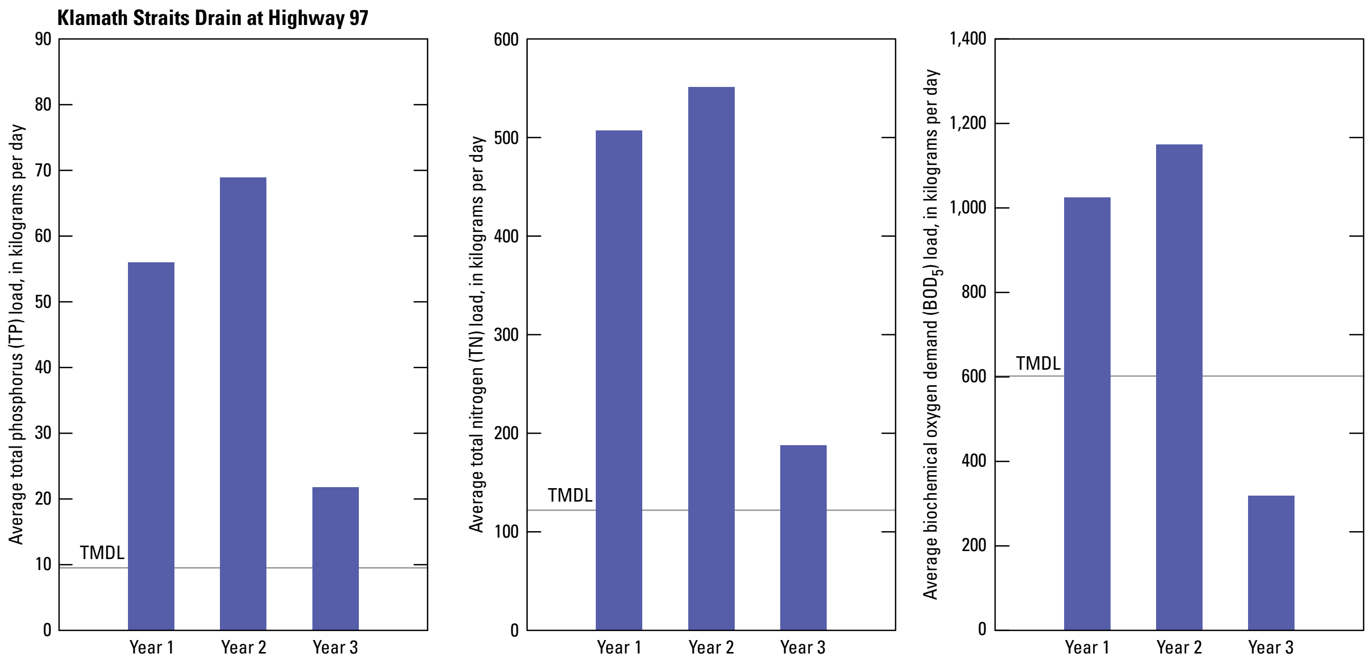


Figure 23. Average daily loads of total phosphorus, total nitrogen, and 5-day biochemical oxygen demand and Total Maximum Daily Load (TMDL) load allocations at site KSD97, south-central Oregon. Site name and description are shown in table 1; site location is shown in figure 1.

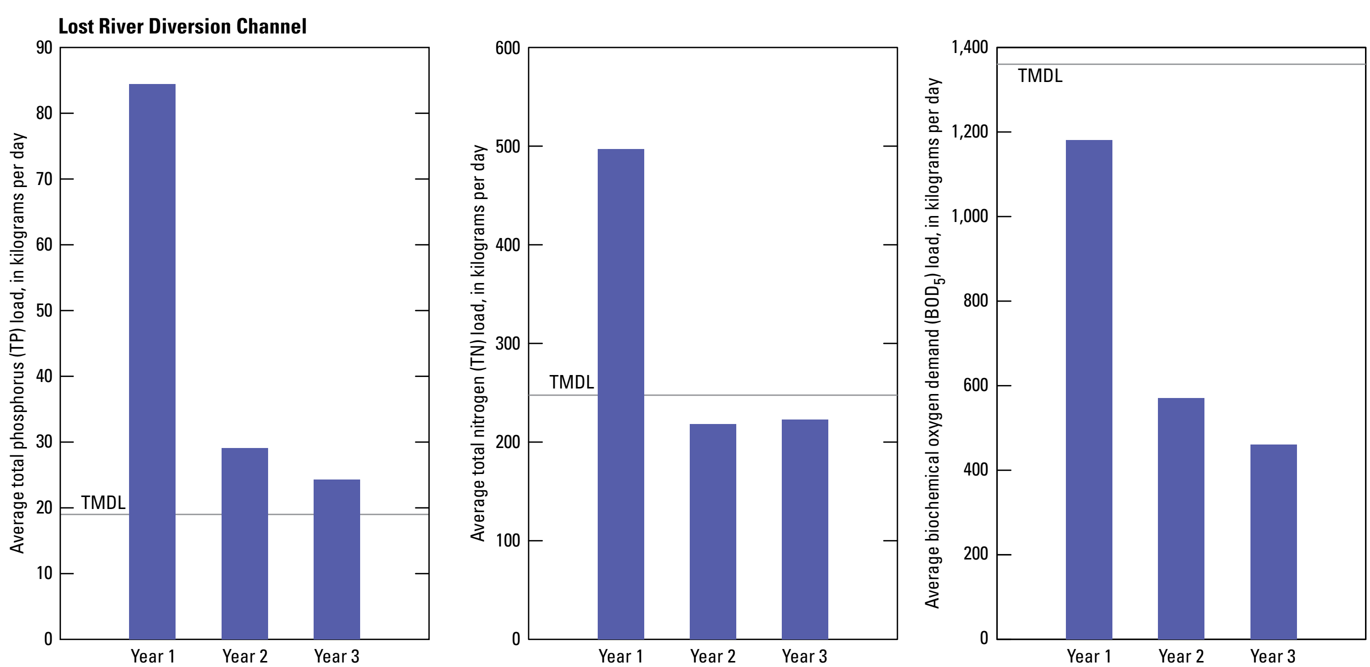


Figure 24. Average daily loads of total phosphorus, total nitrogen, and 5-day biochemical oxygen demand, and Total Maximum Daily Load (TMDL) load allocations at site LRDC, south-central Oregon. Site name and description are shown in table 1; site location is shown in figure 1.

An improved characterization in the form of streamgages that record continuous streamflow at some of the ungaged project sites also will allow for better load estimates. This additional information is critical in understanding water-quality dynamics in the Klamath Straits Drain, and Tule Lake in particular.

The direct measurement of constituent loads diverted through A Canal also is an important missing component to this study, as the diversion of water through the canal greatly affects the computation of load allocations downstream of the Link River Dam. A sampling program that conducts separate assessments of A Canal and the Link River downstream of the A Canal diversion would reduce the uncertainty of constituent load assessments at this important boundary of the Klamath Project.

LOADEST model results for BOD_5 and $CBOD_5$ at sites FMT and KRK showed a low bias of loads during irrigation season, although these differences were more extreme for the seasonal wave models at FMT. The low bias suggests that the LOADEST model is not adequately capturing the cause of the variability in BOD_5 and $CBOD_5$, the source of which primarily is the large biomass from AFA blooms in Upper Klamath Lake that are transported downstream in the latter part of the summer. Alternative models, such as the USGS EGRET (Exploration and Graphics for RivEr Trends) model, may provide for better description of this process as that model describes long-term averages, the patterns of variability, and temporal trends (Hirsch and De Cicco, 2015). The EGRET model involves three components—(1) evaluation of streamflow statistics; (2) graphical display of water-quality sample data as they vary in relation to time, discharge, or season; and (3) application of the Weighted Regressions on Time, Discharge, and Season (WRTDS) smoothing method, which can identify changes that are specific to particular seasons of the year (Hirsch and De Cicco, 2015). In addition to these models, continuous water-quality parameters collected on the Klamath River at the Link River Dam and upstream of the Keno Dam also can be evaluated as surrogates, either independently or in conjunction with the alternative models, to provide for a more accurate assessment of nutrient, BOD_5, and $CBOD_5$ loads.

Acknowledgments

We acknowledge the assistance of Eric Janney and many personnel at the U.S. Geological Survey Klamath Falls Field Station for facilitating data collection efforts, including Robert Blake, Thomas Craig, Blake Eldridge, Charles Goebel, Douglas Labonte, Alex Lee, Celeste Melosh, and Bradley Smith for their efforts collecting and processing water-quality samples and streamflow measurements. We also thank the reviewers who provided constructive comments that improved this document.

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Appendix 1. Loadest Model Summaries for Rejected Models

Appendix 1 is a PDF file and is available for download at https://doi.org/10.3133/sir20185075.

Publishing support provided by the U.S. Geological Survey
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Schenk and others—**Nutrient Loads, Lost and Klamath River Basins, South-Central Oregon and California, 2012–15**—Scientific Investigations Report 2018-5075

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20185075