LOWER CROOKED RIVER WATER QUALITY MONITORING PROJECT

Technical Report

Prepared by:
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Prepared for:
City of Prineville, Crook County, and Ochoco Irrigation District
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MOUNT HOOD ENVIRONMENTAL
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EXECUTIVE SUMMARY

The Crooked River contributes a disproportionate amount of nutrients to Lake Billy Chinook (LBC) relative to other tributary inputs to the reservoir. One recent study found that 86% of the nitrate load and nearly half of the phosphate load to LBC was attributed to the Crooked River, although the Crooked River contributes only 38% of the reservoir's surface water flow (Eilers and Vache 2021). Agriculture is widespread throughout the Crooked River basin and it is often cited as the origin of high nutrient concentrations (Webb 2019, Eilers and Vache 2021, DRA 2021). While several water quality monitoring studies have occurred in the basin (Webb 2019, DRA 2021), none have directly evaluated nutrients within or downstream of irrigation returns.

To address the uncertainties surrounding the origins of nutrients in the Crooked River, Mount Hood Environmental and the Crooked River Watershed Council were contracted by Crook County, the City of Prineville, and Ochoco Irrigation District to collect water quality data throughout the lower Crooked River basin. The primary objective was to identify specific locations that contribute to the Crooked River's elevated nitrate and phosphate. Monthly surface water grab samples were collected at 12 sites in the mainstem Crooked River, 6 sites in tributaries, 3 sites in irrigation returns, and 3 sites in springs between August 2020 and April 2022. Site-specific phosphate and nitrate concentrations were paired with modeled flow to estimate nutrient load throughout the lower Crooked River. Additionally, autosamplers were deployed in April 2022 to capture a potential peak nutrient pulse associated with the flushing of Ochoco Irrigation District's water delivery system.

Nutrient concentrations in the Crooked River exhibited a seasonal pattern, peaking during December and January, and becoming lowest during the spring and summer months when irrigation occurred. We identified several tributaries and irrigation returns with elevated concentrations of phosphate and nitrate, most notably in the Lytle Creek subbasin. For our targeted sampling event, we captured a brief episodic pulse in nitrate associated with irrigation releases, however, the increase was localized and insignificant relative to the Crooked River's total daily load. The source of most nutrients in the Crooked River was found downstream of Smith Rock State Park where spring inputs contribute a significant amount of flow. For example, we found that during spring and summer months, 96% of nitrate load entered the river downstream of the park, with 90% of the load having entered in the lowest 11 rkm. Taken together, tributary and irrigation returns exhibit the highest nutrient concentrations in the basin but represent a small proportion of the total nutrient load in the Crooked River. High volume groundwater inputs in the lower 11 rkm of the Crooked River appear to be the most significant source of nutrients into LBC, in terms of total load contributed to LBC.

Record of Revisions

Revision No.	Revision Date	Change Description	Reason for Change
0	06/13/2022	Initial draft	
1	09/29/2022	Revised discussion text and added acknowledgements	Peer-review

Acknowledgements

We thank Kerri Miazgowicz and Scott Geddes for providing and coordinating laboratory space at OSU Cascades. We also thank the Deschutes Land Trust, the Deschutes Valley Water District, and Central Oregon Irrigation District for providing access to many of our sites in the lower Crooked River basin.

Suggested Citation:

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDIX A FIGURES

BACKGROUND AND PURPOSE

The Pelton Round Butte Hydroelectric Project (PRB) impounds Lake Billy Chinook (LBC), a reservoir on the Deschutes River in Central Oregon. Two large tributaries flow into the reservoir: the Metolius River drains from the Cascade Range in the west and the Crooked River drains from the Ochoco and Maury Mountains in the east. A recent multiyear water quality study in the reservoir revealed high algal densities from fall through spring and moderately high densities of cyanobacteria during the summer (Eilers and Vache 2021). Some of the cyanobacteria species found in Lake Billy Chinook produce cyanotoxins known to adversely affect human health, other organisms, and the environment (Schaedel 2011). In four of the last seven years, cyanotoxin concentrations in the reservoir have exceeded the Oregon Health Authority's health advisory level (OHA 2022). Additionally, there are growing concerns of increased phytoplankton densities in LBC and the lower Deschutes River over the last decade. Since 2009, densities of periphyton (algae and cyanobacteria attached to the substrate) found in the lower river are greater than previously reported. It is asserted that this is largely attributed to recent structural modifications to the reservoir water withdrawal facilities that were completed in 2009 (Eilers and Vache 2021). These modifications introduced the ability to selectively draw water from the surface and bottom of LBC, and have allowed water temperature in the lower Deschutes River to resemble more natural conditions.

The high densities of phytoplankton observed in LBC by Eilers and Vache (2021) were largely attributed to nutrient contributions from the Crooked River. Nitrate and phosphate concentrations, two nutrients important to phytoplankton growth, were greatest at the Crooked River mouth when compared to the Metolius and Deschutes River confluences. Accounting for discharge, it was estimated that the Crooked River contributed 86% of the nitrate load and nearly half of the phosphate load to LBC while contributing 38% of the surface water flow (Eilers and Vache 2021). Therefore, the Crooked River contributes a disproportionately high percentage of nutrients to LBC. The authors asserted that phosphate was largely derived from natural weathering of volcanic rocks across the Deschutes River basin, whereas most of the nitrate was sourced from irrigation returns in the Crooked River. The conclusions of this report were based on (1) data solely collected at the mouth of the Crooked River; and, (2) a historical data review at one location (river-kilometer 48). However, the study did not evaluate nutrient contributions from irrigation returns throughout the Crooked River basin.

To identify the nutrient contributions by irrigation returns, Mount Hood Environmental (MHE) and the Crooked River Watershed Council (CRWC) were contracted to collect water quality data throughout the lower Crooked River basin and identify the specific locations of nutrient inputs. Therefore, the study objectives were to: (1) Identify inputs with high nutrient concentrations; (2) Determine any temporal variability in nutrient concentrations; (3) Determine how stream inputs affect nutrient loading; and, (4) Capture peak concentrations associated with agriculture.

METHODS

Study Area

The Crooked River drains over 11,000 square kilometers (km) in central Oregon and flows nearly 250 km from its headwater tributaries to Lake Billy Chinook (Stuart et al. 1996). Bowman Dam, located on the Crooked River at river-kilometer (rkm) 106, separates the upper and lower Crooked River basins. The dam, which is a federal facility operated by Ochoco Irrigation District (OID) for irrigation storage and flood control, impounds Prineville Reservoir. Prior to the construction of Bowman Dam in 1961, the lower Crooked River was characterized by high flows in the spring and low flows in the summer. Following dam construction, flows have been higher during irrigation releases in the summer and lower when water is stored during the fall and winter months (Figure 1), essentially reversing the natural hydrograph. Throughout the lower 32 km, groundwater springs begin adding flow to the Crooked River with much of the spring input occurring in the lowest 16 km just upstream of Lake Billy Chinook (CRWC 2008). Combined, these springs consistently contribute approximately 1,100 cubic feet per second (CFS), or about 80% of the total flow in the Crooked River delivered to LBC (Eilers and Vache 2021).

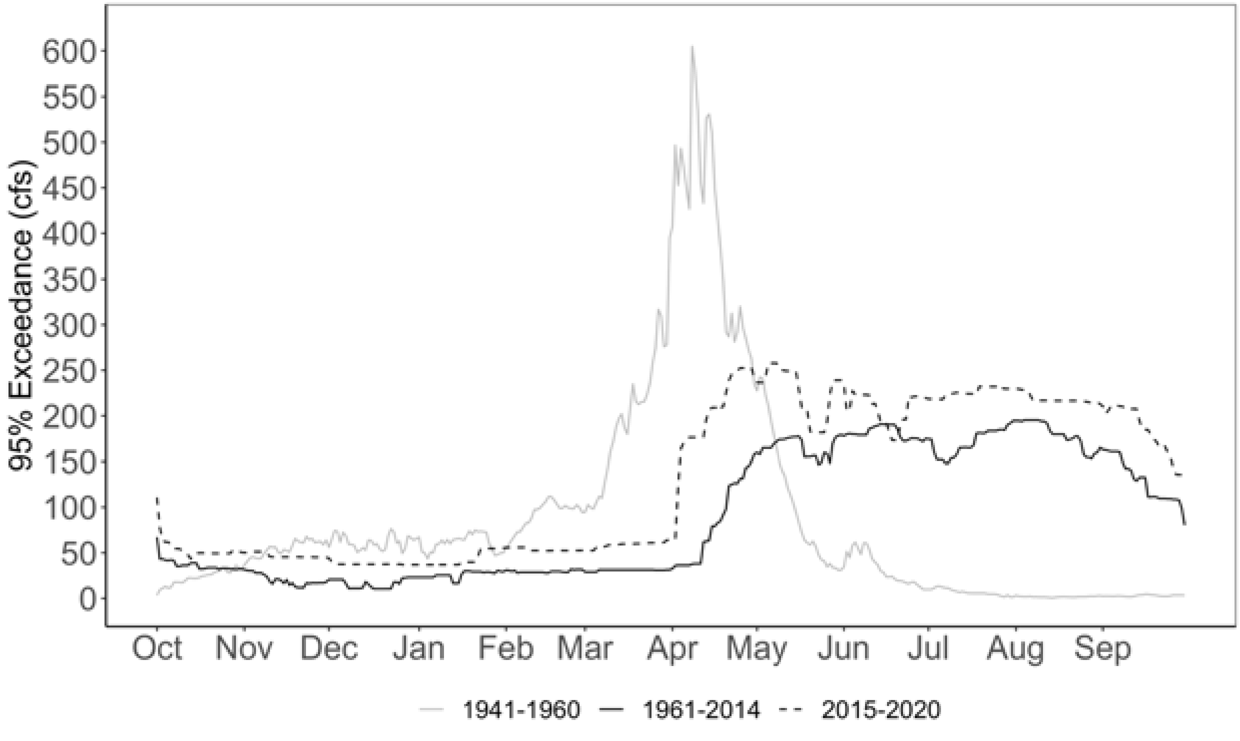

Figure 1. Ninety-five percent exceedance flows in the Crooked River downstream of Bowman Dam. Flows are summarized for three time periods: prior to the construction of Bowman Dam (1941-1960), after construction of Bowman Dam (1961-2014), and following implementation of the Crooked River Act (2015-2020). OWRD Gage #14080500.

Excluding the springs, the largest tributaries to the lower Crooked River include Ochoco Creek, McKay Creek, Lytle Creek, and Dry River. Similar to the Crooked River above Prineville Reservoir, the hydrology of these tributaries is largely defined by peak flows driven by snowmelt in the spring, and low flows during the summer. Ochoco Dam impounds Ochoco Creek at rkm 17 and is managed by OID for irrigation storage and flood control. During the irrigation season (mid-April through mid-October), water is diverted at several locations in Ochoco, McKay, and Lytle Creeks, and all four tributaries receive irrigation return flows. Significant OID returns include the Gap at Crooked River rkm 55 (*max return* = 18.5 cfs), Ryegrass canal at Lytle Creek rkm 2 (*max return* = 40 cfs), and the D-2 drain at Ochoco Creek rkm 10 (*max return* = 2 cfs). Outside of the irrigation season, natural surface and shallow subsurface flow often provide a small amount of continuous discharge in these returns (< 3 cfs).

Water quality data was collected at 12 sites in the mainstem Crooked River, 3 groundwater input sites at Opal Springs, 3 sites in irrigation returns, and 6 sites in tributary streams (Figure 2). In addition to these long-term monitored sites, we collected samples in April 2022 at four small (i.e., less than five cfs), unnamed springs near Opal Springs. Sampling locations were chosen to strike a balance between evaluating nutrient contributions of stream inputs, distributing sites throughout the lower Crooked River basin, and maximizing data collection with available resources. In most cases, sampling sites were located at stream input mouths as well as in the mainstem Crooked River upstream and downstream of the tributary confluence (Table 1). Stream discharge data was available from five gaging stations along the mainstem Crooked River (Figure 2).

Table 1. Summary of water quality monitoring sites in the lower Crooked River basin.

Site	Site Description	River Kilometer	Site Type	Latitude	Longitude
DR-01	Dry River	0.2	Tributary	44.33435	-121.04787
GI-01	The Gap	0.9	Irrigation Return	44.34922	-120.95986
LC-01	Lytle Creek downstream of Ryegrass Canal	0.8	Tributary	44.34843	-120.94714
RI-01	Ryegrass Canal	0.0	Irrigation Return	44.35189	-120.93171
LC-02	Lytle Creek upstream of Ryegrass Canal	2.2	Tributary	44.35285	-120.93171
MC-01	McKay Creek	0.7	Tributary	44.33033	-120.89321
OC-01	Ochoco Creek downstream of D-2 Drain	1.1	Tributary	44.32201	-120.88815
CI-01	D-2 Drain	0.0	Irrigation Return	44.29789	-120.80711
OC-02	Ochoco Creek upstream of D-2 Drain	10.2	Tributary	44.29773	-120.80727
OS-01	Opal Spring, approx. 240 cfs	0.0	Spring	44.49058	-121.29809
OS-02	Unnamed spring near Opal Springs, approx. 1-2 cfs	0.0	Spring	44.47981	-121.30074
OS-03	Unnamed spring near Opal Springs, approx. 4-5 cfs	0.0	Spring	44.47857	-121.30206
US-01	Unnamed spring near Opal Springs, approx. 1-2 cfs	0.0	Spring	44.49165	-121.29740
US-02	Unnamed spring near Opal Springs, approx. 1 cfs	0.0	Spring	44.49145	-121.29753
US-03	Unnamed spring near Opal Springs, approx. 2-4 cfs	0.0	Spring	44.49055	-121.29795
US-04	Unnamed spring near Opal Springs, approx. 3-5 cfs	0.0	Spring	44.49232	-121.29783
CR-01	Crooked River at discharge gage downstream of Opal Springs	0.5	Mainstem	44.49263	-121.29886
CR-02b	Crooked River at discharge gage near Osborne Canyon	11.0	Mainstem	44.42736	-121.23436
CR-02c	Crooked River at Smith Rock State Park discharge gage	30.3	Mainstem	44.36814	-121.13866
CR-03	Crooked River at Lone Pine bridge	37.6	Mainstem	44.34900	-121.08199
CR-04	Crooked River downstream of Dry River	44.8	Mainstem	44.33640	-121.04863
CR-05	Crooked River upstream of Dry River	45.0	Mainstem	44.33705	-121.04814
CR-06	Crooked River downstream of Gap return	54.6	Mainstem	44.34533	-120.96780
CR-08	Crooked River upstream of Ochoco Creek and downstream of Prineville water treatment return	62.6	Mainstem	44.33269	-120.90446
CR-09	Crooked River downstream of McKay Creek	64.8	Mainstem	44.32012	-120.88720
CR-10	Crooked River at Highway 126 bridge	68.3	Mainstem	44.30218	-120.86255
CR-11	Crooked River at Les Schwab Park	71.4	Mainstem	44.28654	-120.84398
CR-13	Crooked River at downstream of Bowman Dam	104.6	Mainstem	44.11013	-120.79438

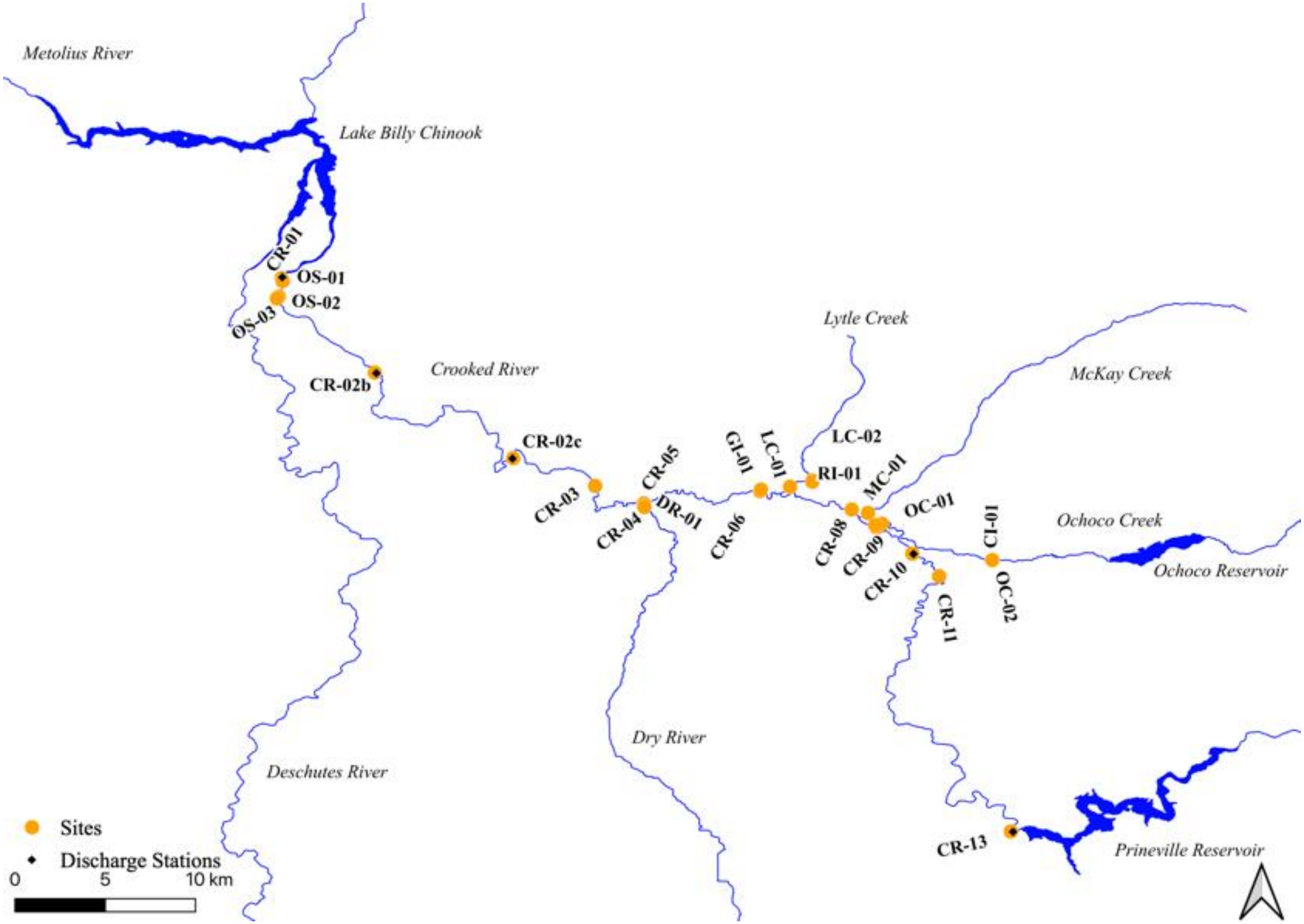

Figure 2. Map of the lower Crooked River basin and water quality monitoring sites.

Monthly Grab Sampling

Grab samples were collected at a subset of stream inputs beginning in August of 2020. Routine monthly sampling at all sites began in June 2021 and concluded in April 2022. Surface water grab samples were collected by dipping clean 125-, 250-, or 500-mL HDPE bottles into flow facing upstream and rinsed three times prior to collection. These samples were collected as close to mid-channel as wading would safely permit and care was taken not to disturb the stream substrate upstream and in proximity of the sampling site. Samples were then labeled and temporarily stored in a cooler with ice before later being transferred to a refrigerator for storage at 4°C. Over the course of the study, laboratory analyses were conducted at the Cooperative Chemical Analytical Laboratory (CCAL; Corvallis, OR), Anatek Labs (Moscow, ID), and by MHE staff at Oregon State University's Cascades extension laboratory (Bend, OR) using a Hach DR3900 spectrophotometer. All samples sent to CCAL were frozen on the day of collection and stored for up to 6 months prior to analysis. Grab samples analyzed by Anatek Labs were preserved with sulfuric acid, stored at 4°C, and analyzed within 28 days of collection. Samples analyzed by MHE were stored at 4°C and were analyzed within 24 hours of collection.

The parameters of most interest to the study included orthophosphate-phosphorus (reported here as "phosphate") and nitrate-nitrogen (reported here as "nitrate"). On some occasions, lab results included nitrate-nitrogen plus nitrite-nitrogen. Nitrite occurs naturally in very low concentrations; therefore, measurements of nitrate-nitrogen plus nitrite-nitrogen are reported here as "nitrate". Several approaches were used to validate results from the spectrophotometer. For example, we measured field and laboratory duplicates to quantify precision, and we measured standard solutions, blank samples, and spiked samples to quantify accuracy. We also analyzed a subset of samples using the spectrophotometer and compared those results to duplicate sample results from CCAL. Nitrate analysis results from the Hach DR3900 spectrophotometer aligned well with results from CCAL (Figure A- 1). However, phosphate results were consistently 30-40% higher with the spectrophotometer when compared with results from CCAL (Figure A- 2). We believe this difference can be attributed to differences in sample storage associated with the two analytical approaches. All samples sent to CCAL were frozen for an extended period of time prior to analysis, whereas samples analyzed using the spectrophotometer were never frozen and were analyzed within 24 hours of collection. Several studies have found freezing water samples, particularly for an extended period of time, can negatively impact phosphate and phosphorus results but has little effect on nitrate results (Chapman and Mostert 1990, Clementson and Wayte 1992, Fellman et al. 2008).

Additional water quality data was collected using a YSI Professional Plus handheld meter but is not included in this report as these parameters were not the focus of the study. Routinely monitored parameters included temperature, dissolved oxygen, and conductivity. Sites were also briefly monitored with the YSI for nitrate and ammonium. However, due to accuracy limitations of ion selective electrodes, this data is not included in the report.

Load Calculations

Nutrient concentrations were used in conjunction with measured and modeled discharge data to calculate nutrient load throughout the lower Crooked River. Continuous data was available at five locations in the mainstem Crooked River (Figure 2). To gain a more detailed understanding of nutrient load, we used flows modeled at 500-meter increments under low flow conditions (Berger et al. 2019). The modeled flows were limited to the sections of river from Bowman Dam to the gage at Smith Rock State Park (approx. rkm 30). To account for the significant amount of flow added by springs downstream of the park, the mean discharge increase observed during our study period at the Osborne Canyon (+ 53 cfs) and Opal Springs (+ 1,027 cfs) gaging stations were added to the modeled flows at Smith Rock. Nutrient concentrations from our monthly surface water grab samples were linearly interpolated between mainstem monitoring sites. Load was then calculated as:

Load (grams/second) = 28.317 * Discharge (cfs) * Concentration (mg/L) / 1000

Model predicted load was compared with actual load measurements at discharge stations using linear regression. Model predicted nutrient load values consistently aligned with actual load measurements, and associated error did not indicate any clear bias (Figure A- 4).

Continuous Monitoring

At the start of each irrigation season, OID releases water from Bowman Dam and diverts approximately 100 cfs through the Feed Canal in order to flush the irrigation system. As part of this process, 80-100 cfs is flushed through Ochoco Creek and McKay Creek and 20-30 cfs is flushed through Lytle Creek for approximately 12 hours. To capture the potential pulse of residual nutrients flushed from irrigation waterways by these water releases, we monitored surface water in the mainstem Crooked River. Two continuous monitoring sites were monitored. Sampling site CR-06, downstream of the input from Lytle Creek, was selected as the site with the greatest potential to observe the highest nutrient concentrations. This assertion was based on monthly concentration data collected throughout this monitoring study. Site CR-09, located upstream of the Ochoco Creek and other irrigation returns, was selected as the designated control site with the expectation that nutrient concentrations would remain stable.

Prior to the initiation of the autosampler schedule (Table 2) and upon retrieval of water samples collected by autosampler, water samples were collected by grab method to capture baseline nutrient concentrations (*Baseline*). For grab sample collections, clean 125- or 250-mL HDPE plastic bottles were dipped into flow facing upstream and rinsed three times prior to collection. Care was taken not to disturb the stream substrate upstream and in proximity of the sampling site. A total of six water samples were collected and securely stored at 4°C until laboratory analysis.

To capture anticipated episodic pulses of nutrients in surface water, samples were collected using a time-series schedule. Sample collection occurred during and immediately following the release of water by OID into the Crooked River. Surface water samples were collected by a pre-programmed automated sampling device (6712 Full-Size Portable Sampler, Teledyne ISCO, Lincoln NE). Autosamplers were placed and secured on the stream bank adjacent to the in-stream sample site. Intake tubing was placed underwater, secured to the streambed with rebar to establish stable placement for the duration of the scheduled collections. A single 300 mL collection occurred at 60- or 90-minute intervals prior to, during, and following water release (*Irrigation Release*) (Table 2). Samples were collected in clean clear glass bottles which were cleaned with phosphate-free soap (Liquinox). Autosamplers were supplied with ice to maintain collected samples at 4ºC. Upon autosampler retrieval, water samples were transferred to 250 mL HDPE plastic bottles and stored on ice to maintain water sample temperatures at 4ºC.

Table 2. Grab and automated sampling schedule at CR-06 and CR-09, April 2022. Samples were analyzed for nitrate and phosphate nutrients.

Event	Date	Collection Time (sampling interval)	Collection Method	Irrigation Status
CR-09 (control)				
Baseline	4/12/2022	08:20	Grab	Flow released from Bowman Dam is diverted into Feed Canal @ 06:00 (~100 cfs)
Irrigation Release	04/12/2022	08:45 – 23:45 (60 minutes)	Autosampler	~80 cfs of diverted flow is released into Ochoco Cr. @ ~ 16:00
	04/13/2022	00:45 – 07:45 (60 minutes)	Autosampler	Flow released into Ochoco Cr. is rediverted @ ~ 06:00
		09:00 – 22:30 (90 minutes)	Autosampler	~80 cfs of diverted flow is released into McKay Cr. @ ~ 16:00
	04/14/2022	00:00 – 16:30 (90 minutes)	Autosampler	Flow released into McKay Cr. is rediverted @ ~ 06:00
Baseline	04/14/2022	17:30	Grab	All flow is diverted
	04/18/2022	18:30	Grab	~30 cfs of diverted flow is released into Lytle Cr. @ ~ 16:00
CR-06 (below irrigation returns)				
Baseline	4/11/2022	09:40	Grab	Flow released from Bowman Dam (not diverted)
	4/12/2022	09:20	Grab	Flow is diverted into Feed Canal @ 06:00 (~100 cfs)
Irrigation Release	04/12/2022	09:45 – 23:45 (60 minutes)	Autosampler	~80 cfs of diverted flow is released into Ochoco Cr. @ ~ 16:00
	4/13/2022	00:45 – 08:45 (60 minutes)	Autosampler	Flow released into Ochoco Cr. is rediverted @ ~ 06:00
		10:30 – 22:30 (90 minutes)	Autosampler	~80 cfs of diverted flow is released into McKay Cr. @ ~ 16:00
	4/14/2022	00:00 – 18:00 (90 minutes)	Autosampler	Flow released into McKay Cr. is rediverted @ ~ 06:00
Baseline	04/18/2022	14:45	Grab	All flow is diverted
Irrigation Release	4/18/2022	16:00 – 23:00 (60 minutes)	Autosampler	~30 cfs of diverted flow is released into Lytle Cr. @ ~ 16:00
	4/19/2022	00:00 – 15:00 (60 minutes)	Autosampler	Flow released into Lytle Cr. is rediverted @ ~ 06:00

RESULTS

Monthly Grab Sampling

Among sampling sites located in tributaries and irrigation returns, nitrate concentrations were highest in the Lytle Creek subbasin, which included LC-01 (*Max* = 6.85 mg/L, *M* = 3.39, *SD* = 2.28), LC-02 (*Max* = 6.68 mg/L, *M* = 3.66, *SD* = 2.15), and RI-01 (*Max* = 6.75 mg/L, *M* = 3.53, *SD* = 2.45) (Figure 3). Nitrate was also high at CI-01 (*Max* = 4.93 mg/L, *M* = 4.27, *SD* = 0.58), which likely explains the increase in nitrate observed from OC-02 (*Max* = 2.18 mg/L, *M* = 0.47, *SD* = 0.57) to OC-01 (*Max* = 2.63 mg/L, *M* = 1.39, *SD* = 0.83). In contrast, nitrate was consistently low at DR-01 (*Max* = 0.66 mg/L, *M* = 0.17, *SD* = 0.14) located in Dry River. With the exception of OC-02 and DR-01, nitrate at our tributary and irrigation return sites exhibited seasonal variation characterized by lower concentrations in the spring and summer months and higher concentrations in the fall and winter.

In the mainstem Crooked River, nitrate followed a similar seasonal pattern with the lowest concentrations observed in July and August, and the highest concentrations observed in December and January (Figure 4). Despite higher concentrations at some tributary and irrigation return sites, summer-time nitrate concentrations remained below 0.5 mg/L at all mainstem sites with the exception of CR-08. During the fall and winter, we observed increases in nitrate concentrations between CR-09 (*Max* = 0.50 mg/L), CR-08 (*Max* = 1.13 mg/L), and CR-06 (*Max* = 1.45 mg/L), likely indicating contributions from Ochoco, McKay, and Lytle Creeks. However, concentrations remained fairly consistent at CR-01 throughout the study (*Max* = 0.57 mg/L, *M* = 0.43, *SD* = 0.07). When compared to 60+ years of ODEQ AWQMP historical data at site CR-03, our nitrate results fell within the expected range and followed a similar trend in seasonal variation (Figure A- 3).

Nitrate concentrations were also consistent at our spring input sites (Figure 5). Mean nitrate at OS-01, OS-02 and OS-03 was 0.22 mg/L (*SD* = 0.05), 0.35 mg/L (*SD* = 0.02) and 0.19 mg/L (*SD* = 0.01), respectively. However, limited sampling at four unnamed springs in close proximity to OS-01 revealed higher nitrate concentrations ranging from 0.65 – 0.82 mg/L.

Phosphate results followed a similar pattern to nitrate where concentrations were higher in some of the tributaries and irrigation returns (Figure 6) than the mainstem Crooked River (Figure 7). Interestingly, phosphate was highest at DR-01 (*Max* = 0.29 mg/L, *M* = 0.22, *SD* = 0.07). Phosphate was also elevated at LC-01 (*Max* = 0.21 mg/L, *M* = 0.11, *SD* = 0.04), LC-02 (*Max* = 0.19 mg/L, *M* = 0.16, *SD* = 0.12), RI-01 (*Max* = 0.22 mg/L, *M* = 0.17, *SD* = 0.05), and CI-01 (*Max* = 0.18 mg/L, *M* = 0.16, *SD* = 0.01). At all other sites, including those located in the mainstem Crooked River and in springs (Figure 8), mean phosphate concentration was below 0.10 mg/L. Elevated phosphate concentrations in tributaries, such as Dry River, did not appear to strongly affect concentrations in the mainstem Crooked River. For example, phosphate was nearly identical at our Crooked River sites downstream (CR-04; *Max* = 0.12 mg/L, *M* = 0.09, *SD* = 0.02) and upstream (CR-05; *Max* = 0.12 mg/L, *M* = 0.09, *SD* = 0.02) of the confluence with

Dry River. Phosphate concentrations also followed a seasonal pattern at most sites where concentrations were higher in the fall and winter than they were during the spring and summer, although this pattern was more pronounced with nitrate. When compared to historical data at CR-03, our phosphate results fell within the expected range and followed a similar trend in seasonal variation (Figure A- 3).

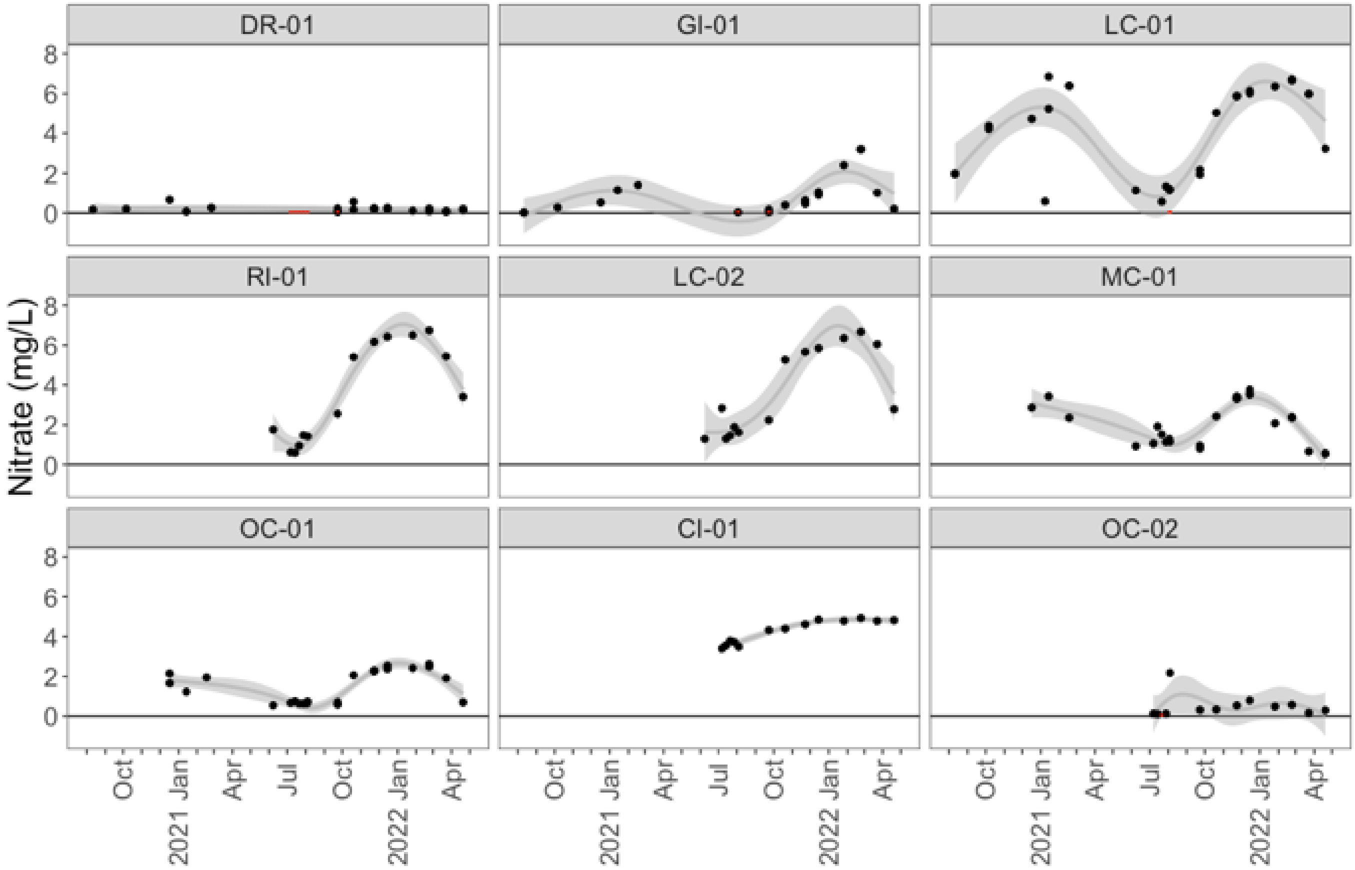

Figure 3. Nitrate concentrations in tributary and irrigation return sites in the lower Crooked River basin. Grab sample measurements are represented by black dots and are fitted using a generalized additive model (dark grey line) with 95% confidence intervals (light grey band). Red bands indicate grab sample results below laboratory practical quantitation limit (0.1 mg/L). Note: Y-axis scales differ between figures.

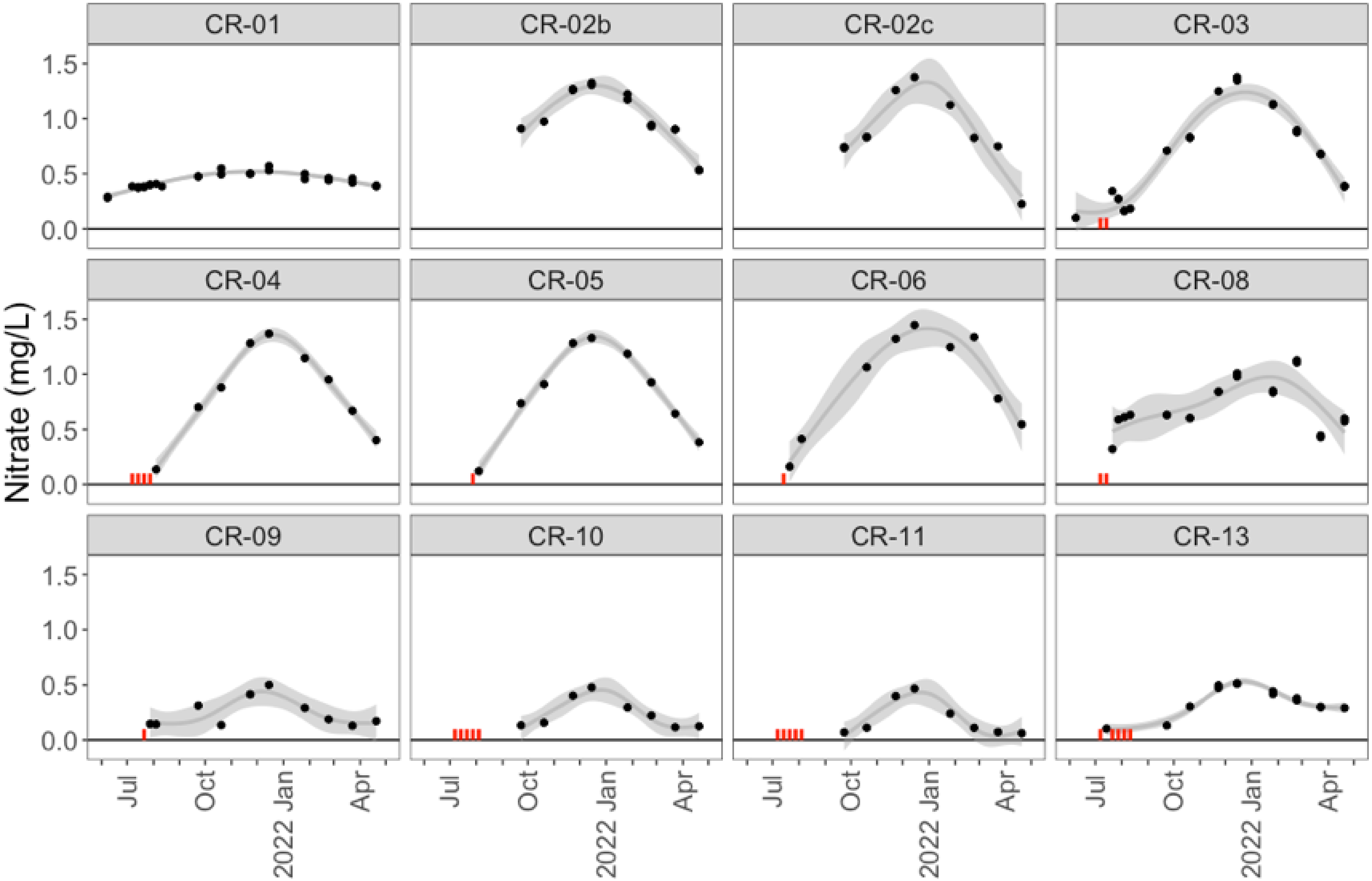

Figure 4. Nitrate concentrations in mainstem lower Crooked River sites. Grab sample measurements are represented by black dots and are fitted using a generalized additive model (dark grey line) with 95% confidence intervals (light grey band). Red bands indicate grab sample results below laboratory practical quantitation limit (0.1 mg/L). Note: Y-axis scales differ between figures.

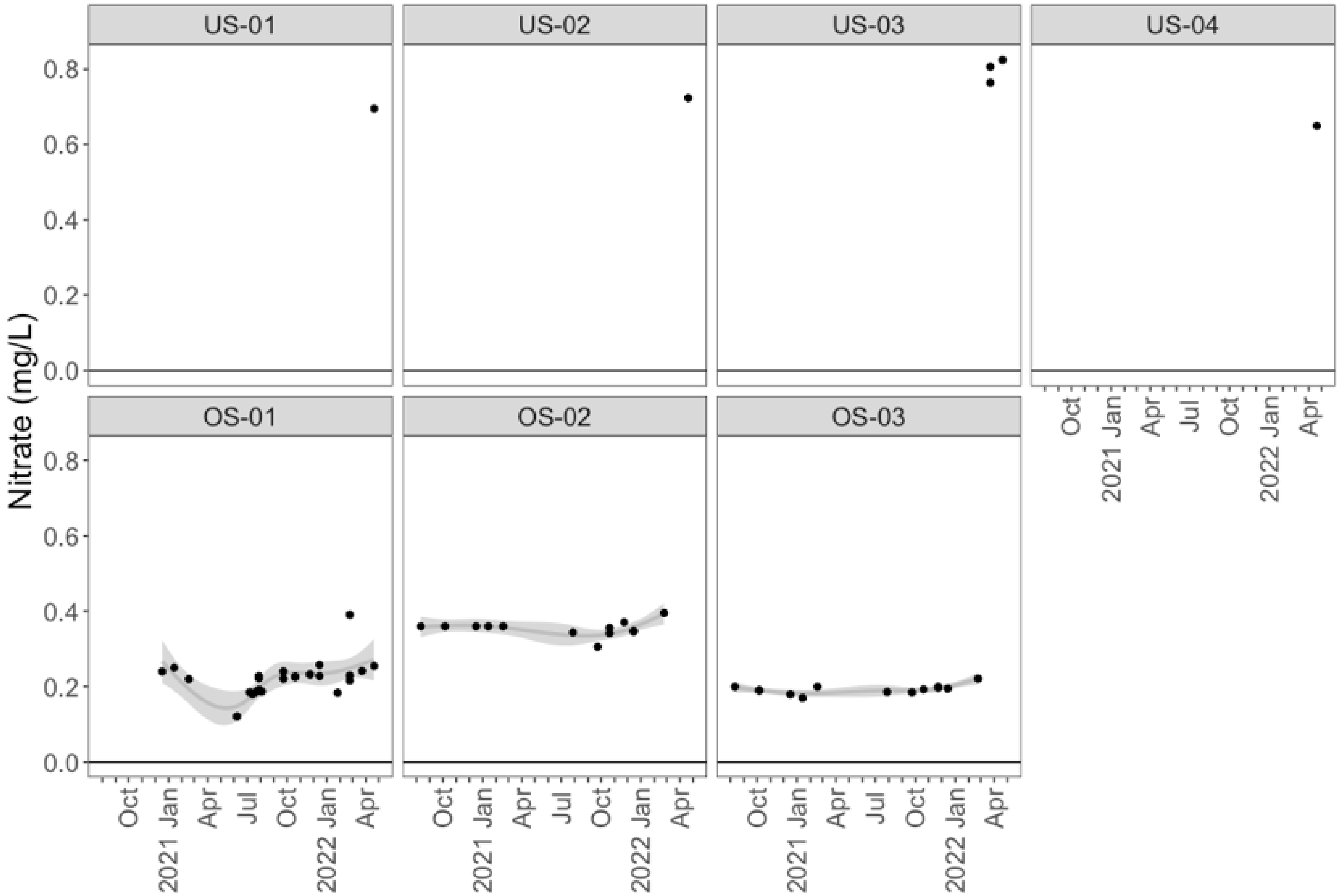

Figure 5. Nitrate concentrations at Opal Spring and adjacent spring input sites. Grab sample measurements are represented by black dots and are fitted using a generalized additive model (dark grey line) with 95% confidence intervals (light grey band). Note: Y-axis scales differ between figures.

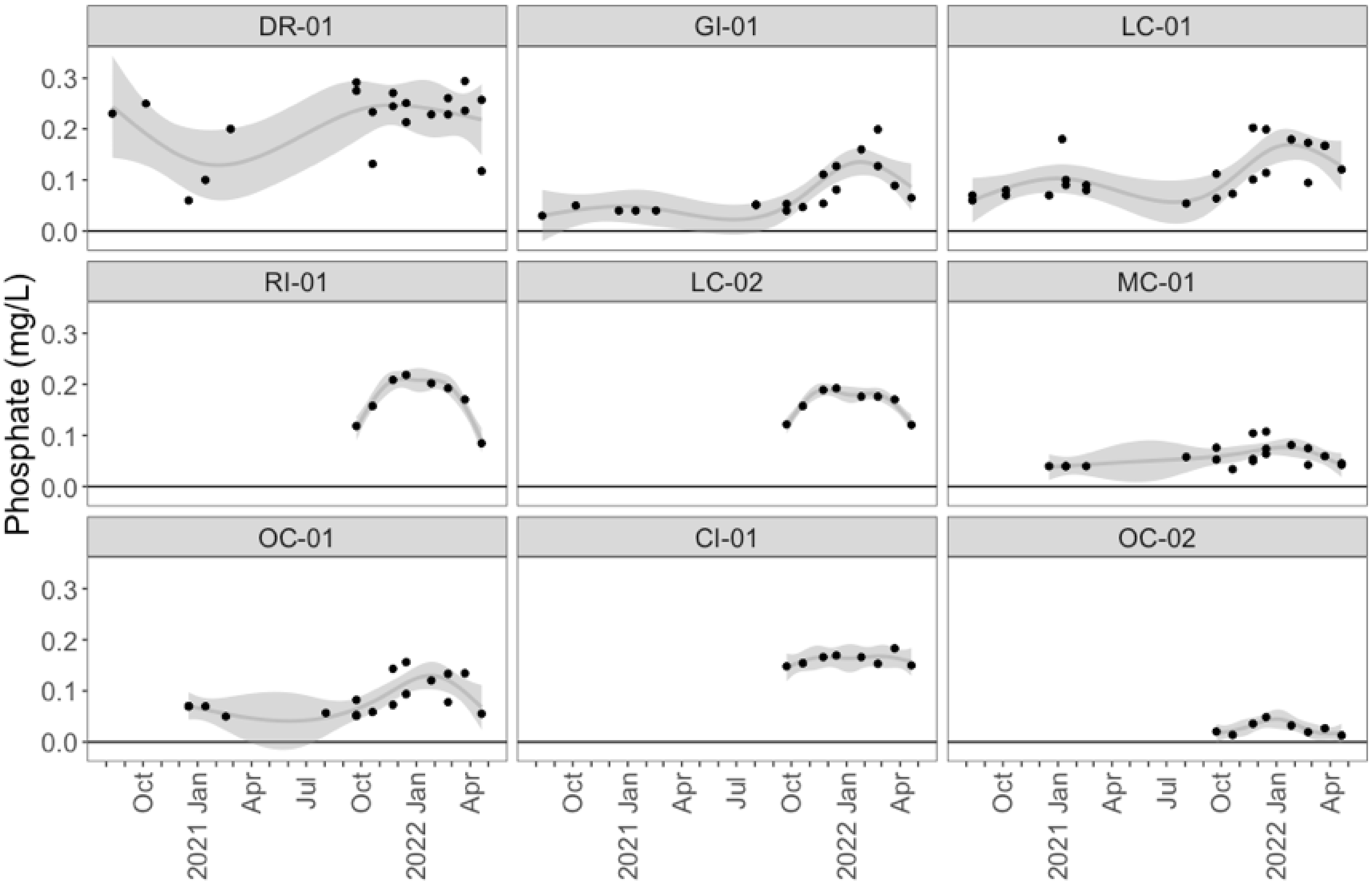

Figure 6. Phosphate concentrations in tributary and irrigation return sites in the lower Crooked River basin. Grab sample measurements are represented by black dots and are fitted using a generalized additive model (dark grey line) with 95% confidence intervals (light grey band). Note: Y-axis scales differ between figures

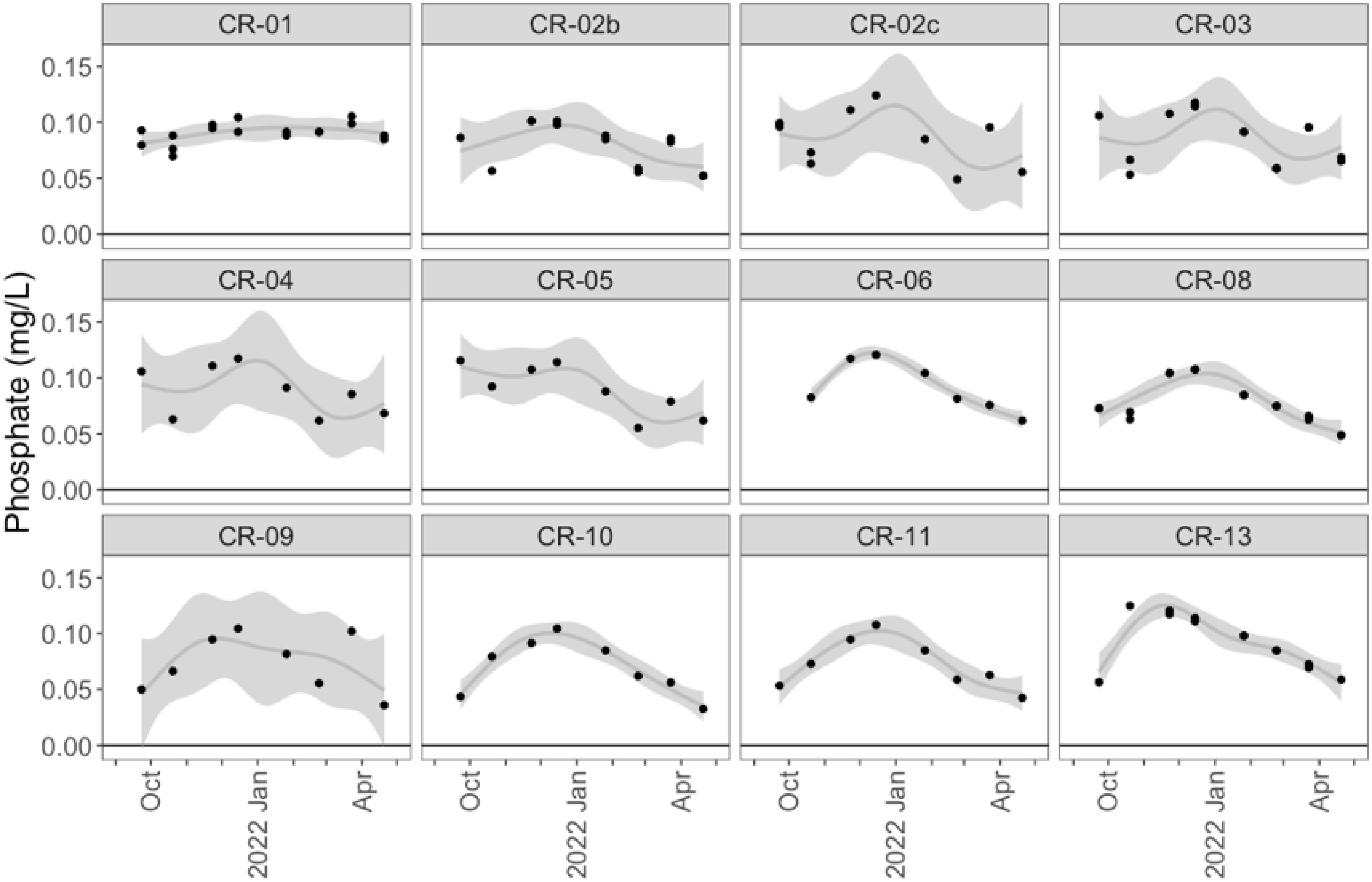

Figure 7. Phosphate concentrations in mainstem lower Crooked River sites. Grab sample measurements are represented by black dots and are fitted using a generalized additive model (dark grey line) with 95% confidence intervals (light grey band). Note: Y-axis scales differ between figures.

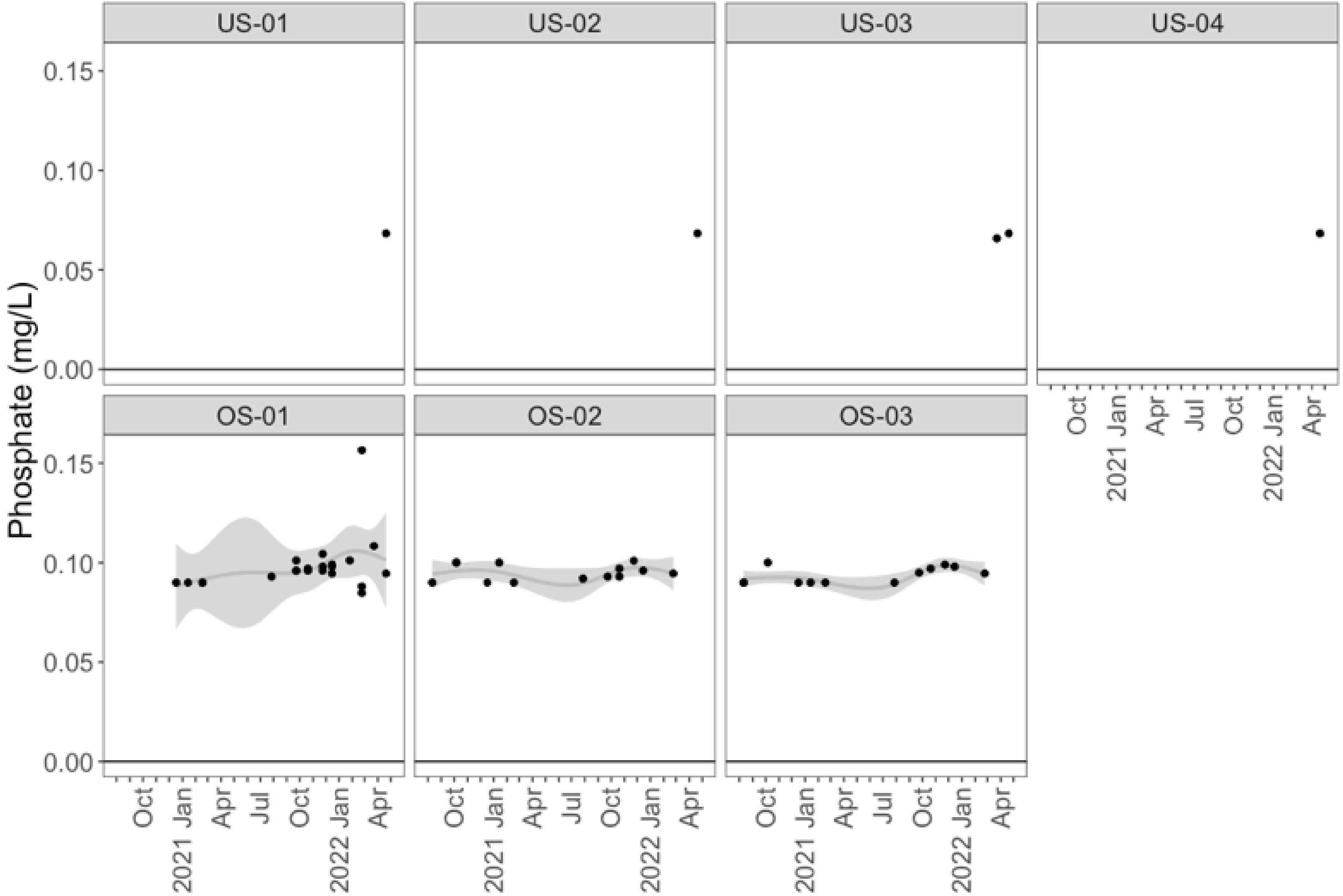

Figure 8. Phosphate concentrations at Opal Spring and adjacent spring input sites. Grab sample measurements are represented by black dots and are fitted using a generalized additive model (dark grey line) with 95% confidence intervals (light grey band). Note: Y-axis scales differ between figures.

Nutrient Load

Our estimates of nitrate load indicated the majority of nutrients entered the Crooked River downstream of Smith Rock State Park (rkm 30). During spring and summer months, nitrate load released at Bowman Dam averaged 0.65 g/s (*SD* = 0.32, Figure 9). There was a noticeable increase in load from upstream of the confluence with Ochoco Creek (*M* = 0.28 g/s, *SD* = 0.24) to downstream of the confluence with McKay Creek (*M* = 1.45 g/s, *SD* = 0.77). However, load decreased as flows moved downstream to Smith Rock State Park (*M* = 0.54 g/s, *SD* = 0.22) before sharply increasing at the mouth of the Crooked River (13.15 g/s, *SD* = 1.67). On average, nitrate load at Smith Rock State Park represented only 4.1% of the total load entering LBC during spring and summer months.

During fall and winter months, nitrate load released at Bowman Dam averaged 0.94 g/s (*SD* = 0.40) and decreased slightly as flows moved downstream before reaching the confluence of Ochoco Creek (*M* = 0.76 g/s, *SD* = 0.32). Load then increased below the confluence with McKay Creek (*M* = 2.52 g/s, *SD* = 0.92) and Lytle Creek (*M* = 4.52 g/s, *SD* = 1.39), and remained relatively stable as flows moved downstream to Smith Rock State Park (*M* = 3.82 g/s, *SD* = 1.00) before sharply increasing at the mouth of the Crooked River (*M* = 17.53 g/s, *SD* = 1.09). Despite an apparent influx of nitrate from Ochoco, McKay and Lytle Creeks, nitrate load at Smith Rock State Park represented only 21.8% of the average total load entering LBC during fall and winter months.

Prior to September 2021, grab samples at mainstem Crooked River sites were not analyzed for Phosphate. As a result, phosphate load was only estimated for September 2021 through April 2022. Similar to nitrate load, most modeled predicted phosphate load entered the Crooked River downstream of Smith Rock State Park (Figure 10). Phosphate load was relatively consistent between Bowman Dam (*M* = 0.24 g/s, *SD* = 0.07) and downstream of the confluence with McKay Creek (*M* = 0.23 g/s, *SD* = 0.06). We observed an increase in load downstream of the confluence with Lytle Creek (*M* = 0.33 g/s, *SD* = 0.10). Phosphate load remained relatively consistent as flows moved downstream to Smith Rock (*M* = 0.29 g/s, *SD* = 0.12) before sharply increasing at the mouth of the Crooked River (*M* = 3.23 g/s, *SD* = 0.33). On average, phosphate load at Smith Rock State Park represented only 8.8% of the total load entering LBC.

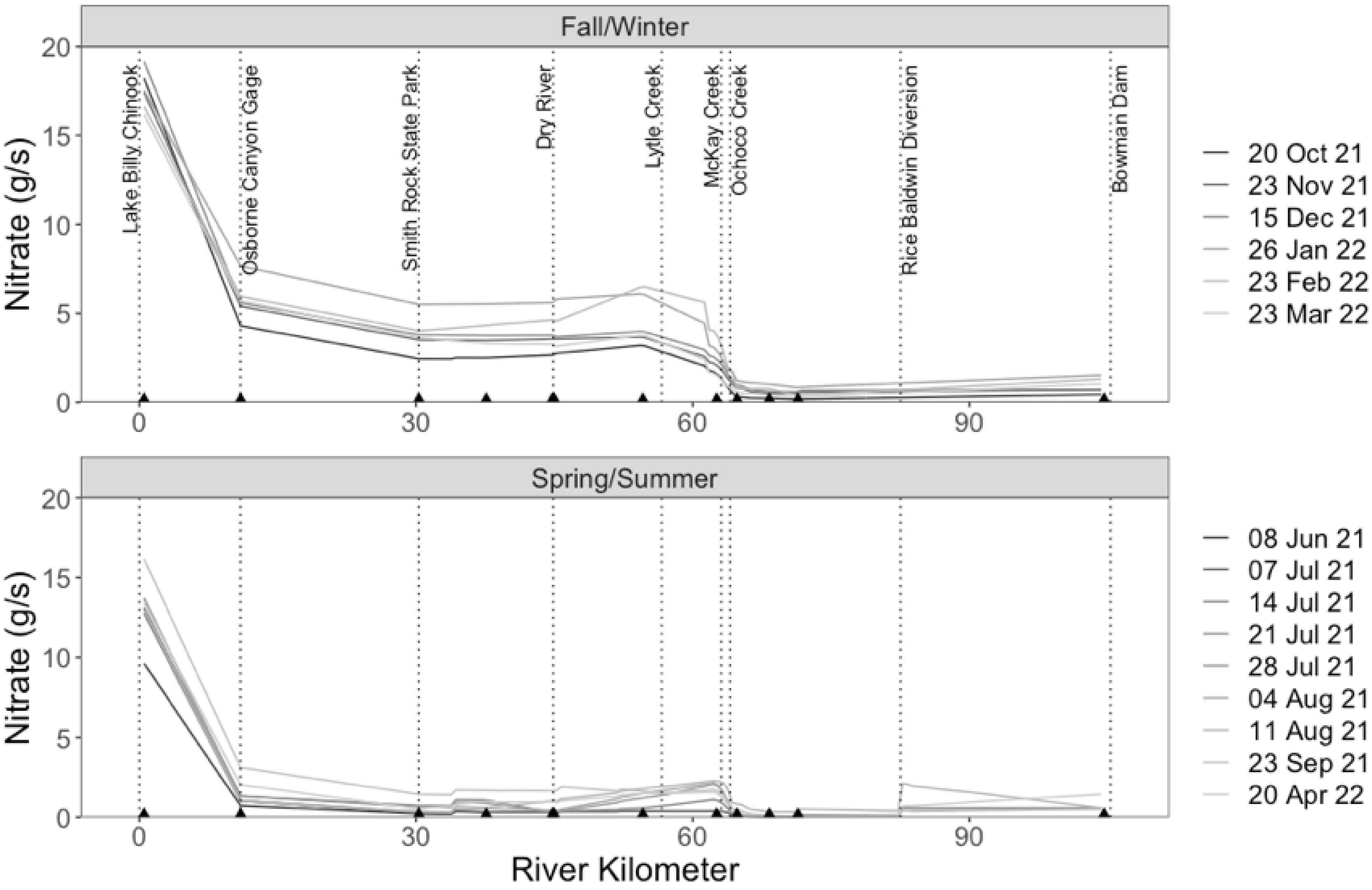

Figure 9. Longitudinal profile of estimated nitrate load in the lower Crooked River during the fall and winter (top) and the spring and summer (bottom). Vertical dotted lines indicate the location of key features. Black triangles indicate the location of water quality monitoring sites used to inform load estimates.

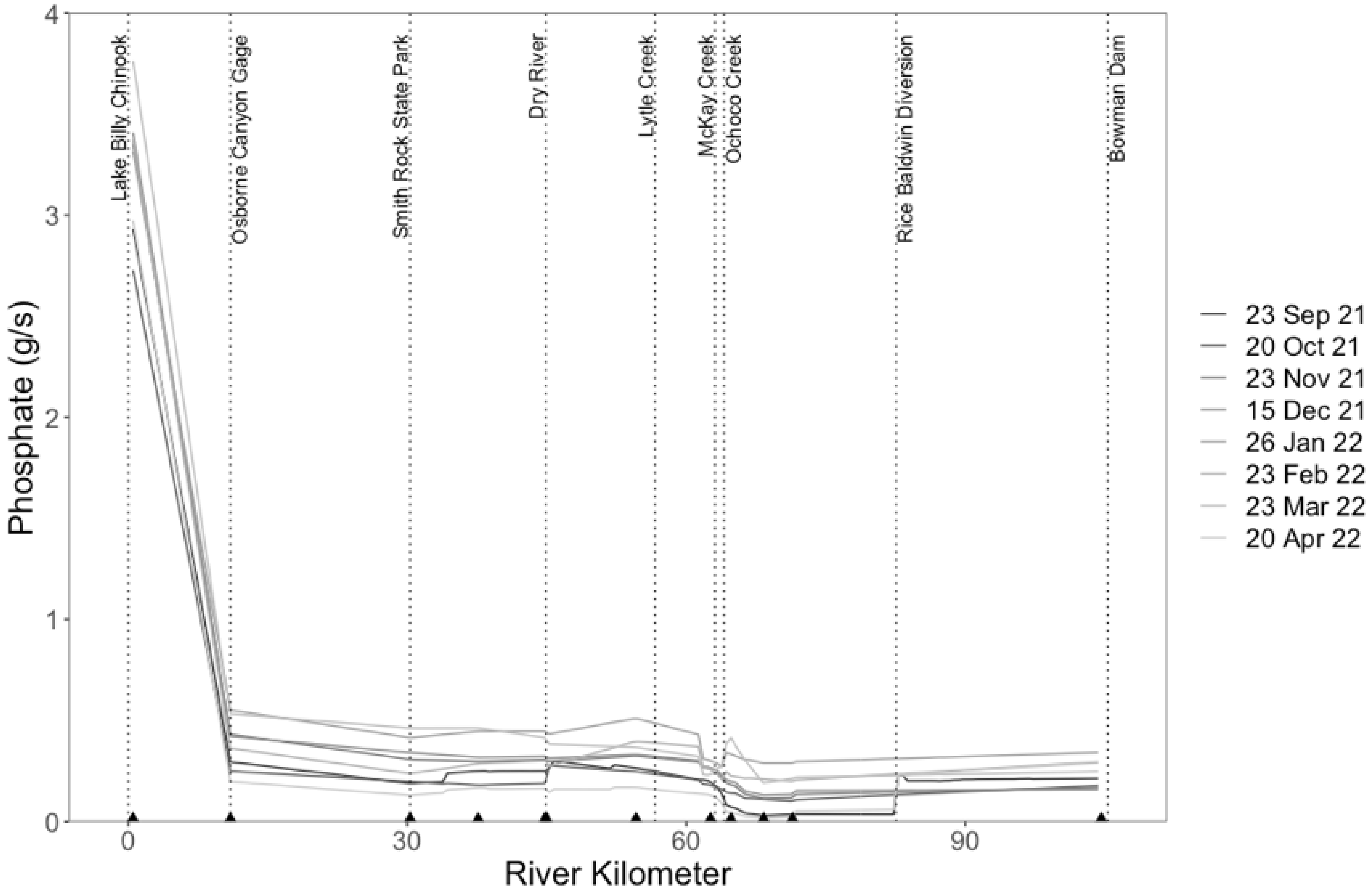

Figure 10. Longitudinal profile of estimated phosphate load in the lower Crooked River. Vertical dotted lines indicate the location of key features. Black triangles indicate the location of water quality monitoring sites used to inform load estimates.

Continuous Monitoring

Samples collected at CR-09 approximately 40 hours following water release from Bowman Dam resulted in phosphate concentrations at 0.07 mg/L while phosphate load was estimated at 0.45 g/s (Figure 11). Phosphate concentrations gradually decreased to nearly 0.02 mg/L across the automated sampling period. By April 20, ten days following water release at Bowman Dam, the baseline concentration stabilized at 0.03 mg/L. Phosphate concentrations throughout the sampling period remained within the concentration range observed from monthly sampling events at CR-09 (Figure 7). Phosphate load at CR-09 was a function of discharge. Phosphate load peaked at 0.46 g/s when discharge measured at 218 cfs. Subsequently, phosphate load stabilized to less than 0.05 g/s as discharge stabilized at less than 25 cfs. Nitrate concentrations remained between 0.1 and 0.2 mg/L throughout the sampling period at CR-09 (Figure 12). Similar to phosphate at CR-09, nitrate load was a function of discharge where peak load (0.75 g/s) coincided with peak discharge (220 cfs), and load stabilized around 0.10 g/s as discharge approached 25 cfs.

At site CR-06, nitrate concentrations and load calculations concurrently fluctuated with discharge measurements. Nitrate concentration was near its highest level at low discharge, as observed with baseline results 0.88 mg/L at approximately 50 cfs (Figure 14). As discharge increased to approximately 180 cfs on the night of April 11, concentrations decreased to 0.40 mg/L. The effect of OID’s diversion at the Feed Canal on the morning of April 12 translated to decreased discharge at CR-06 at approximately 21:00. Discharge subsequently increased as diverted flows were released in Ochoco Creek, during which time we observed a four-hour long spike in mainstem nitrate concentration (*Max* = 0.89 mg/L) and load (*Max* = 4.71 g/s). We observed a similar pattern 24 hours later corresponding with diverted flows being released in McKay Creek: nitrate concentration (*Max* = 0.65 mg/L) and load (*Max* = 2.82 g/s) spiked for approximately three hours at CR-06. Diverted flows were released into Lytle Creek at 16:00 on April 18 and concentrations at CR-06 subsequently increased from 0.39 mg/L to 0.64 mg/L while nitrate load increased from 1.06 g/s to 1.73 g/s. At the final grab sample on April 20, nitrate concentration stabilized at 0.56 mg/L, while load was estimated at 0.97 g/s.

The baseline phosphate concentration at CR-06 on April 11 was observed at 0.06 mg/L. During irrigation diversions and releases into Ochoco and McKay Creeks between April 12-14, phosphate load measurements concurrently fluctuated with discharge while concentrations remained between 0.06 to 0.08 mg/L (Figure 13). During the period of time when flows were released into Lytle Creek, phosphate concentrations at CR-06 increased from 0.05 mg/L to 0.07 mg/L while load increased from 0.13 g/s to 0.19 g/s. At the final grab sample on April 20, phosphate concentrations stabilized at 0.07 mg/L, while load was estimated at 0.10 g/s.

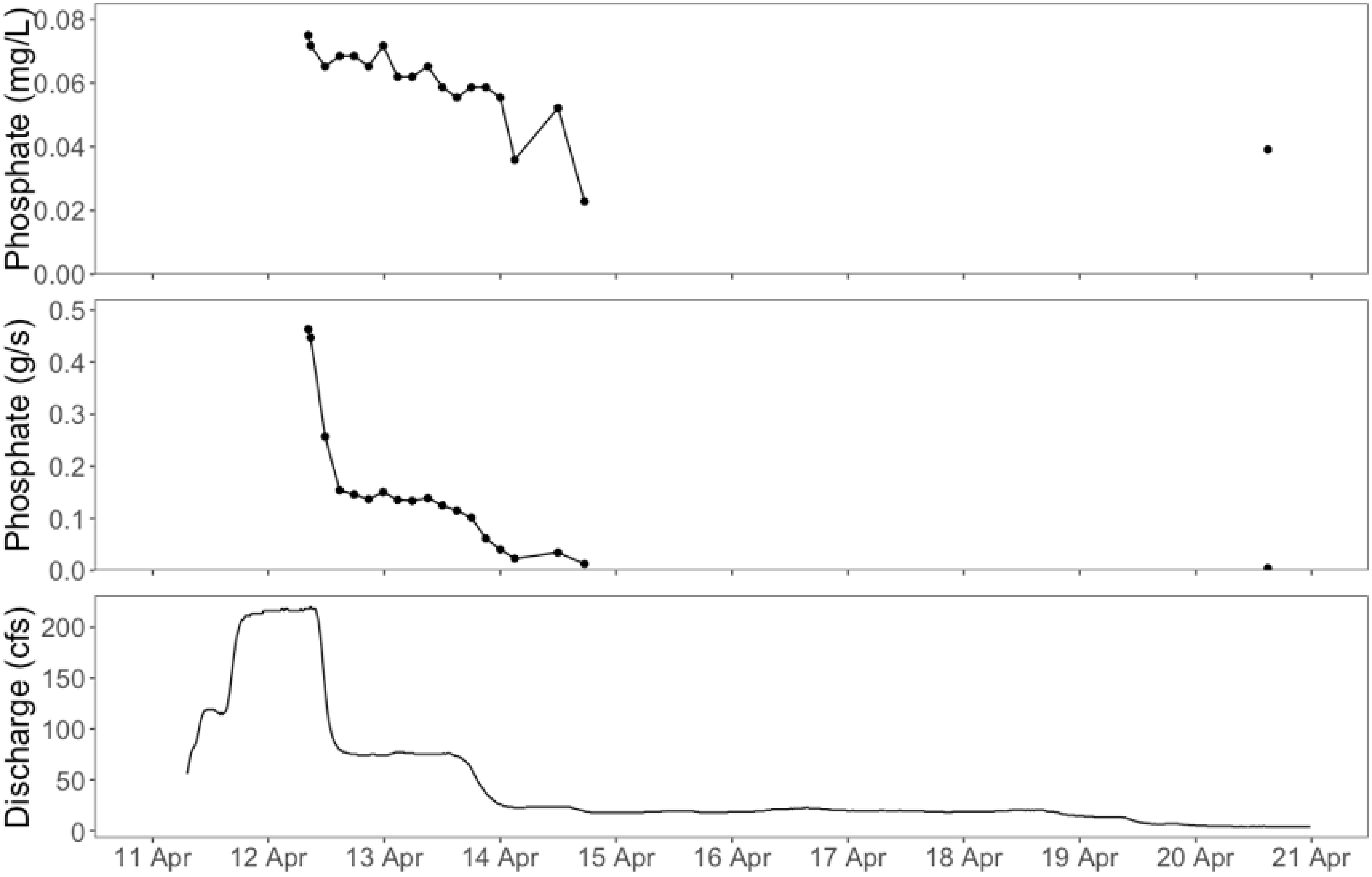

Figure 11. Phosphate concentration (top) and load (middle) observed during targeted event continuous monitoring at CR-09. Continuous discharge (black line) at OWRD gage #14081500 is shown on the bottom plot.

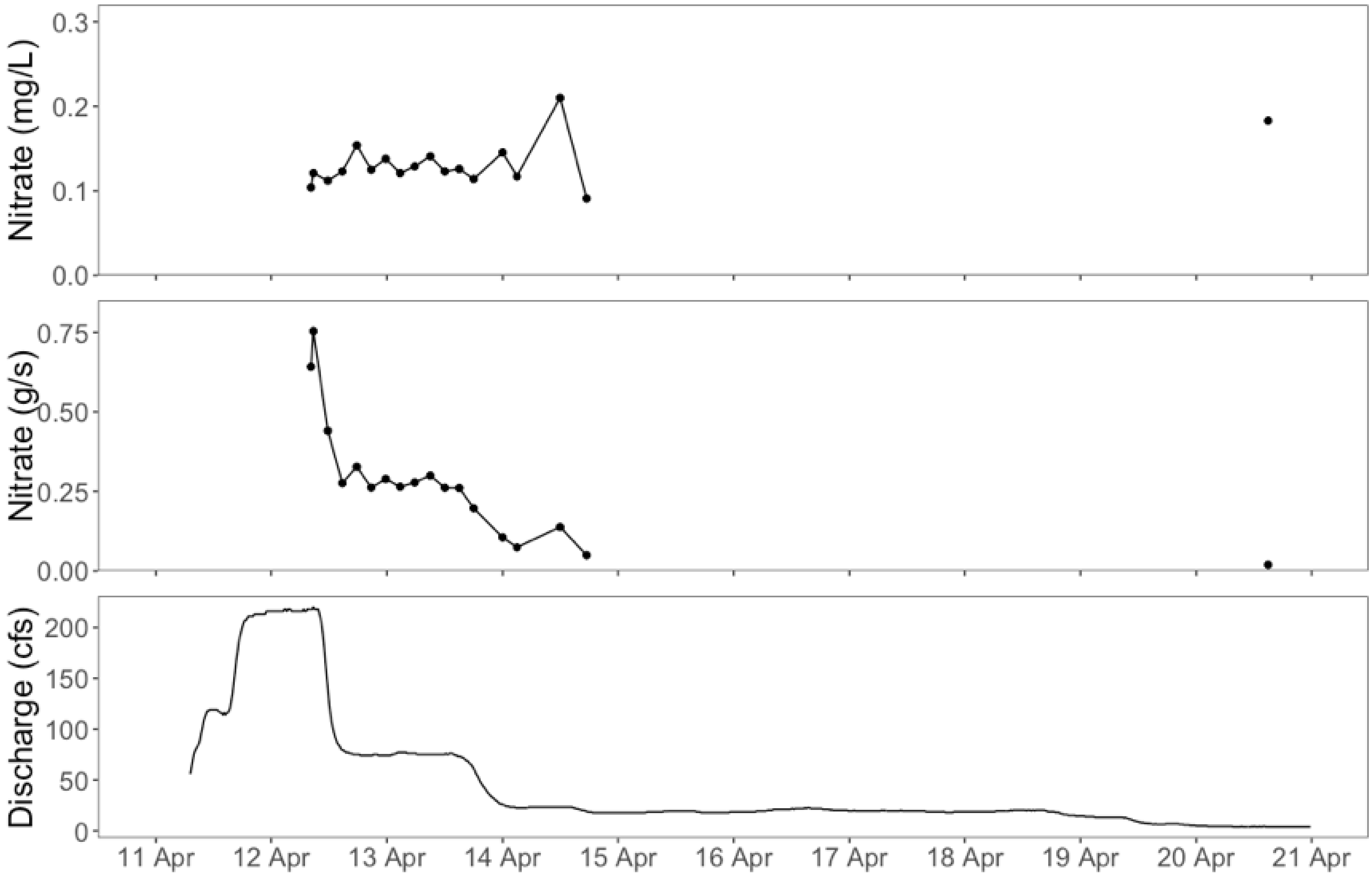

Figure 12. Nitrate concentration (top) and load (middle) observed during targeted event continuous monitoring at CR-09. Continuous discharge (black line) at OWRD gage #14081500 is shown on the bottom plot.

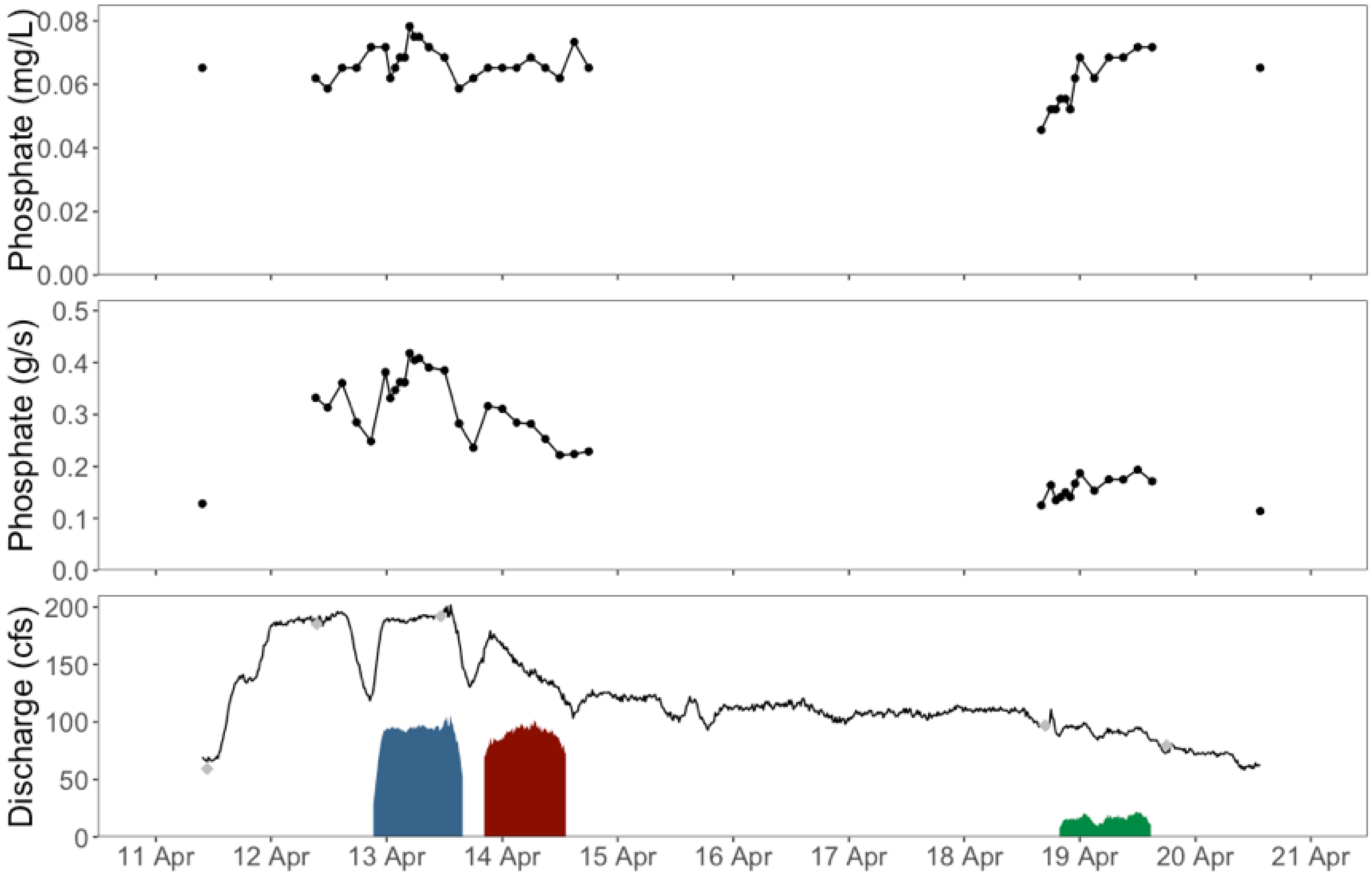

Figure 13. Phosphate concentration (top) and load (middle) observed during targeted event continuous monitoring at CR-06. Estimated continuous discharge (black line) and discrete discharge measurements (grey diamonds) are shown on the bottom plot, as well as the estimated contribution of irrigation flushing flows through Ochoco Creek (blue), McKay Creek (red), and Lytle Creek (green).

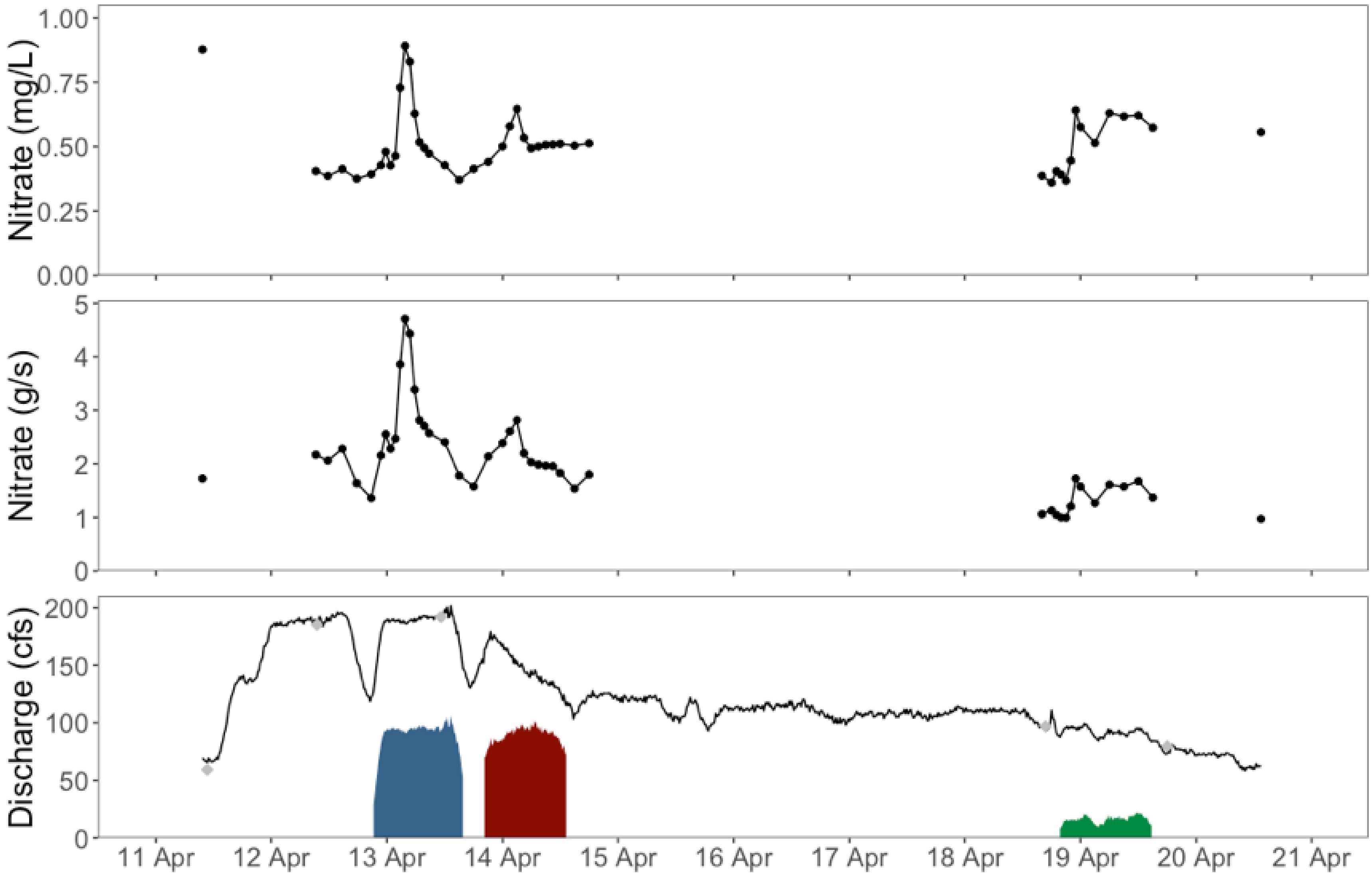

Figure 14. Nitrate concentration (top) and load (middle) observed during targeted event continuous monitoring at CR-06. Estimated continuous discharge (black line) and discrete discharge measurements (grey diamonds) are shown on the bottom plot, as well as the estimated contribution of irrigation flushing flows through Ochoco Creek (blue), McKay Creek (red), and Lytle Creek (green).

DISCUSSION

Lower Crooked River nutrient concentrations observed during this study corroborate previously reported water quality monitoring data. The average nitrate concentration (0.43 mg/L at CR-01) at the mouth of the Crooked River was similar to observations of 0.40 mg/L by Eilers and Vache (2021). Nitrate and phosphate data were within the range of ODEQ's AWQMP long-term monitoring data at Lone Pine bridge (CR-03). In addition, nitrate concentrations were highest in Lytle, McKay, and Ochoco Creeks, with the highest phosphate concentrations in Dry River. These peak concentrations were consistent with CRWC's 2010-2014 findings. Taken together with previous observations over a decade, we are confident the data are reliable and accurate.

Lower Crooked River nutrient concentrations varied seasonally. Nitrate concentrations were highest during the fall and winter and lowest in the spring and summer, likely due to increased uptake rates associated with increased water temperature, aquatic vegetation, and algae densities. The most dramatic change in nitrate concentrations across all input streams was Lytle Creek, where we observed a ten-fold increase between the summer and winter months. Eilers and Vache (2021) observed a similar pattern in LBC where high algal densities were attributed to higher concentrations of nitrate from fall through spring and moderately high densities of cyanobacteria were attributed to lower concentrations of nitrate during the summer. Therefore, it has been asserted that reducing nitrate in the Crooked River would decrease algal growth and promote cyanobacteria growth in LBC (Eilers and Vache 2021). Phosphate exhibited the same seasonal pattern at most sites, albeit to a lesser degree than nitrate.

Elevated nutrient concentrations in the lower Crooked River basin have been attributed to agriculture and irrigation returns (Webb 2020, Eilers and Vache 2021). Therefore, it is asserted that anthropogenic (i.e., agriculture) sources on the Crooked are responsible for high nutrients and phytoplankton found in LBC (Webb 2020, Eilers and Vache 2021, DRA 2021). This association is largely dependent on concentration measurements at a given location. However, a riverine system is dynamic with ground and surface water inputs, and spot nutrient measurements provide a limited understanding on total nutrients within the system. To address this, we modeled nutrient load in the mainstem Crooked River to estimate the contribution of tributaries and irrigation returns. While the highest nutrient concentrations were found in some of our input locations (i.e., Lytle Creek), we found that they had a minimal effect on the Crooked River's total load. This was most apparent during spring and summer months when, after accounting for inputs from all tributary and irrigation returns that occur between Bowman Dam and Smith Rock State Park, average nitrate load actually decreased throughout this section of the mainstem Crooked River. However, contributions from these tributaries and irrigation returns, particularly from Lytle Creek, increased nitrate load in the mainstem Crooked River during the fall and winter months. To a lesser degree, phosphate inputs from tributaries and irrigation returns were negligible throughout the mainstem. For example, we observed an increase of 0.05 g/s in phosphate load between Bowman Dam and Smith Rock State Park. This equates to 1.5% of the Crooked River's contribution to LBC. Taken together, our observations indicate that nutrient concentrations are elevated in some tributaries and irrigation returns, particularly during the fall and winter months. However, due to the relatively low discharge present in the tributaries and irrigation returns, elevated nutrient concentrations remain localized and their effect on total load in the mainstem Crooked River is minimal. Our targeted sampling during the start of irrigation season had a small, episodic effect on Crooked River nutrient loading. The observed pulse during flushing flows represented a 5% increase in daily nitrate load to LBC.

The Crooked River's largest nutrient load contribution occurs downstream of Smith Rock State Park. During spring and summer months, 96% of nitrate load entered the river downstream of the park, with 90% of the load having entered in the lower 11 rkm. To a lesser degree, 78% of nitrate load entered the river downstream of the park and 66% entered in the lowest 11 rkm during fall and winter months. Approximately 1,100 cfs, or 80% of Crooked River flow, enters the Crooked River from countless springs spread throughout the lower 30 rkm downstream of Smith Rock (Eilers and Vache 2021). In an attempt to understand nutrient contribution by these springs, we monitored nitrate at Opal Spring. Opal Spring consistently discharges approximately 240 cfs and is the largest individual spring in the lower Crooked River. Nitrate load of Opal Spring was 1.50 g/s, accounting for approximately 8-12% of load entering LBC. It is unknown whether the nitrate source is anthropogenic; however, a previous analysis of carbon and hydrogen isotopes found evidence that water from Opal Spring predates the 1950s (Caldwell 1998). This finding suggests that at least some of Opal Spring's nitrate is naturally occurring. In addition to Opal Spring, many other smaller volume springs were observed in the nearby canyon walls, where concentrations were over three times greater than Opal Spring. Caldwell (1998) reported that a separate spring near Opal Spring had a shorter residence time and may have differed in origin, therefore it is possible that some of these springs may contain anthropogenic nutrients. It appears that Caldwell (1998) is the only investigation with information on the residence time of these springs. Therefore, further investigation is warranted to determine the extent to which the large nitrate load in the lower 11 km of the Crooked River is of natural or anthropogenic origin.

Our basin-wide sampling design across several tributaries, all seasons, and irrigation regimes, corroborated historic nutrient concentration data throughout the lower Crooked River. Through the use of concentration data and discharge data, we were able to identify the largest source of nutrient load and determine how tributaries of high nutrient concentration affect the mainstem Crooked River load. However, it is clear that there is a need for further investigative work to identify natural and anthropogenic sources (Table 3). An updated isotope study in the lower 11 km and tributaries of high nutrient concentration (i.e. Lytle Creek) would be important to determine nitrate origin. If nutrient reduction is identified as a goal among stakeholders, it is critical to identify whether nutrients are anthropogenically sourced. Anecdotal evidence of nitrate levels in drinking water wells within the Lytle Creek subbasin suggests endogenous nitrate may be naturally high. In addition to isotope studies, sampling a targeted rain event to capture peak nutrient runoff in agricultural areas is also warranted. Applying our automated sampling design at 60- or 90-minute intervals during a rain event in the winter or spring, when most of the precipitation occurs in the basin, would help to quantify nutrient runoff.

Table 3. Summary of current data gaps in our understanding of the Crooked River's nutrient contribution to Lake Billy Chinook with potential approaches to address those uncertainties.

Data Gaps	**Potential Approach**
Overland runoff effects on nutrient load in the mainstem Crooked River	Continuous automated sampling prior to, during, and following first significant rain event(s)
Nitrate concentrations at unnamed springs adjacent to Opal Spring	Monthly collection of grab samples
Contribution of natural or anthropogenic nitrate at Opal Springs and adjacent unnamed springs	Nitrogen isotope analysis
Contribution of natural or anthropogenic nitrate within Lytle Creek subbasin	Nitrogen isotope analysis

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APPENDIX

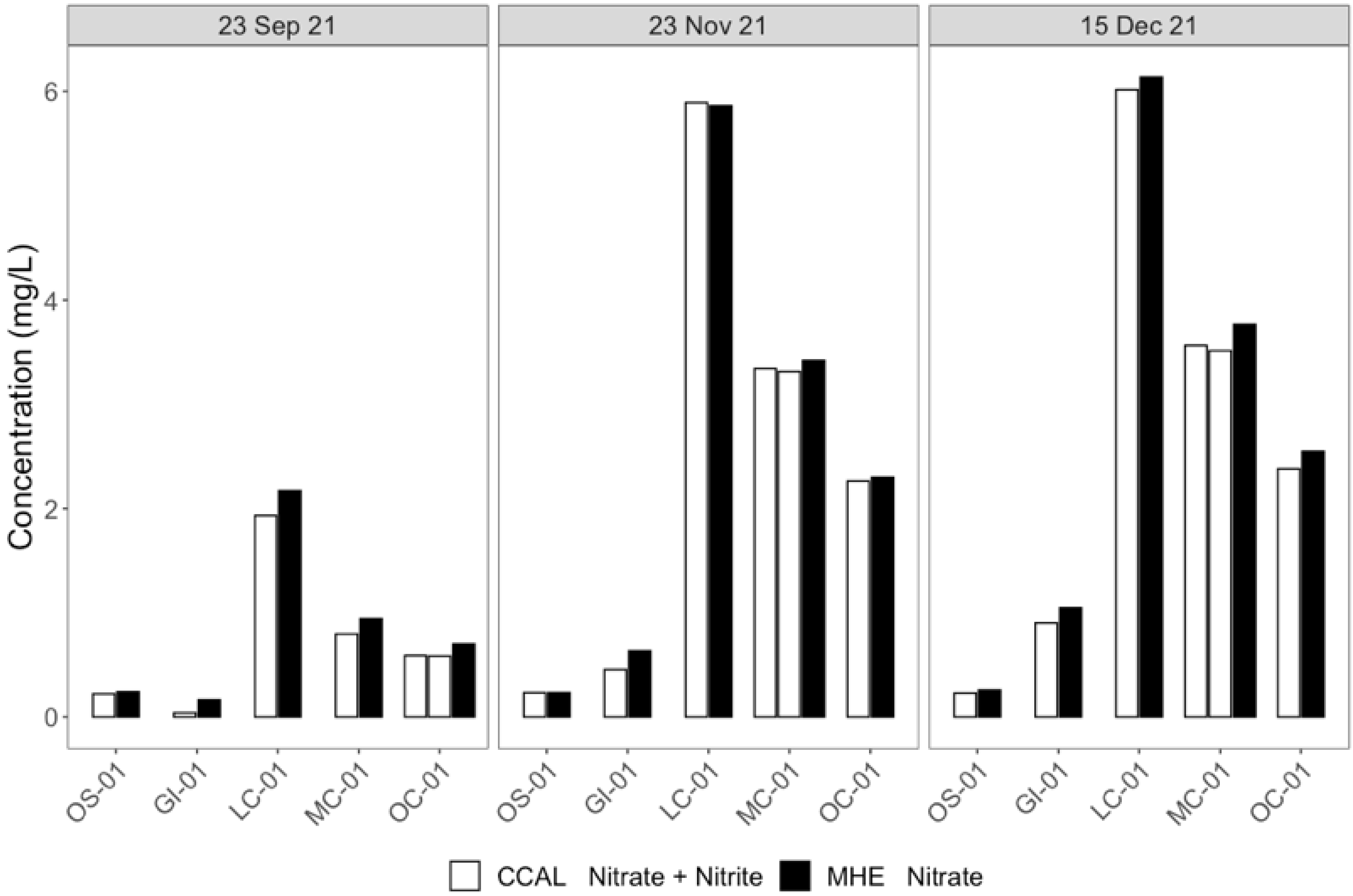

Figure A- 1. Nitrate concentration results from CCAL (white) and results from duplicate samples analyzed using a Hach DR3900 spectrophotometer (black).

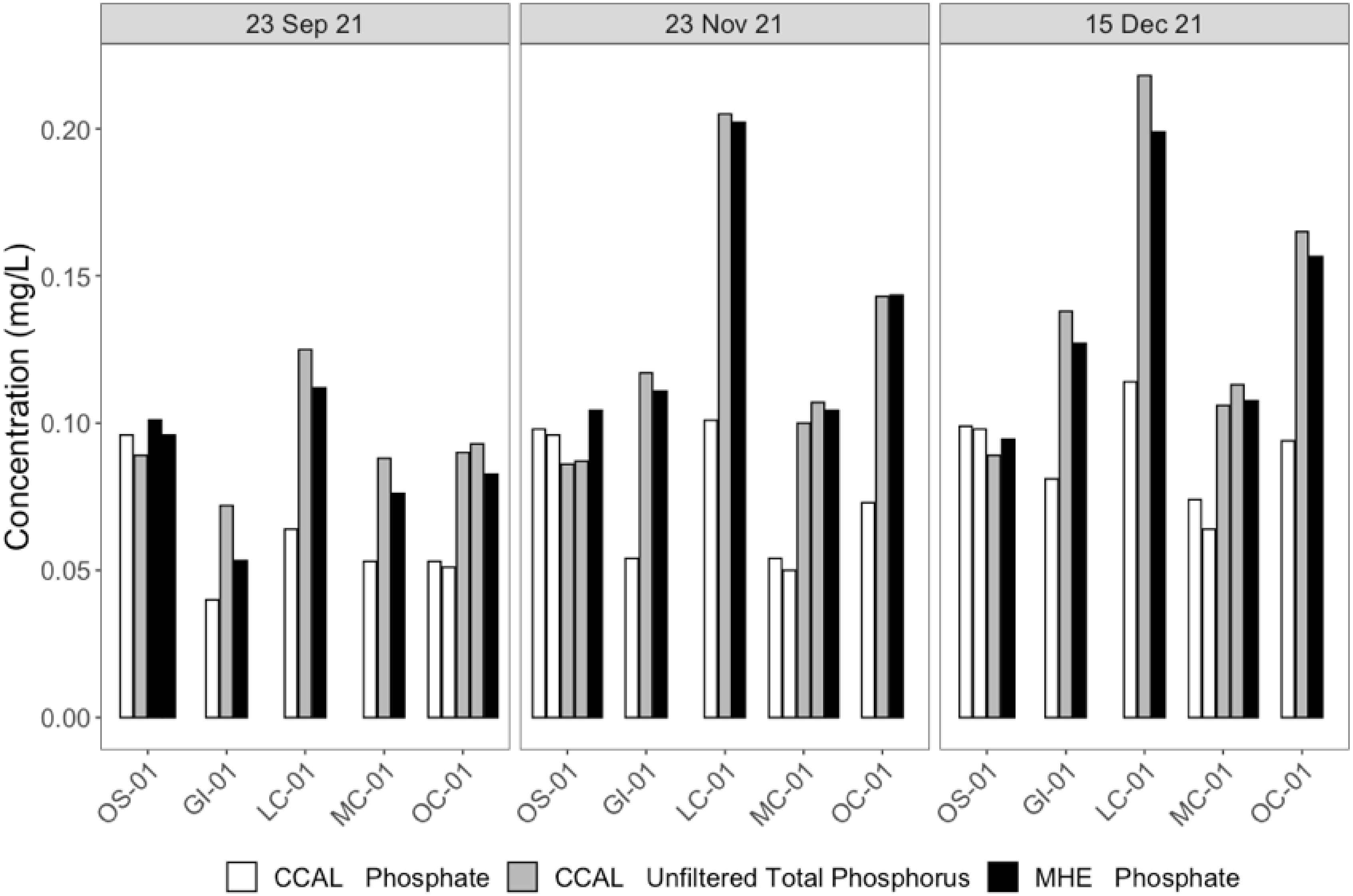

Figure A- 2. CCAL results for phosphate (white) and unfiltered total phosphorus (grey), as well as phosphate results from duplicate samples analyzed using a Hach DR3900 spectrophotometer (black).

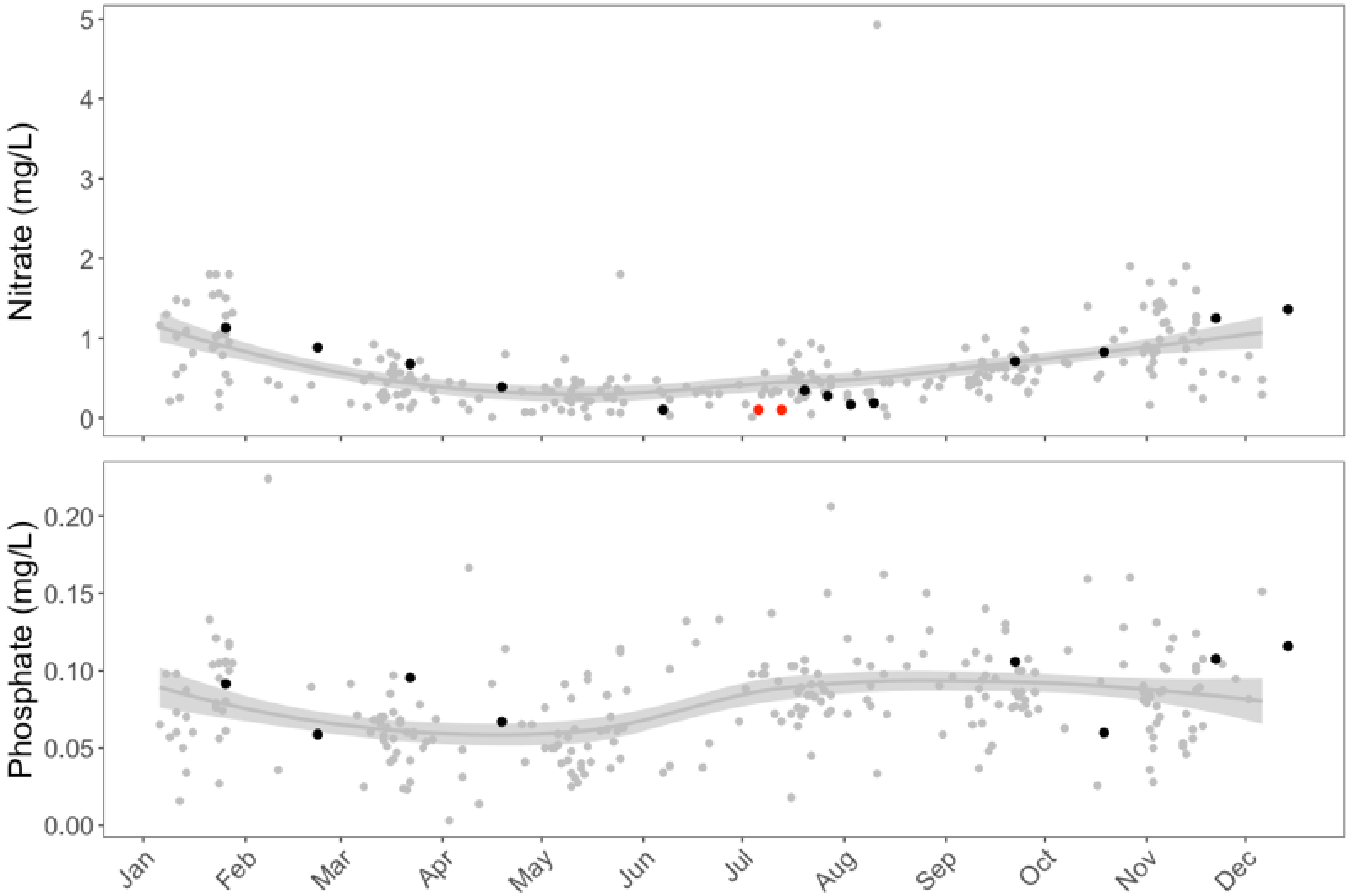

Figure A- 3. Nitrate (top) and phosphate (bottom) concentrations over time in the lower Crooked River at Lone Pine bridge (ODEQ site: 10517-ORDEQ; study site: CR-03). Grey dots describe ODEQ historical data fitted using a generalized additive model (dark grey line) with 95% confidence intervals (light grey band). Black dots describe results from this study and red dots indicate results from this study that are below laboratory practical quantitation limit (0.1 mg/L).

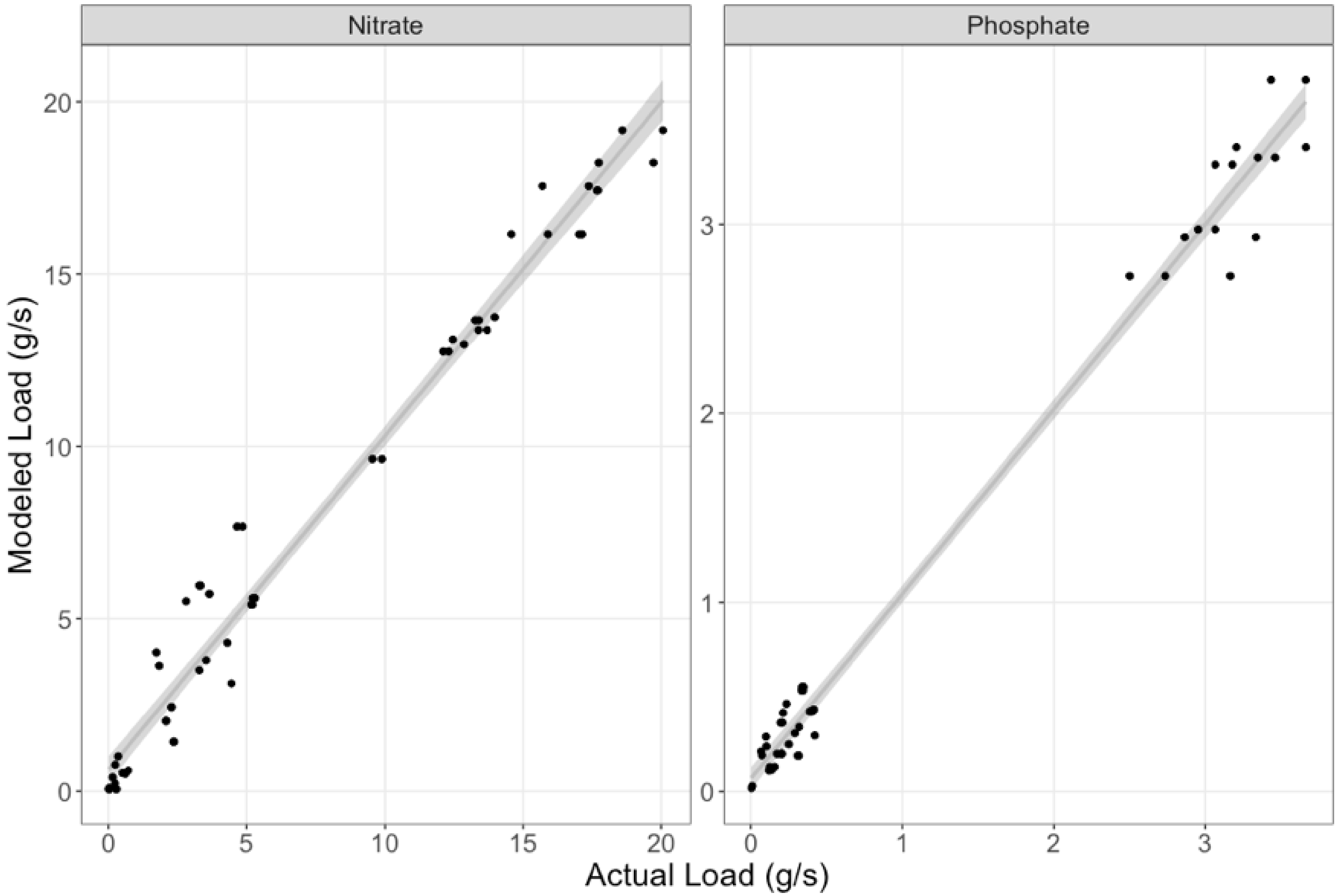

Figure A- 4. Modeled load estimates vs. actual load for nitrate (left) and phosphate (right).