Appendix B: WARMF Lake

Section 1: Introduction

Construction of Falls Lake was authorized by Congress as part of the Flood Control Act in 1965. The reservoir began filling in January 1983. The designated uses of Falls Lake include drinking water supply, recreation, fishing, aquatic life, and wildlife. Design and construction of the impoundment were conducted by the USACE, which continues to manage the reservoir today.

In 2008, the NC Department of Environmental Quality (DEQ) placed Falls Lake on the 303(d) list for non-attainment of the State's chlorophyll-a criterion (40 µg/L). In 2010, the Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy (the "Strategy" or the "Rules"). The Strategy requires two stages of nutrient reductions for Falls Lake. The goal of Stage I is to achieve compliance with the chlorophyll-a standard in the lower half of the lake (below Highway 50). The goal of Stage II is to comply with the chlorophyll-a standard everywhere in the lake. The Strategy dictates load reduction requirements for local governments and other entities, which were based on a lake nutrient response model developed by the NC Division of Water Resources (DWR).

NC's Clean Water Act Section 303(d) assessment methodology in place in 2008 is available here: https://www.deq.nc.gov/water-quality/planning/tmdl/303d/2008-methods-20100505/download. At that time, an assessment unit could be listed as not meeting the standard if greater than 10 percent of samples were greater than 40 µg/L and a minimum of 10 samples were collected. This assessment methodology was also applied in 2010 and 2012. In 2014, the assessment methodology was changed to include 90 percent confidence in the assessment: https://www.deq.nc.gov/energy-mineral-and-land-resources/land-quality/violations/2014/2014-303-d-lm-emc-approved-updated1-13-14/download. The 2014 assessment methodology was also used in 2016.

In 2018, the procedure was amended again, requiring a minimum of 9 samples, greater than 10 percent exceedance with greater than or equal to 90 percent confidence. If the 90 percent confidence threshold could not be met, but there were at least four excursions in newer data not previously assessed, then the assessment unit could be listed as not meeting the water quality standard and added to the 303(d) list. It was in 2018 that NC also added additional requirements for an assessment unit to be delisted: "For delisting waters, if the 2018 assessment results in greater than 10% exceedance rate with less than 90% statistical confidence and the water was on the 2016 303(d) list, the water will be delisted if there are less than 2 excursions of the criterion in newer data that have not been previously assessed. If the 2018 assessment results in less than 10% exceedance rate and the water was on the 2016 303(d) list, the water will be delisted if there is greater than 40% statistical confidence that there is less than a 10% exceedance of the criterion or if there are less than 3 excursions of the criterion in newer data that have not been previously assessed." The 2018 method also applied in 2020 and 2022 and will be applied in 2024 with the year "2016" being replaced with the prior assessment period (i.e., 2022 303(d) list for 2024 assessment). The delisting methodology does not consider the number of samples collected --- the only 1 or 2 exceedances of the criteria applies regardless of the number of samples collected, be it 10 or 100. Thus, waterbodies with extensive monitoring like Falls Lake, are unlikely to ever be deemed in attainment for a parameter like chlorophyll-a.

In 2016, the UNRBA initiated a Modeling and Regulatory Support project as part of its re-examination of the Falls Lake Nutrient Management Strategy. The Falls Lake Nutrient Management Strategy developed by DWR and approved by the EMC requires very large reductions in nutrient loading to the lake. Because the modeling developed by the State used as the basis of the rules was developed on a compressed schedule with limited data, there is a lot of uncertainty in the required loading targets. For this reason, the rules allow for a "re-examination" of the required nutrient load reductions.

The UNRBA selected different types of models to support the re-examination. The watershed model was developed using the Watershed Analysis Risk Management Framework (WARMF). This model predicts the mass of nutrient loading to the lake from various sources in the watershed. These loads serve as input to the lake nutrient response models which predict the growth of algae in response to nutrient loads. Because the prediction of algal growth in the lake informs the revised nutrient management strategy, the UNRBA decided to develop multiple lake nutrient response models including WARMF Lake, the Environmental Fluid Dynamics Code model (EFDC), and a statistical/Bayesian lake model. Having multiple models reduces the reliance on a single model and provides corroboration for the results. This appendix provides the technical information regarding the development, calibration, and application of WARMF Lake.

Many organizations including the UNRBA, NC Collaboratory, US Geologic Survey (USGS), NC Division of Water Resources (DWR), NC Wildlife Resources Commission (WRC), NC State University Center for Applied Aquatic Ecology (CAAE), Cities of Durham and Raleigh, US Army Corps of Engineers (USACE), US Forest Service (USFS), and US Environmental Protection Agency (EPA) have conducted monitoring and studies on Falls Lake or its tributaries that informed development of the three UNRBA lake models. The UNRBA has invested over $10 million in the monitoring and modeling studies of Falls Lake and its watershed. Section 4 of the main lake modeling report summarizes the extensive data sets used to develop these models.

During development of the WARMF Lake and EFDC models for Falls Lake, the modeling team, modeling staff from the DWR, the “third-party” reviewers funded by the NC Collaboratory, and other interested subject matter experts met multiple times to review the lake model calibrations. Discussions focused on chlorophyll-a concentrations, algal group data collected by the DWR, and sediment release studies conducted on Falls Lake. In response to this input, the UNRBA provided additional funds to test the model, improve calibration in reference to these studies, and document these efforts. Additional documentation of these efforts is included in Appendix D to the main lake modeling report and this appendix.

Section 2: Development of WARMF Lake

2.1 Description of the Model Framework

WARMF is an EPA-approved and peer-reviewed model that has been used nationwide for water quality assessment and Total Maximum Daily Load (TMDL) development. WARMF is comprised of two integrated sub-models: the WARMF Watershed model and WARMF Lake model. The representations of watershed processes within WARMF are comprehensive and based on fundamental principles of physics and chemistry. It is a continuous, lumped parameter, watershed−scale model that simulates hydrology and the movement and transformation of sediment, nutrients, and other constituents on pervious and impervious surfaces, in soil profiles, and within streams and impoundments. The WARMF watershed model was developed and calibrated to focus on the simulation of streamflow, temperature, chlorophyll-a, sediment, nutrients (nitrogen and phosphorus), and carbon. WARMF watershed simulation results were used as inputs to both WARMF Lake and EFDC.

The WARMF lake model is included as part of the WARMF model application and is internally linked to the WARMF watershed model. This means that the output of all parameters simulated by the WARMF Watershed Model is input to WARMF Lake Model for simulation of water quality in the lake. This direct linkage allows for simulation of lake impacts due to potential nutrient management changes in the watershed. The WARMF lake model is a moderately complex, pseudo-2D mechanistic model that simulates vertical stratification and allows for subdivision of the lake body into multiple linked segments. The model performs a mass balance and simulates chemical/physical processes within each vertical layer of a lake segment. WARMF lake was used to simulate water quality in Falls Lake as well as in five smaller impoundments in the watershed. Figure B-1 and Figure B-2 depict the hydrologic processes simulated by WARMF Lake for a cross section view and arial view, respectively. Figure B-3 depicts the water quality processes simulated by the model.

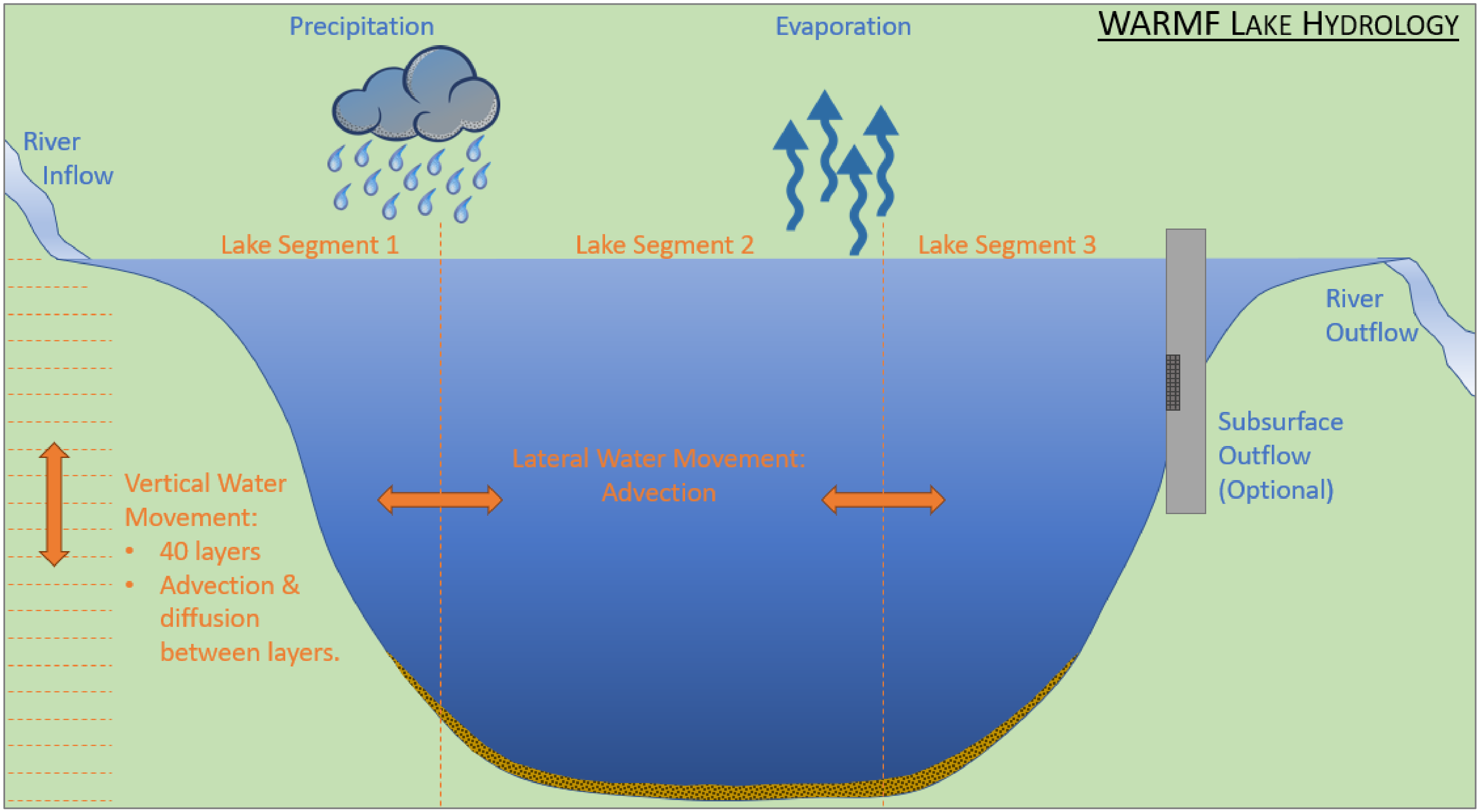

Figure B-1. Conceptual diagram of the WARMF Lake Hydrologic Model, Cross Section View

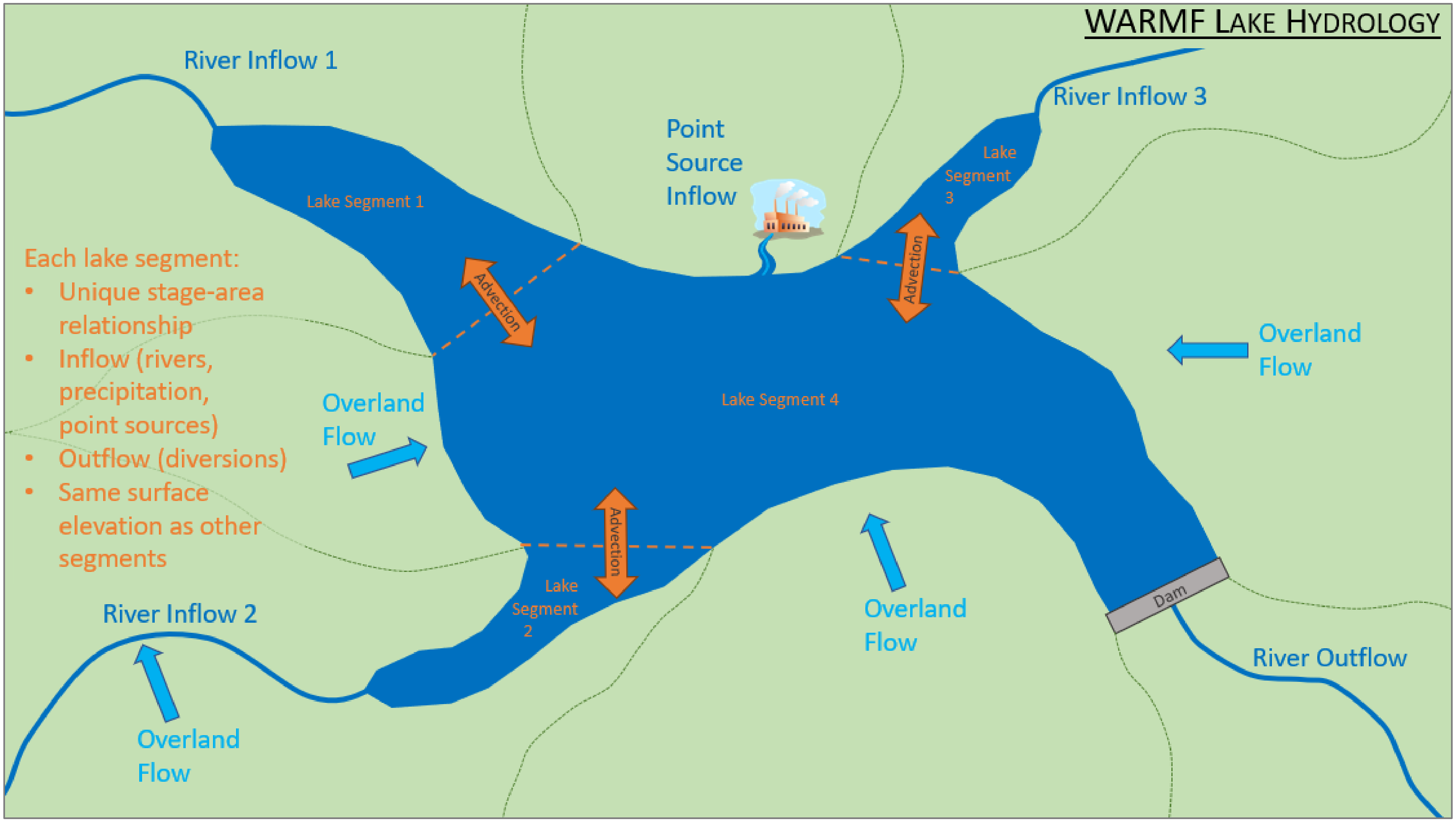

Figure B-2. Conceptual diagram of the WARMF Lake Hydrologic Model, Arial View

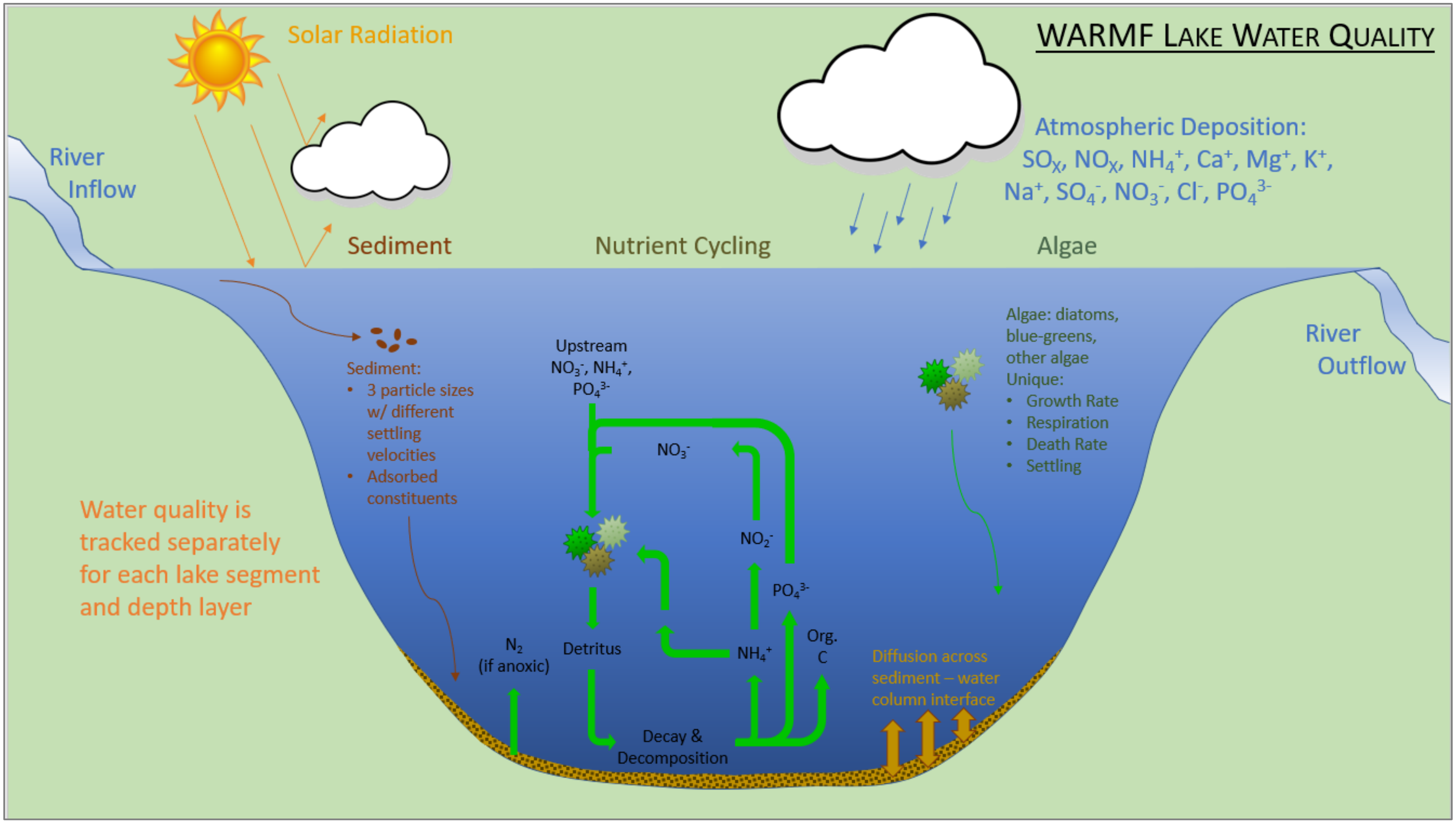

Figure B-3. Conceptual diagram of the WARMF Lake Water Quality Model

2.2 Model Configuration for Falls Lake

The WARMF Lake model was selected by the UNRBA as a computationally simpler (when compared to the EFDC model), segment-based model which, in concept, allows for shorter model run times. The water column for each segment is dynamically divided by the model (the user does not specify the number or the depth of layers) into a maximum of 40 layers, with fewer layers utilized when the lake level falls, or in shallow regions. In the Falls Lake model, each layer is approximately 0.75 meters thick.

2.2.1 Water Movement

Water can move from one segment into adjacent segments via advection in either direction but cannot move in different directions within a model segment in a timestep. Luettich et al. (2023) observed that "the surface flow often moves in the same direction as the wind and can be either towards or away from the dam. Currents at mid-depth or below may flow in the direction opposing the surface flow causing the current direction to reverse with depth and creating a wind-driven exchange flow." As WARMF Lake is simulating the net flow magnitude and direction, directional transport of algae at specific time steps may not be accurate. This aspect of the model may result in missed timing of simulated chlorophyll-a concentrations compared to point-in-time measurements and introduces some uncertainty into the model results.

During discussions with the UNRBA modeling team, the "third-party" reviewers and DWR modelers expressed that they do not expect that the mechanistic models of Falls Lake would simulate isolated peaks in chlorophyll-a concentrations, especially when such peaks do not correspond to clear physical drivers. They noted that mechanistic models are not capable of simulating all peaks because of their limitations in accounting for the physical, chemical, and biological processes and their inability to simulate anomalous events. The reviewers indicated that they expect the models to predict the general trends in nutrient and chlorophyll-a concentrations (e.g., trends associated with seasonality and varying hydrologic inputs) and that the performance results should be evaluated in the context of the model limitations.

The MRSW decided that modifying WARMF Lake to simulate bi-directional flow within a segment was not in the scope of the project and would be costly in terms of schedule and budget. This would also conflict with the original intent of the multi-modeling approach to use different types of models to simulate water quality in Falls Lake. The Falls Lake EFDC model provides hydrodynamic simulations that do account for bi-directional flow.

2.2.2 Linkage to the Watershed Model

The WARMF Lake model is directly linked to the WARMF watershed model and operates on the same 6-hour time step. WARMF Lake simulates 2015 to 2018 with 2014 serving as an initialization year. Estimates of stream flow and constituent loading come directly from the WARMF watershed model. Meteorological inputs for WARMF Lake are the same as the WARMF watershed model inputs and are documented in the UNRBA Watershed Model Report (BC and Systech Water Resources 2023).

2.2.3 Lake Segmentation

During meetings with the MRSW, the modeling team provided data summaries and recommendations for segmentation of Falls Lake. Based on feedback received during these meetings from the MRSW, DWR staff, and Collaboratory-funded "third-party" reviewers, the main part of Falls Lake was split at major constrictions to form six mainstem segments (four above Highway 50 and two below). Eight lake arms were also defined to simulate these areas. The lake segmentation and the goal of calibrating each segment to stations located near the downstream end was approved by the MRSW during their November 2020 meeting, considering input provided by the modeling team and those reviewing that process. The purpose of calibrating the segments to the downstream end is to accurately represent transport of material from one segment to the next and to simulate water quality near the City of Raleigh drinking water intake.

Figure B-4 provides a map of the Falls Lake segments including the mainstem segments along the old Neuse River channel and arms of the lake. Figure B-4 shows the order of the mainstem segments 1 through 6 from the upstream to downstream end of the reservoir. This numbering scheme is used to label time series figures in a logical, simplified order with Segment 1 being the most upstream and Segment 6 being the most downstream. These numbers are not those assigned by the WARMF model to represent each Falls Lake segment. Table B-1 provides a list of each Falls Lake WARMF model segment, segment number assigned by the WARMF model, and mainstem segment order for referencing figures and tables of performance statistics.

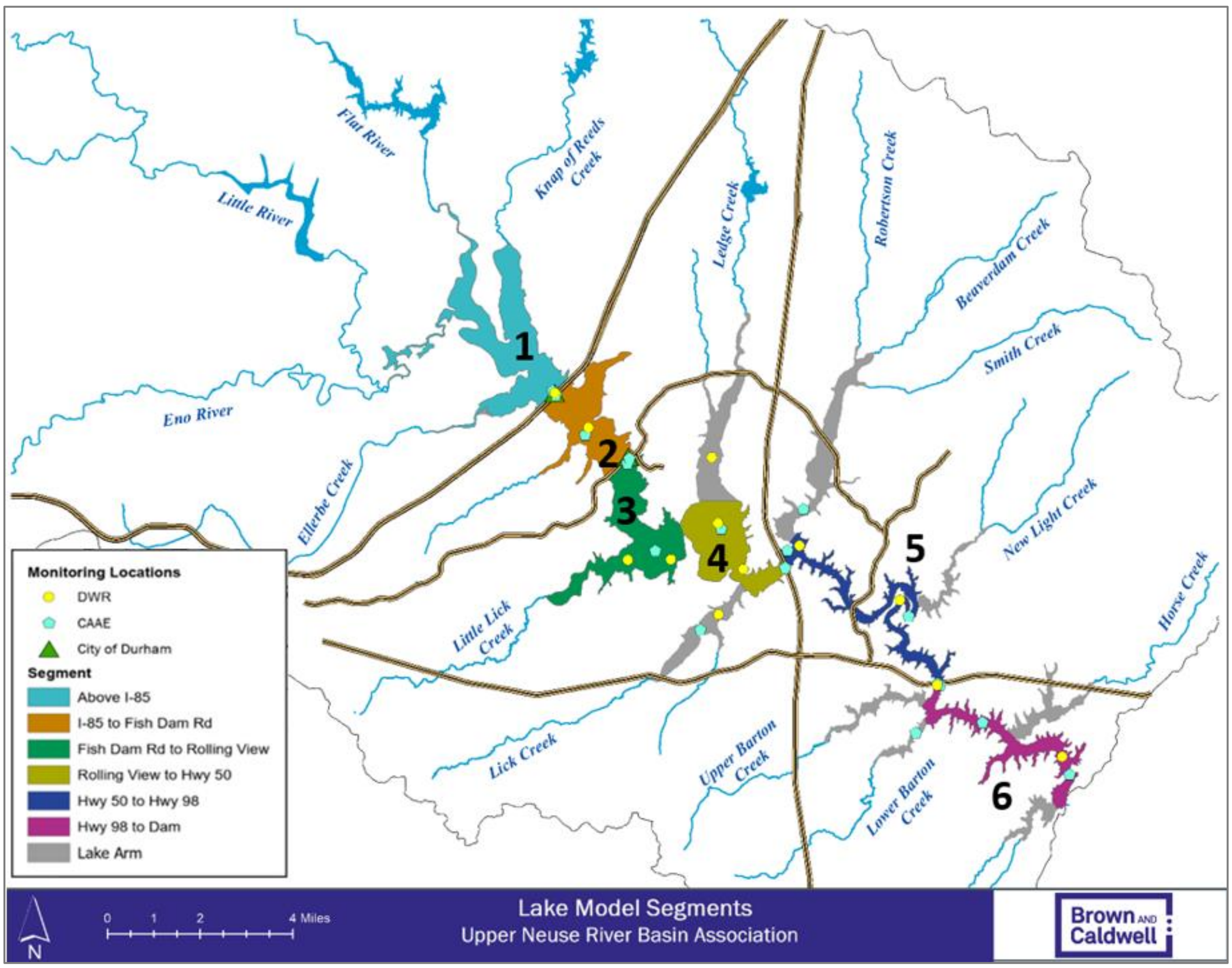

Figure B-4. WARMF Lake Modeling Segments and Lake Monitoring Stations

Table B-1. WARMF Lake Segment Numbers and Types		
Segment Number	Description	Type (Mainstem Number)
288	Above I-85	Mainstem (1)
266	I-85 to Fish Dam Rd	Mainstem (2)
284	Fish Dam Rd to Rolling View	Mainstem (3)
274	Rolling View to Hwy 50	Mainstem (4)
277	Beaverdam Impoundment	Arm
285	New Light Creek Arm	Arm
280	Upper Barton Creek	Arm
281	Lower Barton Creek Arm	Arm
268	Horse Creek Arm	Arm
276	Lick Creek Arm	Arm
278	Ledge Creek Arm	Arm
279	Hwy 50 to Hwy 98	Mainstem (5)
286	Hwy 98 to Dam	Mainstem (6)
269	Honeycutt Arm	Arm

2.2.4 Bathymetry

The bathymetry of each WARMF Lake modeling segment was developed using the following data:

- Shoreline and road shape files including numerous bridges and causeways in the Falls Lake system downloaded from National Hydrography Dataset (NHD) and Census Tiger Roads, respectively
- Bathymetry data (Falls_Lake_2017_ASCII_HF_DTM_10_ft_Grid.txt) resulting from the UNRBA bathymetric survey of Falls Lake.

Figure B-5 and Figure B-6 show the stage area curves for the mainstem segments and lake arms, respectively. Normal pool is marked on each figure with a vertical dashed line at a stage of 251.5 feet. The y-axis for these figures is consistent to compare the relative size of the lake segments and lake arms. At normal pool, the surface area of each of the lake arms is less than 1,000 acres and each of the main stem segments is less than 2,000 acres. At the top of the flood control pool (264.8 feet), the surface area of each of the lake arms remains below 2,000 acres and all except the upper most main lake segment remains below 2,600 acres. The surface area of the mainstem segment above Interstate 85 (I-85) increases rapidly to 6,500 acres at the top of the flood control pool. This is because the topography adjacent to the upper part of the lake is gently sloped, and the water spreads out shallowly across the terrain as the lake elevation rises. Even at a water level of 245 feet, the shape of the stage-area curve for this uppermost segment deviates from the others, and water surface area increases rapidly relative to water depth.

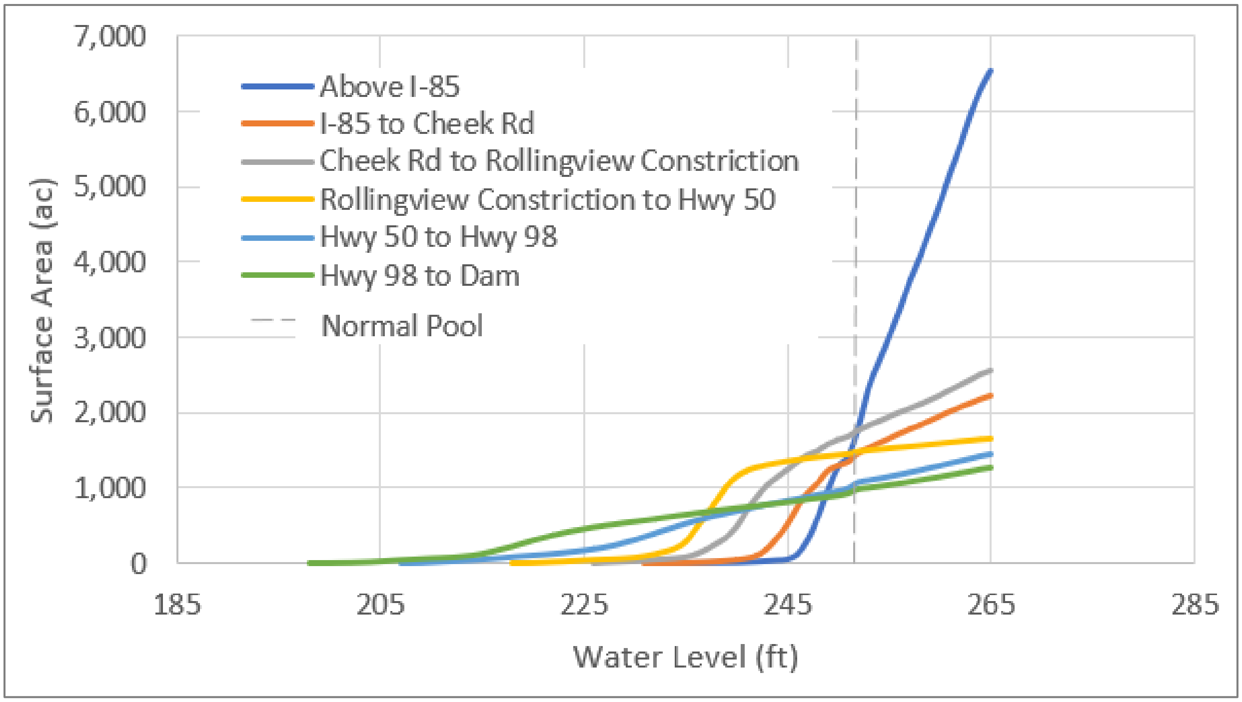

Figure B-5. Stage-Area Curve for the Mainstem Segments of Falls Lake

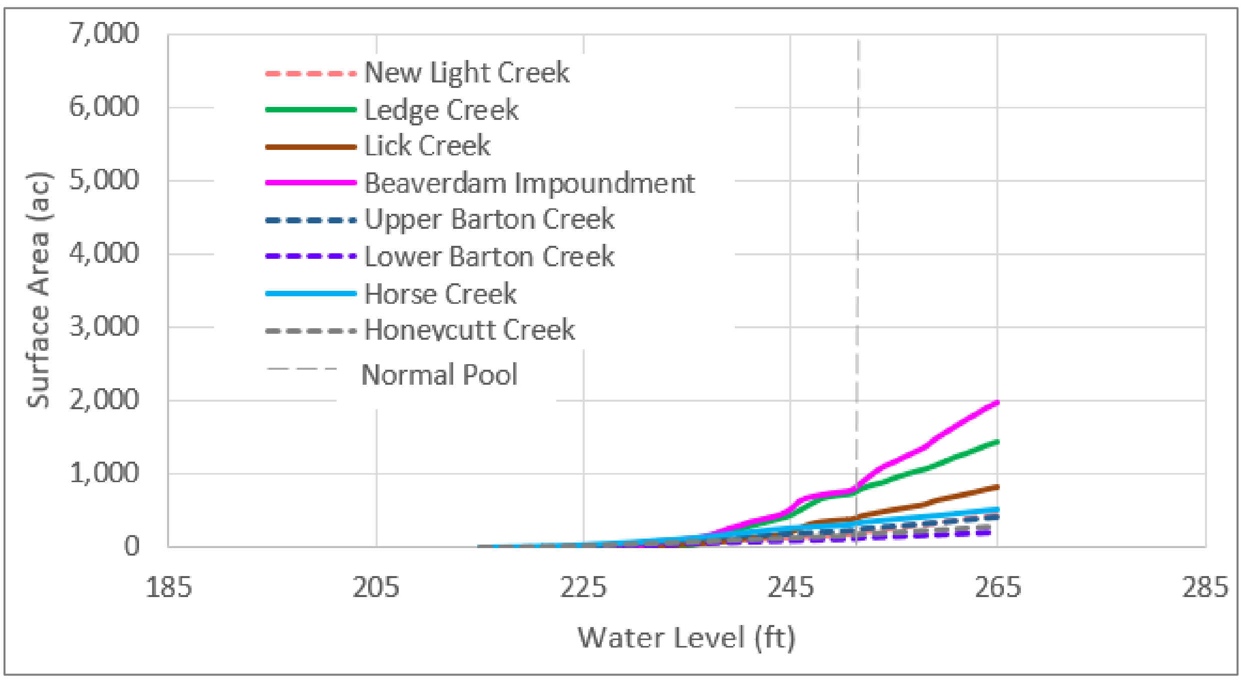

Figure B-6. Stage-Area Curve for the Lake Arms of Falls Lake

2.3 Meteorological and Tributary Inputs

The WARMF Lake model for Falls Lake is embedded within the WARMF watershed model for Falls Lake. Meteorological inputs and tributary inputs of streamflow, sediment, nutrient, and total organic carbon are described in the UNRBA Watershed Model Report.

2.4 Lake Water Quality Data and Studies of Falls Lake

Section 4 of the main lake modeling report summarizes and provides links to the numerous databases and published studies on Falls Lake. A description of how each of the studies relates to the UNRBA lake models is provided in Table 4-1 of the main report. This information is not repeated in this appendix. A map of the Falls Lake monitoring stations is provided in Figure B-7. As noted above, WARMF Lake was calibrated to the monitoring stations at the downstream end of each model segment. Table B-2 provides station information for the WARMF Lake calibration stations.

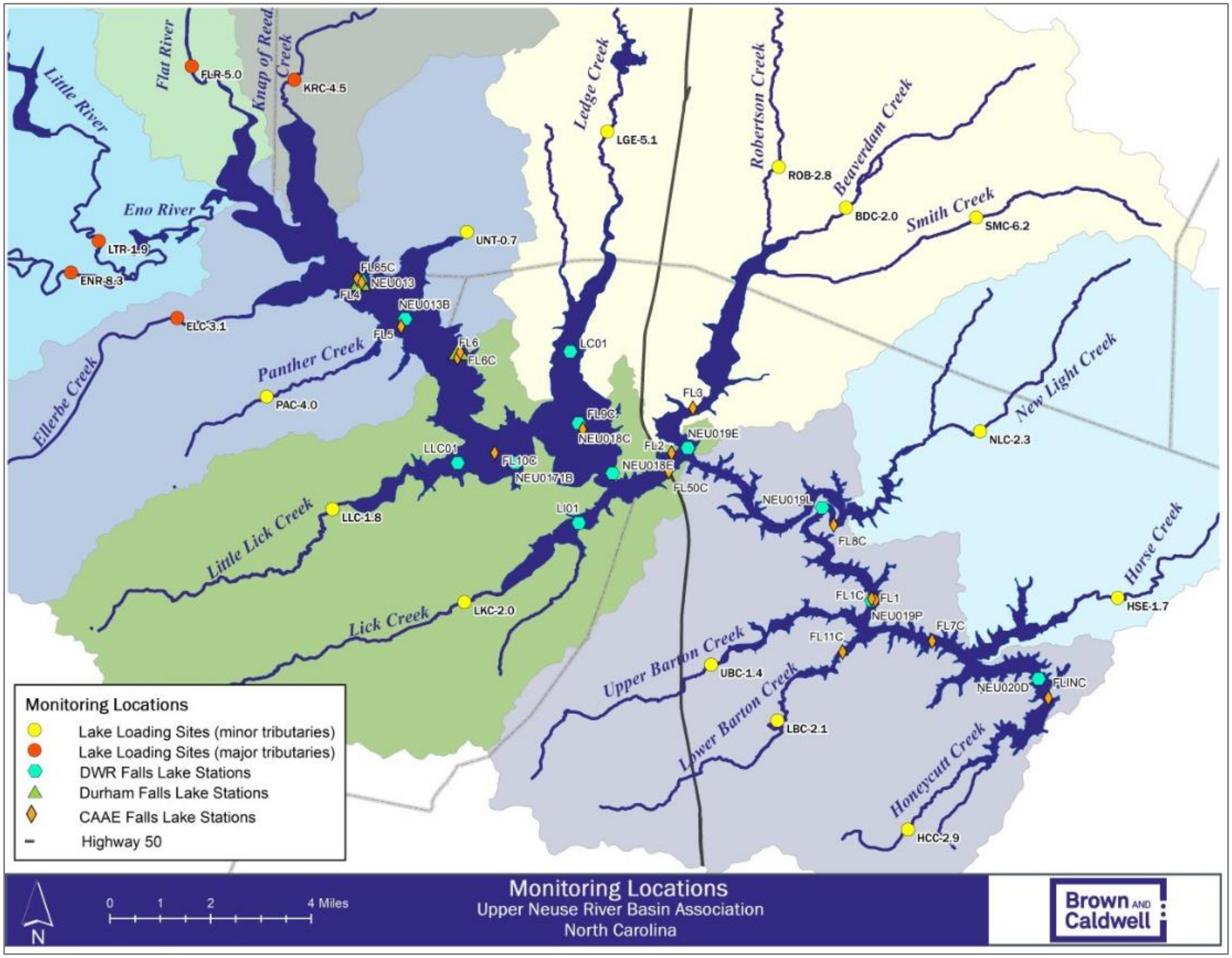

Figure B-7. Locations of Falls Lake Monitoring Locations

Table B-2. Calibration Stations and Locations for the UNRBA Falls Lake WARMF Lake Model

Station	Organization	Location description	Latitude	Longitude	Above or Below Highway 50	Waterbody Type	Frequency	Parameter Types[1]	WARMF Segment Number
FL-DS4	City of Durham	near I-85, "ND Downstream 3"	36.07013	-78.77954	Above	Main	Seasonal, Weekly	Field, chemical	1
FL-SR1801	City of Durham	at State Road 1801, "ND Downstream 4"	36.05010	-78.75125	Above	Main	Seasonal, Weekly	Field, chemical	2
NEU013	DWR	upstream of I-85	36.07024	-78.77945	Above	Main	Monthly	Field, chemical	1
NEU013B	DWR	downstream of I-85	36.05928	-78.76656	Above	Main	Monthly	Field, chemical	2
NEU0171B	DWR	between Little Lick and Ledge Creeks	36.01799	-78.73492	Above	Main	Monthly	Field, chemical	3
NEU018E	DWR	upstream of Lick Creek	36.01494	-78.70696	Above	Main	Monthly	Field, chemical	4
NEU019P	DWR	at Hwy 98 (Durham Road)	35.97838	-78.63248	Below	Main	Monthly	Field, chemical	5
NEU020D	DWR	upstream of dam	35.95591	-78.58444	Below	Main	Monthly	Field, chemical	6
FL1	NC_CAAE	Falls Lake 1	35.97854	-78.63138	Below	Main	Monthly	Field, chemical	5
FL2	NC_CAAE	Falls Lake 2	36.02080	-78.68999	Above	Main	Monthly	Field, chemical	4
FL4	NC_CAAE	Falls Lake 4	36.07088	-78.78034	Above	Main	Monthly	Field, chemical	1
FL5	NC_CAAE	Falls Lake 5	36.05711	-78.76779	Above	Main	Monthly	Field, chemical	2
FL6	NC_CAAE	Falls Lake 6	36.04812	-78.75155	Above	Main	Monthly	Field, chemical	2
FL6C	NC_CAAE	Falls Lake 6 Channel	36.04971	-78.75078	Above	Main	Monthly	Chla, SecchiD	2
FL10C	NC_CAAE	Falls Lake 10 Channel	36.02082	-78.74087	Above	Main	Monthly	Chla, SecchiD	3
FL4C	NC_CAAE	Falls Lake I85 Channel, later FL85C	36.06973	-78.77912	Above	Main	Monthly	Field, chemical	1
FL85C	NC_CAAE	Falls Lake I85 Channel, formerly FL4C	36.06973	-78.77912	Above	Main	Twice per month	Field, chemical	1
FL50C	NC_CAAE	Falls Lake Hwy 50 Channel	36.01538	-78.69083	Above	Main	Twice per month	Field, chemical	4
FLINC	NC_CAAE	Falls Lake Intake Channel	35.95039	-78.58167	Below	Main	Twice per month	Field, chemical	6

1. *Field Parameters include temperature, dissolved oxygen (DO), pH, and conductivity. Chemical parameters include nutrients, chlorophyll-a (Chla), total organic carbon, and associated measurements like Secchi depth (SecchiD). At some stations, only chlorophyll-a and Secchi depth were measured (Chla, SecchiD).*

2.5 Hydrologic Simulation

Hydrologic parameters simulated by the model include water elevation and segment volume. Flow inputs include tributaries, adjacent watershed modeling catchments, and precipitation (there are no point source discharges directly to Falls Lake). Evaporation from the lake surface is also simulated by the model using meteorological data specified in the WARMF watershed model for Falls Lake. Withdrawals and dam releases are time series inputs. The City of Raleigh Public Utility Department provided water supply withdrawal rates (personal communication to Alix Matos, Brown & Caldwell, 4/23/2019). The withdrawal gate is near the dam. Releases from the Falls Lake Dam to the Neuse River were based on reported streamflow at USGS station 0208706575. To correct for uncertainties associated with tributary inputs, evaporation rates, losses to groundwater, etc. the WARMF model option to set the water level at or below the gaged level was utilized.

2.6 Water Quality Simulation

WARMF simulates a large suite of chemical, physical, and biological water quality parameters (Systech Water Resources 2017). The model code allows for an adjustable list of simulated parameters for each specific WARMF application. An important part of WARMF simulations are chemical, physical and biological reactions and processes that control the movement and transformation of constituents through each modeled lake segment and layer.

Water quality calculations are performed at a 6-hour time step for each of the Falls Lake WARMF model segments and model layers. Inputs of flows and water quality constituent loads are provided by the WARMF watershed model for tributaries and overland flow from modeling catchments adjacent to Falls Lake. Constituents are also input from wet and dry atmospheric deposition as described in the UNRBA Watershed Model Report.

Physical parameters simulated by WARMF Lake include temperature, total suspended sediment (clay/silt/sand fractions), detritus, and turbidity. Chemical parameters simulated by the Falls Lake model include, ammonia, nitrate plus nitrite, ortho-phosphate, total organic carbon (TOC), total phosphorus (TP), total nitrogen (TN), and total Kjeldahl nitrogen (TKN). Biological parameters simulated by the model include blue-green algae, diatoms, and other algae (e.g., green). The model uses a carbon to chlorophyll-a ratio for each algae group simulated to estimate the concentration of chlorophyll-a in the water.

2.7 Initial Conditions for Falls Lake Sediments

WARMF Lake simulates nutrient releases from lake sediments based on the sediment and water column concentrations, average sediment depth for each segment, diffusion coefficients, and adsorption isotherms. As the model proceeds through time, nutrients can be added to or removed from the lake sediments depending on the physical, chemical, and biological reactions occurring in and between the water column and the lake sediments. As described in the UNRBA Watershed Model Report, the watershed model had to be run for 25 years to separate the soil chemistry in the modeling catchments into land-use specific conditions. This approach allows the watershed model to properly reflect loading from specific land uses based on nutrient application rates. To retain the initial sediment quality for Falls Lake based on conditions observed during the study period, the initial conditions for Falls Lake sediment were reset at the start of each model iteration. This approach was used to reduce the uncertainty and apply the most recent sediment quality data to the modeling effort, rather than try to estimate sediment quality in Falls Lake 25 years before the calibration period and before the sediment quality data were collected.

The initial conditions for the lake sediments were based on the UNRBA sediment depth study and UNRBA sediment quality studies summarized in the UNRBA 2019 Annual Monitoring Report. Table B-3 provides the initial average sediment depth for each WARMF Lake segment.

Table B-3. Initial Sediment Depth for WARMF Lake Segments

Segment Number	Description	Type	Initial Sediment Depth (cm)
288	Above I-85	Mainstem (1)	1.4
266	I-85 to Fish Dam Rd	Mainstem (2)	2.8
284	Fish Dam Rd to Rolling View	Mainstem (3)	3.4
274	Rolling View to Hwy 50	Mainstem (4)	6.8
277	Beaverdam Impoundment	Arm	8.8
285	New Light Creek Arm	Arm	5.7
280	Upper Barton Creek	Arm	6.6
281	Lower Barton Creek Arm	Arm	6.0
268	Horse Creek Arm	Arm	6.3
276	Lick Creek Arm	Arm	3.5
278	Ledge Creek Arm	Arm	3.0
279	Hwy 50 to Hwy 98	Mainstem (5)	6.8
286	Hwy 98 to Dam	Mainstem (6)	13.6
269	Honeycutt Arm	Arm	12.4

Based on the average of the sediment quality measurements, the initial sediment ammonia concentration was set to 0.7 milligrams of nitrogen per gram of sediment (mg-N/g). The initial sediment phosphate concentration was set to 0.9 mg-P/g, and the initial sediment organic carbon concentration was set to 25.6 mg-C/g. The initial sediment concentration of detritus was set to 3.7 mg-C/g; initial detritus provides a starting pool of organic matter to decompose into nitrogen, phosphorus, and organic carbon.

Section 3: Water Quality Calibration

Calibration of WARMF Lake involves adjustment of model coefficients that describe the physical, chemical, and biological processes occurring in Falls Lake. When possible, reaction rate coefficients were held constant across the entire lake. However, variation in measurements for some parameters provided justification for spatially varying rates. For example, variation in accumulated sediment depth and analysis of sediment depth and nutrient releases from sediments provides justification for varying sediment diffusion rates).

Model calibration is an iterative process where changing one coefficient may have the desired effect on one parameter (improved fit to observed data) but may have a worsening effect on another parameter(s). Decisions on whether to further refine the calibration depends on resource constraints, project schedules, model limitations in terms of simulating site-specific processes not well accounted for by the model framework, and relative benefit of additional refinement. Best professional judgement is an important component in all modeling efforts. A decision has to be made on when to stop the calibration process. To support these decisions, the UNRBA and the modeling team worked with the subject matter experts, “third-party” reviewers, and DWR modeling staff. As the model was developed and calibrated, variations in model coefficients and the corresponding effect on output was evaluated using all available data (water column concentrations, measurements of nutrient releases from sediments, etc.). These evaluations were used to determine when calibration was sufficient for the purposes of the project (i.e., understanding how lake water quality would change in response to changing nutrient loads). The additional testing performed was used to better define when continued calibration efforts would not yield overall improvements to the model calibration.

3.1 Layering Approach

The water quality observations collected in Falls Lake by DWR and other organizations are usually photic-zone composites. As described in the UNRBA Modeling Quality Assurance Project Plan (QAPP), only data collected under a state-approved monitoring QAPP as photic zone composite data are included in assessment of model performance. The photic-zone is assumed to be the depth over which algae can grow, and it is approximated as twice the Secchi depth. This is an accepted and established approach for lake modeling and was used by DWR (2009) to develop their Falls Lake model. Secchi depth can change at each location and on each sampling day. DWR collects photic-zone composite samples for chlorophyll-a, nutrients, total suspended solids, turbidity, and phytoplankton measurements. EFDC and WARMF Lake simulate the water column as several layers. Water quality results for each layer represent the average condition over the volume of that layer.

On October 5, 2021, the MRSW reviewed recommendations from the modeling team on how to compare simulated water quality values to photic-zone composite data collected in Falls Lake. The discussion considered the locations of the monitoring stations located near the downstream end of each WARMF Lake segment and the distribution of observed Secchi depths (Figure B-8). The MRSW had previously approved calibrating WARMF Lake segments to stations near the downstream end of each segment in November 2020. The numbers below each box and whisker in Figure B-8 specify the segment in which each station is located. Only stations along the mainstem with data collected under an approved QAPP where both nutrient and chlorophyll-a data were collected are used for calibration of WARMF Lake. Table B-4 summarizes the averaging approach approved by the MRSW for the Falls Lake WARMF model.

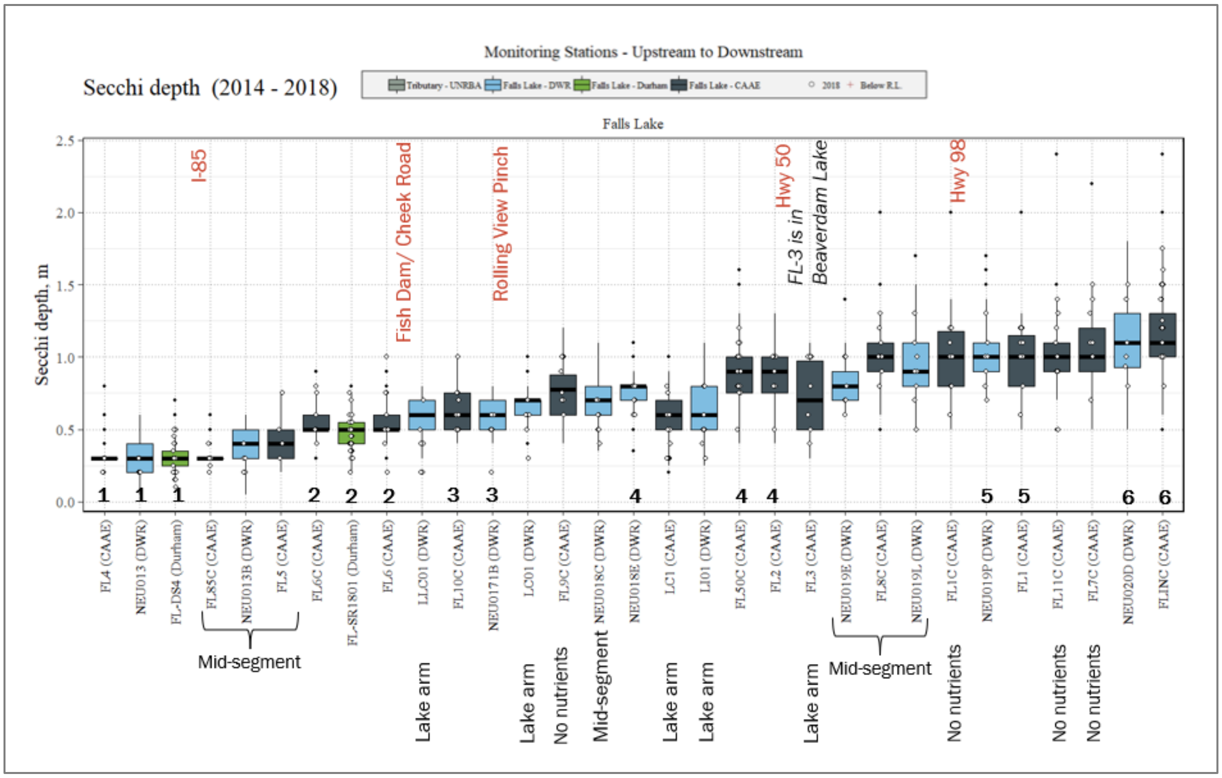

Figure B-8. Distribution of Secchi Depth Data for Stations used to Calibration the WARMF Lake Model

Numbers Correspond to Calibration Stations for the Six Main WARMF Lake Segments

Table B-4. WARMF Lake Segment Layers to Average for Comparison to Photic-Zone Composite Samples			
Mainstem Segment Order	Typical[1] Secchi Depth (m)	Typical Photic Zone (m)	Top Layers to Average
1	0.4	0.8	1
2	0.6	1.2	1, 2
3	0.75	1.5	1, 2
4	1	2	1, 2, 3
5	1.1	2.2	1, 2, 3
6	1.25	2.5	1, 2, 3

3.2 Calibration Parameters

Model coefficients describe the rates at which physical, chemical, and biological processes occur. Most of the model coefficients for the Falls Lake WARMF model were set as reservoir wide values. In some cases, segment-specific values were assigned due to physical, geological, and morphological differences across the lake segments. Table B-5 and Table B-7 provide the model coefficients for the Falls Lake WARMF Lake model. Initial model runs were conducted using default coefficients, which were subsequently adjusted during the calibration process.

Table B-5. WARMF Lake Reservoir-Wide Sediment, Water Column, and Meteorological Model Coefficients	
Model Coefficient, Units	**Value**
Precipitation Weight (unitless)	0.9
Wind speed multiplier (unitless)	1.0
Radiation absorbed in top layer (fraction)	0.5
Depth of radiation fraction, m	0.5
Phosphate lake sediment adsorption isotherm, L/kg	10,000
Ammonia lake sediment adsorption isotherm, L/kg	60
Sediment bed biochemical oxygen demand decay, 1/d	0.5
Sediment bed sulfate reduction, 1/d	0.05
Sediment bed organic matter decay, 1/d	0.01
Sediment bed nitrification, 1/d	0.015
Sediment bed denitrification, 1/d	0.5
Sediment bed detritus decay, 1/d	0.01
Water column maximum density gradient diffusion, m^2/s	0.0005
Water column maximum wind diffusion, m^2/s	0.0005
Water column biochemical oxygen demand decay, 1/d	0.5
Water column sulfate reduction, 1/d	0.05
Water column organic matter decay, 1/d	0.01
Water column nitrification, 1/d	0.015
Water column denitrification, 1/d	0.5
Water column detritus decay, 1/d	0.01
Net sand settling/resuspension, m/d	1036.8

Table B-6. WARMF Lake Reservoir-Wide Algal Group Model Coefficients			
Model Coefficient, Units	**Blue Green**	**Diatoms**	**Other Algae (Prymnesiophytes, Euglenoids, Greens, etc.)**
Respiration, 1/d	0.01	0.01	0.01
Mortality, 1/d	0.02	0.1	0.02
Growth, 1/d	0.9	1.8	0.9
Nitrogen Half-Saturation, mg/L	0.005	0.005	0.005
Phosphorus Half-Saturation, mg/L	0.005	0.005	0.005
Silica Half-Saturation, mg/L	0.005	0.005	0.005
Light Half-Saturation, W/m^2	200	55	150
Lower Growth Temperature, C	10	0	5
Upper Growth Temperature, C	40	30	40
Optimum Growth Temperature, C	31	8	17
Settling rate, m/d	0.02	0.2	0.06

Table B-7. WARMF Lake Segment-Specific Model Coefficients							
Lake Segment ID	Sediment Diffusion, m^2/d	Blue-Green Settling, m/d	Diatom Settling, m/d	Other Algae Settling, m/d	Detritus Settling, m/d	Net Clay Settling, m/d	Net Silt Settling, m/d
288	0.000008	0.02	0.2	0.06	0.25	0.001	0.001
266	0.000008	0.02	0.2	0.06	0.25	0.1	3
284	0.000008	0.02	0.2	0.06	0.25	0.21	3
274	0.00003	0.018	0.18	0.054	0.25	0.1	3
277	0.00003	0.018	0.18	0.054	1	0.5	3
285	0.00003	0.018	0.18	0.054	1	0.5	3
280	0.00003	0.018	0.18	0.054	1	0.5	3
281	0.00003	0.018	0.18	0.054	1	0.5	3
268	0.00003	0.018	0.18	0.054	1	1	3
276	0.00003	0.018	0.18	0.054	0.25	0.5	3
278	0.000008	0.018	0.18	0.054	0.25	0.5	3
279	0.00003	0.018	0.18	0.054	1	0.8	3
286	0.00003	0.018	0.18	0.054	1	1	3

3.3 Model Calibration and Validation Results

The WARMF Lake model for Falls Lake was calibrated using data collected during the two-year period from January 1, 2015, to December 31, 2016, and validated to data collected during the two-year period from January 1, 2017, to December 31, 2018. DWR modeling staff and "third-party" model reviewers provided review and input during model development and calibration. Input from these parties was used to guide calibration decisions. All critical decisions were also reviewed and confirmed by the MRSW. The availability of four years of monitoring data including special studies on Falls Lake was critical for this calibration/validation process. Calibrated and validated state variables in the WARMF Lake water quality model included chlorophyll-a, total organic carbon, nutrients, and suspended sediments.

3.3.1 Performance Statistics

Model performance and acceptance criteria form the basis by which judgments are made on whether the models are sufficiently calibrated to support management planning decisions. The UNRBA Modeling QAPP describes the performance criteria for the WARMF Lake model which are the same as for the WARMF watershed model. Performance criteria were the subject of several discussions during the review meetings, and the approaches outlined here were confirmed as acceptable and effective for measuring performance. Additional statistics are provided in the model-specific appendices and described in the QAPP. Percent bias is defined as follows:

Percent Bias (%Bias):

$$\%Bias = 100 * \frac{\sum P - O}{\sum O}$$

Where,

O is the observed measurement (or aggregate of the observed)

P is the predicted model result (or aggregate of the predictions)

For water quality variables, a 3-tiered system of categorizing statistical performance developed by Donigian (2002) was used for calibration guidance at the locations where statistical water quality calibration was performed. The system is based on the percent bias measure (defined above) with the categorized values shown in Table B-8. As described previously, these statistical measures are used to supplement graphical evaluation of the model results and aid in determining the endpoints of model calibration.

Table B-8. General Watershed Model Calibration Guidance

Parameter	% Bias Criteria		
	Very Good	Good	Fair
Suspended Sediment	< ± 20	± 20-30	± 30-45
Water Temperature	< ± 7	± 8-12	± 13-18
Nutrients/chlorophyll-a	< ± 15	± 15-25	± 25-35

WARMF requires timestep consistency across watershed and lake sub-models, so the 6-hr timestep selected for the WARMF watershed model applies to all linked WARMF lake models. To evaluate lake model performance, the simulation time step containing the point-in-time observation is used for calculation of performance statistics.

Model performance is evaluated for each of the six main lake segments along Falls Lake with Segment 1 representing the segment upstream of Interstate 85 and Segment 6 being the segment from Highway 98 to the dam. Table B-9 provides the performance statistics for percent bias and the additional statistics listed in the QAPP. Mean and median values for the observed data are also provided in this table. Meeting the performance criteria for percent bias is more difficult when concentrations are very low. This is a common issue in assessing model calibration for nutrient levels in lakes and estuaries when the numbers are consistently low for inorganic forms of nutrients. As a result, a high percent bias can occur from a very small change in concentration. For example, if the observed mean concentration is 0.03 mg-N/L and the simulated mean was 0.045 mg-N/L, this would give a percent bias of +50 percent due a concentration difference of only 0.015 mg-N/L. However, if the observed mean concentration was 1 mg-N/L and the simulated value was 1.5 mg-N/L, there is still a +50 percent bias, but the difference in simulated nitrogen concentration would be more ecologically significant. Low level inorganic nutrient levels are common in lake systems because algae quickly consume inorganic nutrients.

Segments 1 through 4 are upstream of Highway 50, and ammonia and nitrate plus nitrite are generally overpredicted in these segments. Simulation of ammonia and nitrate plus nitrite is improved in segments 5 and 6 which are in the deeper narrower part of the lake. Throughout the lake, most of the total nitrogen is in the organic nitrogen form (TKN minus ammonia) because the inorganic forms (ammonia and nitrate plus nitrite) are quickly consumed by algae and the relatively large input of organic material from the watershed is slowly converted to inorganic forms. Both TKN and total nitrogen have “very good” percent bias in all segments/periods except one that is just over the threshold and ranked as “good.” TSS percent bias is “very good” in segments 3, 5, and 6 and “very good” to “fair” in segments 1 and 2; segment 4 ranks “fair” or predicts an average TSS concentration that is more than 35 percent higher than observed. Note that WARMF simulates TSS as only the inorganic fraction (specifically TSS = clay + silt). Laboratory measurements of TSS were adjusted to remove the organic fraction by subtracting concentrations of volatile suspended solids (VSS). The number of TSS measurements available for calibration is smaller than the other parameters because VSS was not always measured. If VSS was not collected, the TSS value was not included in the comparison.

Total phosphorus percent bias is “very good” in Segments 3, 4, 5, and 6; “good” to “very good” in segment 2, and “fair” to “good” in segment 1. Total organic carbon model bias is “very good” in all segments/periods except one that is just below the threshold and ranked as “good.” Water temperature ranks “very good” in segments 1 and 2 and moves toward “good” with one “fair” ranking in the downstream direction. Model bias for chlorophyll-a is generally “good” to very good” except in two segments in the validation period when the model underpredicts chlorophyll-a by more than 35 percent. As documented in Appendix D, chlorophyll-a concentrations were generally higher in the validation period compared to the calibration period due to blooms of Prymnesiophytes.

Additional calibration effort results in improvements to some parameters and locations while sacrificing other parameters and locations. Subject matter experts suggested keeping model coefficients consistent across all lake segments. The modeling team revised the majority of the coefficients to maintain consistency across the lake except for settling rates and sediment diffusion rates. As a result, model performance in some segments worsened, but the consensus was the model would be better applied to evaluate scenarios if this approach was used to set final values. Following consultation with and input from the subject matter experts, DWR modeling staff, and MRSW, the calibration was deemed appropriate, and the model finalized and considered a reasonable tool for assessing nutrient management and regulatory decisions.

Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model													
Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Ammonia Nitrogen as N, mg/l	1	Full	232	150.9	0.029	0.072	0.026	0.026	0.044	0.047	0.000	4.603	-20.184
Ammonia Nitrogen as N, mg/l	1	Calibration	113	146.2	0.029	0.072	0.026	0.026	0.043	0.047	0.000	3.859	-13.891
Ammonia Nitrogen as N, mg/l	1	Validation	119	155.4	0.029	0.073	0.026	0.054	0.044	0.047	0.001	6.561	-42.043
Ammonia Nitrogen as N, mg/l	2	Full	215	39.5	0.031	0.043	0.028	0.028	0.012	0.017	0.000	2.375	-4.642
Ammonia Nitrogen as N, mg/l	2	Calibration	107	25.8	0.029	0.037	0.028	0.028	0.008	0.009	0.004	2.803	-6.857
Ammonia Nitrogen as N, mg/l	2	Validation	108	51.8	0.033	0.050	0.028	0.028	0.017	0.025	0.004	2.246	-4.047
Ammonia Nitrogen as N, mg/l	3	Full	54	57.7	0.019	0.029	0.010	0.010	0.011	0.022	0.005	1.822	-2.319
Ammonia Nitrogen as N, mg/l	3	Calibration	33	10.9	0.022	0.025	0.010	0.010	0.002	0.018	0.055	1.239	-0.535
Ammonia Nitrogen as N, mg/l	3	Validation	21	185.2	0.013	0.036	0.010	0.010	0.024	0.029	0.043	5.541	-29.702
Ammonia Nitrogen as N, mg/l	4	Full	139	167.8	0.019	0.051	0.009	0.043	0.032	0.044	0.004	2.595	-5.734
Ammonia Nitrogen as N, mg/l	4	Calibration	61	131.1	0.024	0.055	0.009	0.057	0.031	0.044	0.002	2.086	-3.351
Ammonia Nitrogen as N, mg/l	4	Validation	78	212.5	0.015	0.048	0.009	0.033	0.033	0.043	0.053	3.521	-11.400
Ammonia Nitrogen as N, mg/l	5	Full	87	5.2	0.045	0.047	0.010	0.037	0.002	0.049	0.003	1.212	-0.470
Ammonia Nitrogen as N, mg/l	5	Calibration	45	1.9	0.047	0.048	0.020	0.048	0.001	0.056	0.038	1.270	-0.612
Ammonia Nitrogen as N, mg/l	5	Validation	42	9.1	0.042	0.046	0.010	0.034	0.004	0.042	0.007	1.135	-0.289
Ammonia Nitrogen as N, mg/l	6	Full	109	-28.6	0.060	0.043	0.009	0.039	-0.017	0.060	0.001	1.092	-0.192
Ammonia Nitrogen as N, mg/l	6	Calibration	52	-11.9	0.049	0.043	0.009	0.041	-0.006	0.056	0.028	1.219	-0.486

Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model													
Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Ammonia Nitrogen as N, mg/l	6	Validation	57	-39.3	0.070	0.043	0.009	0.030	-0.028	0.063	0.019	1.050	-0.103
Chlorophyll-a, µg/l	1	Full	284	3.1	42.1	43.4	39.6	40.0	1.3	26.688	0.058	1.745	-2.044
Chlorophyll-a, µg/l	1	Calibration	169	18.1	39.3	46.4	37.9	54.5	7.1	26.217	0.147	1.739	-2.025
Chlorophyll-a, µg/l	1	Validation	115	-15.6	46.4	39.1	42.1	32.1	-7.2	27.380	0.002	1.818	-2.305
Chlorophyll-a, µg/l	2	Full	277	-2.2	36.6	35.8	35.6	37.6	-0.8	19.336	0.000	1.504	-1.261
Chlorophyll-a, µg/l	2	Calibration	147	20.3	31.4	37.7	30.6	38.3	6.4	18.635	0.007	1.775	-2.151
Chlorophyll-a, µg/l	2	Validation	130	-21.0	42.5	33.6	38.8	35.5	-8.9	20.129	0.000	1.488	-1.213
Chlorophyll-a, µg/l	3	Full	111	-5.6	35.3	33.3	33.5	34.1	-2.0	15.853	0.009	1.445	-1.087
Chlorophyll-a, µg/l	3	Calibration	69	10.1	31.6	34.8	30.8	36.4	3.2	14.812	0.003	1.387	-0.923
Chlorophyll-a, µg/l	3	Validation	42	-25.3	41.2	30.8	40.2	32.6	-10.4	17.563	0.029	1.671	-1.791
Chlorophyll-a, µg/l	4	Full	243	-15.8	32.4	27.3	30.5	26.0	-5.1	13.733	0.011	1.405	-0.973
Chlorophyll-a, µg/l	4	Calibration	146	-2.7	28.8	28.0	28.0	27.2	-0.8	11.001	0.000	1.342	-0.800
Chlorophyll-a, µg/l	4	Validation	97	-30.7	37.8	26.2	36.0	23.6	-11.6	17.844	0.023	1.593	-1.536
Chlorophyll-a, µg/l	5	Full	87	-1.9	26.5	26.0	22.0	25.0	-0.5	14.158	0.041	1.327	-0.760
Chlorophyll-a, µg/l	5	Calibration	45	22.9	21.4	26.3	20.0	25.5	4.9	9.715	0.014	1.335	-0.782
Chlorophyll-a, µg/l	5	Validation	42	-19.7	32.0	25.7	27.9	23.4	-6.3	18.919	0.121	1.454	-1.114
Chlorophyll-a, µg/l	6	Full	212	12.7	21.6	24.3	18.0	23.8	2.7	11.850	0.010	1.290	-0.664
Chlorophyll-a, µg/l	6	Calibration	136	19.1	20.2	24.0	17.6	23.5	3.9	9.988	0.002	1.227	-0.506
Chlorophyll-a, µg/l	6	Validation	76	3.1	24.1	24.8	18.9	25.5	0.7	15.181	0.052	1.363	-0.857
Nitrate-Nitrite as N, mg/l	1	Full	234	116.9	0.077	0.166	0.025	0.154	0.090	0.132	0.000	2.332	-4.440
Nitrate-Nitrite as N, mg/l	1	Calibration	115	200.4	0.064	0.193	0.025	0.183	0.129	0.165	0.003	2.641	-5.974
Nitrate-Nitrite as N, mg/l	1	Validation	119	58.2	0.088	0.140	0.100	0.133	0.051	0.101	0.016	1.910	-2.648
Nitrate-Nitrite as N, mg/l	2	Full	218	5.1	0.078	0.083	0.028	0.028	0.004	0.070	0.036	1.097	-0.204
Nitrate-Nitrite as N, mg/l	2	Calibration	109	27.1	0.059	0.074	0.028	0.028	0.016	0.059	0.014	1.288	-0.659
Nitrate-Nitrite as N, mg/l	2	Validation	109	-8.0	0.098	0.091	0.100	0.028	-0.008	0.081	0.041	1.060	-0.123
Nitrate-Nitrite as N, mg/l	3	Full	54	-8.9	0.060	0.055	0.010	0.023	-0.005	0.082	0.032	1.328	-0.765

	Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model												
Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Nitrate-Nitrite as N, mg/l	3	Calibration	33	-46.6	0.081	0.043	0.020	0.021	-0.038	0.088	0.027	1.163	-0.351
Nitrate-Nitrite as N, mg/l	3	Validation	21	165.7	0.027	0.073	0.010	0.024	0.045	0.072	0.052	3.415	-10.662
Nitrate-Nitrite as N, mg/l	4	Full	139	95.9	0.030	0.058	0.008	0.030	0.028	0.066	0.046	1.678	-1.816
Nitrate-Nitrite as N, mg/l	4	Calibration	61	32.0	0.049	0.065	0.008	0.058	0.016	0.088	0.131	1.441	-1.076
Nitrate-Nitrite as N, mg/l	4	Validation	78	263.6	0.015	0.053	0.008	0.008	0.038	0.049	0.023	4.177	-16.445
Nitrate-Nitrite as N, mg/l	5	Full	87	5.9	0.052	0.055	0.020	0.025	0.003	0.070	0.078	1.505	-1.264
Nitrate-Nitrite as N, mg/l	5	Calibration	45	-0.4	0.068	0.067	0.030	0.040	0.000	0.101	0.229	1.566	-1.453
Nitrate-Nitrite as N, mg/l	5	Validation	42	18.9	0.035	0.042	0.009	0.009	0.007	0.036	0.001	1.447	-1.095
Nitrate-Nitrite as N, mg/l	6	Full	109	-7.5	0.060	0.055	0.020	0.028	-0.005	0.074	0.051	1.437	-1.065
Nitrate-Nitrite as N, mg/l	6	Calibration	52	12.1	0.066	0.074	0.023	0.055	0.008	0.103	0.204	1.606	-1.579
Nitrate-Nitrite as N, mg/l	6	Validation	57	-29.2	0.054	0.038	0.007	0.017	-0.016	0.047	0.013	1.141	-0.302
Total Kjeldahl Nitrogen as N, mg/l	1	Full	204	3.3	0.96	1.00	0.92	0.97	0.032	0.184	0.138	0.952	0.094
Total Kjeldahl Nitrogen as N, mg/l	1	Calibration	115	6.9	0.94	1.00	0.90	0.99	0.064	0.187	0.233	0.919	0.156
Total Kjeldahl Nitrogen as N, mg/l	1	Validation	89	-0.9	1.00	0.99	0.99	0.97	-0.009	0.179	0.051	0.995	0.010
Total Kjeldahl Nitrogen as N, mg/l	2	Full	190	0.0	0.83	0.83	0.84	0.82	0.000	0.169	0.047	1.351	-0.826
Total Kjeldahl Nitrogen as N, mg/l	2	Calibration	109	-1.7	0.82	0.80	0.82	0.80	-0.014	0.169	0.123	1.478	-1.183
Total Kjeldahl Nitrogen as N, mg/l	2	Validation	81	2.1	0.86	0.87	0.86	0.84	0.018	0.169	0.032	1.251	-0.566
Total Kjeldahl Nitrogen as N, mg/l	3	Full	54	8.7	0.76	0.82	0.75	0.81	0.066	0.159	0.038	2.390	-4.714
Total Kjeldahl Nitrogen as N, mg/l	3	Calibration	33	13.5	0.73	0.83	0.73	0.81	0.099	0.185	0.060	2.818	-6.942
Total Kjeldahl Nitrogen as N, mg/l	3	Validation	21	1.7	0.80	0.81	0.78	0.79	0.014	0.118	0.004	2.007	-3.027
Total Kjeldahl Nitrogen as N, mg/l	4	Full	139	6.9	0.72	0.77	0.72	0.77	0.050	0.120	0.002	1.606	-1.579

	Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model												
Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Total Kjeldahl Nitrogen as N, mg/l	4	Calibration	61	12.8	0.68	0.77	0.67	0.78	0.087	0.160	0.023	2.562	-5.563
Total Kjeldahl Nitrogen as N, mg/l	4	Validation	78	2.7	0.75	0.77	0.75	0.77	0.020	0.089	0.073	1.097	-0.203
Total Kjeldahl Nitrogen as N, mg/l	5	Full	87	8.2	0.66	0.72	0.66	0.73	0.054	0.132	0.036	1.196	-0.430
Total Kjeldahl Nitrogen as N, mg/l	5	Calibration	45	11.4	0.65	0.73	0.64	0.74	0.074	0.173	0.035	1.216	-0.479
Total Kjeldahl Nitrogen as N, mg/l	5	Validation	42	4.9	0.68	0.71	0.67	0.72	0.033	0.088	0.068	1.079	-0.164
Total Kjeldahl Nitrogen as N, mg/l	6	Full	109	3.4	0.62	0.64	0.61	0.65	0.021	0.115	0.048	1.212	-0.470
Total Kjeldahl Nitrogen as N, mg/l	6	Calibration	52	11.3	0.58	0.64	0.57	0.66	0.065	0.121	0.170	1.387	-0.923
Total Kjeldahl Nitrogen as N, mg/l	6	Validation	57	-2.9	0.65	0.64	0.66	0.65	-0.019	0.109	0.003	1.158	-0.342
Total N - calculated, mg/l	1	Full	204	13.0	1.03	1.17	0.98	1.14	0.134	0.216	0.131	1.171	-0.370
Total N - calculated, mg/l	1	Calibration	115	18.5	1.01	1.19	0.95	1.15	0.186	0.233	0.277	1.259	-0.584
Total N - calculated, mg/l	1	Validation	89	6.3	1.07	1.13	1.04	1.12	0.068	0.194	0.020	1.079	-0.164
Total N - calculated, mg/l	2	Full	190	0.3	0.90	0.91	0.89	0.89	0.003	0.172	0.002	1.176	-0.384
Total N - calculated, mg/l	2	Calibration	109	-1.1	0.88	0.87	0.87	0.84	-0.009	0.153	0.005	1.353	-0.830
Total N - calculated, mg/l	2	Validation	81	2.0	0.94	0.96	0.93	0.98	0.019	0.199	0.006	1.126	-0.267
Total N - calculated, mg/l	3	Full	54	6.8	0.82	0.87	0.81	0.87	0.056	0.124	0.239	1.451	-1.105
Total N - calculated, mg/l	3	Calibration	33	7.0	0.81	0.87	0.81	0.86	0.057	0.117	0.422	1.279	-0.636
Total N - calculated, mg/l	3	Validation	21	6.6	0.83	0.88	0.79	0.90	0.054	0.134	0.019	1.720	-1.960

Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model													
Total N - calculated, mg/l	4	Full	139	10.1	0.75	0.83	0.74	0.84	0.076	0.122	0.110	1.303	-0.698
Total N - calculated, mg/l	4	Calibration	61	13.8	0.73	0.83	0.73	0.82	0.101	0.139	0.178	1.442	-1.080
Total N - calculated, mg/l	4	Validation	78	7.3	0.77	0.82	0.76	0.84	0.056	0.108	0.069	1.202	-0.445
Total N - calculated, mg/l	5	Full	87	7.6	0.72	0.77	0.71	0.76	0.055	0.122	0.128	1.004	-0.009
Total N - calculated, mg/l	5	Calibration	45	9.9	0.72	0.79	0.71	0.77	0.072	0.140	0.141	0.989	0.023
Total N - calculated, mg/l	5	Validation	42	5.1	0.71	0.75	0.71	0.76	0.037	0.103	0.100	1.037	-0.076
Total N - calculated, mg/l	6	Full	109	2.2	0.68	0.69	0.67	0.68	0.015	0.128	0.081	1.005	-0.010
Total N - calculated, mg/l	6	Calibration	52	11.1	0.64	0.72	0.62	0.71	0.072	0.117	0.319	0.934	0.128
Total N - calculated, mg/l	6	Validation	57	-5.2	0.71	0.67	0.73	0.68	-0.036	0.138	0.005	1.103	-0.216
Total Organic Carbon, mg/l	1	Full	235	12.9	8.1	9.1	7.9	8.9	1.045	1.830	0.002	1.581	-1.499
Total Organic Carbon, mg/l	1	Calibration	116	12.7	8.5	9.5	8.2	9.4	1.072	1.889	0.002	1.732	-2.001
Total Organic Carbon, mg/l	1	Validation	119	13.1	7.8	8.8	7.5	8.6	1.019	1.772	0.049	1.517	-1.303
Total Organic Carbon, mg/l	2	Full	219	1.4	8.0	8.2	7.9	8.0	0.116	1.527	0.001	1.421	-1.020
Total Organic Carbon, mg/l	2	Calibration	109	-1.5	8.3	8.1	8.0	8.2	-0.121	1.634	0.003	1.427	-1.035
Total Organic Carbon, mg/l	2	Validation	110	4.5	7.8	8.2	7.6	7.9	0.352	1.421	0.000	1.449	-1.100
Total Organic Carbon, mg/l	3	Full	54	5.6	7.6	8.1	7.4	8.0	0.424	1.646	0.091	1.386	-0.921
Total Organic Carbon, mg/l	3	Calibration	33	5.3	7.8	8.2	7.3	8.2	0.414	1.806	0.103	1.345	-0.808

Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model													
Total Organic Carbon, mg/l	3	Validation	21	6.0	7.3	7.8	7.6	8.0	0.440	1.396	0.040	1.522	-1.316
Total Organic Carbon, mg/l	4	Full	139	-5.6	7.8	7.4	7.6	7.2	-0.438	1.520	0.043	1.491	-1.224
Total Organic Carbon, mg/l	4	Calibration	61	-2.8	7.6	7.4	7.3	7.2	-0.214	1.749	0.060	1.426	-1.032
Total Organic Carbon, mg/l	4	Validation	78	-7.7	7.9	7.3	8.0	7.2	-0.613	1.341	0.023	1.624	-1.638
Total Organic Carbon, mg/l	5	Full	87	-8.8	7.5	6.9	7.3	6.9	-0.663	1.326	0.224	1.379	-0.902
Total Organic Carbon, mg/l	5	Calibration	45	-6.1	7.5	7.0	7.2	6.9	-0.458	1.575	0.215	1.380	-0.903
Total Organic Carbon, mg/l	5	Validation	42	-11.6	7.6	6.7	7.6	6.7	-0.883	1.059	0.302	1.357	-0.841
Total Organic Carbon, mg/l	6	Full	109	-15.0	7.2	6.1	7.0	6.2	-1.079	1.480	0.178	1.207	-0.456
Total Organic Carbon, mg/l	6	Calibration	52	-11.1	7.0	6.2	6.7	6.3	-0.778	1.530	0.234	1.467	-1.151
Total Organic Carbon, mg/l	6	Validation	57	-18.4	7.4	6.0	7.2	5.9	-1.354	1.435	0.255	1.103	-0.216
Total Phosphorus as P, mg/l	1	Full	225	-21.9	0.097	0.076	0.090	0.074	-0.021	0.044	0.004	1.141	-0.302
Total Phosphorus as P, mg/l	1	Calibration	114	-25.2	0.100	0.075	0.089	0.073	-0.025	0.046	0.000	1.103	-0.216
Total Phosphorus as P, mg/l	1	Validation	111	-18.3	0.095	0.078	0.090	0.076	-0.017	0.043	0.019	1.203	-0.447
Total Phosphorus as P, mg/l	2	Full	212	-7.2	0.055	0.051	0.057	0.027	-0.004	0.030	0.002	1.286	-0.653
Total Phosphorus as P, mg/l	2	Calibration	106	-15.2	0.052	0.044	0.027	0.027	-0.008	0.025	0.016	1.214	-0.474
Total Phosphorus as P, mg/l	2	Validation	106	-0.1	0.058	0.058	0.060	0.065	0.000	0.034	0.007	1.357	-0.842
Total Phosphorus as P, mg/l	3	Full	54	-7.2	0.060	0.056	0.050	0.054	-0.004	0.020	0.030	1.039	-0.080

	Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model												
Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Total Phosphorus as P, mg/l	3	Calibration	33	-12.9	0.064	0.056	0.050	0.050	-0.008	0.023	0.034	1.016	-0.033
Total Phosphorus as P, mg/l	3	Validation	21	3.2	0.054	0.056	0.050	0.055	0.002	0.015	0.046	1.647	-1.712
Total Phosphorus as P, mg/l	4	Full	139	-2.8	0.048	0.047	0.044	0.045	-0.001	0.015	0.039	1.059	-0.121
Total Phosphorus as P, mg/l	4	Calibration	61	-11.4	0.052	0.046	0.047	0.042	-0.006	0.019	0.043	1.016	-0.031
Total Phosphorus as P, mg/l	4	Validation	78	4.8	0.046	0.048	0.043	0.045	0.002	0.013	0.086	1.471	-1.163
Total Phosphorus as P, mg/l	5	Full	87	-1.7	0.040	0.040	0.036	0.037	-0.001	0.016	0.008	1.062	-0.128
Total Phosphorus as P, mg/l	5	Calibration	45	0.6	0.040	0.040	0.040	0.039	0.000	0.014	0.058	1.138	-0.294
Total Phosphorus as P, mg/l	5	Validation	42	-4.1	0.041	0.039	0.035	0.036	-0.002	0.019	0.000	1.032	-0.065
Total Phosphorus as P, mg/l	6	Full	109	11.4	0.032	0.035	0.030	0.032	0.004	0.011	0.194	1.177	-0.385
Total Phosphorus as P, mg/l	6	Calibration	52	8.2	0.033	0.036	0.030	0.031	0.003	0.010	0.330	0.985	0.029
Total Phosphorus as P, mg/l	6	Validation	57	14.5	0.030	0.035	0.030	0.032	0.004	0.012	0.045	1.478	-1.184
Total Suspended Solids, mg/l	1	Full	35	7.2	19.5	20.9	17.0	7.0	1.396	23.701	0.031	3.393	-10.513
Total Suspended Solids, mg/l	1	Calibration	15	45.5	16.7	24.2	13.9	5.6	7.576	28.094	0.090	3.858	-13.887
Total Suspended Solids, mg/l	1	Validation	20	-15.0	21.6	18.4	19.0	7.2	-3.240	20.407	0.000	2.981	-7.889
Total Suspended Solids, mg/l	2	Full	36	-32.5	13.9	9.4	11.9	2.0	-4.514	13.493	0.025	2.597	-5.745
Total Suspended Solids, mg/l	2	Calibration	16	-27.3	12.6	9.2	11.7	2.0	-3.439	14.459	0.171	2.629	-5.909
Total Suspended Solids, mg/l	2	Validation	20	-36.1	14.9	9.5	14.0	3.6	-5.375	12.720	0.013	2.554	-5.523

	Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model												
Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Total Suspended Solids, mg/l	3	Full	37	4.3	6.2	6.5	6.4	3.0	0.267	5.978	0.034	2.765	-6.644
Total Suspended Solids, mg/l	3	Calibration	16	0.6	6.2	6.3	4.8	3.0	0.039	6.074	0.080	2.603	-5.777
Total Suspended Solids, mg/l	3	Validation	21	7.1	6.2	6.6	6.4	3.0	0.440	5.905	0.010	2.847	-7.106
Total Suspended Solids, mg/l	4	Full	37	61.2	5.0	8.0	5.1	2.1	3.051	7.193	0.004	4.982	-23.821
Total Suspended Solids, mg/l	4	Calibration	16	36.1	5.5	7.5	5.2	2.1	1.981	6.823	0.002	5.123	-25.242
Total Suspended Solids, mg/l	4	Validation	21	83.9	4.6	8.5	5.1	2.1	3.866	7.475	0.004	4.911	-23.122
Total Suspended Solids, mg/l	5	Full	37	0.4	3.1	3.2	2.7	2.7	0.013	0.956	0.009	1.624	-1.638
Total Suspended Solids, mg/l	5	Calibration	16	-16.6	3.2	2.7	2.7	2.7	-0.529	0.529	NA	1.035	-0.071
Total Suspended Solids, mg/l	5	Validation	21	13.8	3.1	3.5	2.7	2.7	0.427	1.281	0.013	1.921	-2.691
Total Suspended Solids, mg/l	6	Full	37	-2.4	2.2	2.2	2.0	2.0	-0.052	0.453	0.005	1.446	-1.091
Total Suspended Solids, mg/l	6	Calibration	16	-9.1	2.2	2.0	2.0	2.0	-0.197	0.197	NA	1.000	0.000
Total Suspended Solids, mg/l	6	Validation	21	2.6	2.2	2.3	2.0	2.0	0.058	0.648	0.010	1.613	-1.601
Water Temperature, C	1	Full	60	2.9	18.8	19.3	19.0	18.7	0.547	2.110	0.967	0.311	0.903
Water Temperature, C	1	Calibration	37	3.6	17.8	18.4	16.8	15.5	0.644	2.245	0.969	0.319	0.898
Water Temperature, C	1	Validation	23	1.9	20.4	20.8	21.8	25.3	0.391	1.893	0.967	0.301	0.910
Water Temperature, C	2	Full	54	5.6	18.4	19.4	17.7	17.6	1.029	2.103	0.974	0.318	0.899
Water Temperature, C	2	Calibration	34	5.0	17.9	18.8	16.5	16.0	0.892	1.951	0.976	0.296	0.912
Water Temperature, C	2	Validation	20	6.6	19.2	20.4	19.5	20.4	1.260	2.360	0.973	0.346	0.881
Water Temperature, C	3	Full	53	6.6	17.8	19.0	17.2	17.2	1.171	2.252	0.971	0.340	0.884
Water Temperature, C	3	Calibration	32	5.0	17.4	18.3	16.6	15.6	0.878	1.968	0.974	0.301	0.909

	Table B-9. Simulated and Observed Means, Medians, and Performance Statistics for Falls Lake WARMF Lake Model												
Parameter	Segment	Period	N	Percent Bias	Observed Mean	WARMF Mean	Observed Median	WARMF Median	Average Difference	AE	R2	RSR	NSE
Water Temperature, C	3	Validation	21	8.8	18.5	20.1	19.4	18.9	1.618	2.686	0.969	0.383	0.853
Water Temperature, C	4	Full	57	8.6	17.8	19.4	18.0	17.5	1.541	2.420	0.971	0.396	0.843
Water Temperature, C	4	Calibration	36	9.2	17.4	19.0	17.8	16.7	1.605	2.524	0.966	0.424	0.820
Water Temperature, C	4	Validation	21	7.7	18.6	20.0	19.5	19.7	1.432	2.241	0.981	0.345	0.881
Water Temperature, C	5	Full	56	12.0	17.6	19.7	18.7	17.9	2.113	3.370	0.940	0.575	0.669
Water Temperature, C	5	Calibration	36	13.3	16.9	19.1	17.2	17.3	2.244	3.567	0.927	0.643	0.586
Water Temperature, C	5	Validation	20	10.0	18.8	20.7	20.1	20.9	1.876	3.016	0.969	0.463	0.786
Water Temperature, C	6	Full	57	10.5	17.5	19.3	18.4	18.3	1.834	2.963	0.953	0.523	0.726
Water Temperature, C	6	Calibration	36	11.4	17.0	19.0	17.4	17.6	1.934	3.137	0.944	0.585	0.658
Water Temperature, C	6	Validation	21	9.1	18.3	20.0	20.1	20.4	1.663	2.664	0.972	0.422	0.822

1. *Full period is 2015 to 2018; calibration is 2015 to 2016; validation is 2017 to 2018*

3.3.2 Graphical Evaluation

The simulated water quality time series are graphically compared against observations to evaluate the concentration magnitude, range, seasonal pattern, and timing of the model results. As with the UNRBA Watershed Model Report, the UNRBA expressed the importance of visualizing uncertainty around laboratory measurements when evaluating model output. The UNRBA MRSW, DWR, and "third-party" model reviewers discussed methods and terminology to show the potential range of "observed" values using the relative percent difference (RPD) allowed by each laboratory when evaluating field duplicates. Methods for dealing with observations less than the reporting limit were also discussed. For field measurements, the stated accuracy of field meters was used. The following methods were used to develop the time series comparison figures. Note this uncertainty evaluation approach is different from the approach used in the UNRBA Watershed Modeling Report. The data used to calibrate and evaluate the WARMF Lake model were collected by external organizations (e.g., DWR, CAAE), while watershed data were collected as part of the UNRBA monitoring program under different quality assurance protocols and laboratory testing procedures.

- For observations that were less than the reporting limit, the value is displayed as one-half the reporting limit. This is a common approach for dealing with values characterized by laboratory analysis as less than the reporting limit. Vertical bars extend from a concentration of zero to the reporting limit to show the potential range. This bar is labeled "Zero to the Reporting Limit". The reporting limits change depending on the organization and parameter displayed.
- For observations that were greater than the reporting limit, vertical bars are shown on the figure and labeled in the legend as "+/- Allowable RPD of the Laboratory Duplicates"
    - CAAE observations are shown with a bar that is +/-15% of the observation point based on the CAAE monitoring QAPP
    - DWR values for chlorophyll-a, TOC, TKN, and TSS use +/-20% based on the DWR Monitoring QAPP
    - Calculated values for TN using DWR data use +-20% because the majority of the TN in Falls Lake is TKN, and the value for TKN is +/-20%
    - DWR values for ammonia, nitrate plus nitrite and all phosphorus species including total use +/-10% based on the DWR Monitoring QAPP
    - City of Durham values for all parameters use +/-10% except for dissolved and total organic carbon which use +/-15% based on the City of Durham's quality control acceptance criteria
    - Temperature uses +/-0.2 C labeled "+/- Typical accuracy of calibrated field meters" as provided in the City of Durham QAPP for common field meters

Figure B-9 through Figure B-62 show the simulated water quality concentrations compared to observations collected at the downstream end of each of the six mainstem lake segments. Figure B-63 through Figure B-71 provide scatter plots of the simulated and observed concentrations for all six segments.

Comparisons of the general patterns of simulated and observed data and model performance rankings are described below for the full model period (2015 to 2018). Model performance rankings are based on comparison to the reported value based on laboratory analysis or field measurement. Performance rankings are not adjusted for the allowable relative per difference for the laboratory duplicates or typical accuracy of field meters shown on the figures for visual purposes only.

- Temperature simulations follow the seasonal patterns of observations. Temperature is important to calibration of other water quality parameters because it controls biological and chemical reaction rates as well as thermal stratification of the reservoir. Model performance is ranked is "good" to "very good" for the six main lake segments.

- Simulations of ammonia concentrations perform better in the segments downstream of Highway 50 (segments 5 and 6) where the mean observed concentration ranges from 0.04 mg-N/L to 0.06 mg-N/L. Roughly one-quarter of the observations are less than reporting limit in these two segments, and the model performance is ranked either "fair" or "very good." In the segments upstream of Highway 50, more than one-half of the observations are less than the reporting limit, and mean concentrations ranged from 0.02 mg-N/L to 0.03 mg-N/L. The observations less than the reporting limit are designated by orange bars on the time series figures. The length of the orange bar extends from zero to the reporting limit. The model does not meet the performance criteria in these segments (1 through 4) and generally overestimates ammonia concentrations. Meeting the percent bias criteria is difficult when observed values are very low. In addition, the subject matter experts and "third-party" model reviewers suggested that reaction rates be set as lake-wide parameters and not as segment-specific rates. This change to the calibration improved the robustness of the model but worsened the model performance in some segments for some parameters. Further adjustment of model coefficients explored during calibration such as nitrification rate or organic matter decay rate improved the ammonia calibration but worsened other parameters like nitrate and total organic carbon which generally had a "very good" model performance rankings (see below).
- The model performance for nitrate is "very good" in segments 2, 3, 5, and 6. Segment 1 does not meet the performance criteria for nitrate, but the mean concentration is 0.08 mg-N/L and 35 percent of observations are less than the reporting limit. Segment 4 does not meet performance criteria either: the mean concentration is 0.03 mg-N/L and 46 percent of observations are less than the reporting limit. This is an example of a parameter where model performance was "very good" in most of the lake but did not meet the performance criteria in the upper most segment (1) or a middle segment (4). Further adjustment of model coefficients would have generally worsened the model performance.
- Mean observed concentrations of Total Kjeldahl Nitrogen (TKN) range from 0.6 mg-N/L in Segment 6 to 0.96 mg-N/L in Segment 1. The model performance is ranked "very good" for all six main lake segments.
- The model performance for total nitrogen is also ranked "very good" for all six main lake segments. Mean observed total nitrogen concentrations range from 0.7 mg-N/L (Segment 6) to 1.0 mg-N/L (Segment 1) and is mostly comprised of organic nitrogen (the predominate component of TKN in this watershed and lake system.)
- The WARMF model output for total suspended solids (TSS) includes only silt and clay. Laboratory measurements include all suspended particles greater than a specified size. Simulated concentrations of TSS are compared to measured TSS minus measured volatile suspended solids (VSS) in the evaluation of model performance to eliminate the portion of TSS that is organic material. TSS measurements without a paired VSS measurement were excluded from the performance evaluation. There are fewer observations for TSS-VSS compared to the other water quality parameters (roughly 35 samples per segment over the four-year study period). Simulated concentrations were sometimes much higher values than the range of observed values because the simulated values are mass-based, calculated values that depend on watershed loading. TSS and TSS-VSS are higher following large storm events which increase erosion from land surfaces and streambanks. Water quality sampling is not usually conducted during large storms due to safety concerns, so observations may not represent the full range of actual values for a system. Despite these challenges, the model performance for TSS-VSS is "very good" in segments 1, 3, 5 and 6 and "fair" in segment 2. The model does not meet the

performance criteria in Segment 4. This is an example of a parameter where model performance was “very good” in most of the lake. One segment under-predicted TSS-VSS and one segment over-predicted it. Adjustment of model coefficients would generally worsen the model performance the lake.

- Total phosphorus performance is “good” in the uppermost segment (1) and “very good” in Segments 2 through 6. Mean observed concentrations of total phosphorus range from 0.03 mg-P/L in Segment 6 to 0.097 mg-P/L in Segment 1. Thirty percent of the observations in Segment 1 are less than the reporting limit; almost one-half of the observations in Segment 2 are less than the reporting limit. Different organizations sample different parts of the lake, and reporting limits vary across the organizations.
- Chlorophyll-a follows the seasonal patterns in the lake, and the range of simulated values is similar to those observed. The model performance is “very good” in Segments 1, 2, 3, 5, and 6, and “good” in Segment 4. Mean chlorophyll-a concentrations range from 20.6 µg/L in Segment 6 to 42.2 µg/L in Segment 1.
- The model performance for total organic carbon is ranked “very good” for all six main lake segments. Mean observed total organic carbon concentrations range from 7.2 mg/L (Segment 6) to 8.1 mg/L (Segment 1).

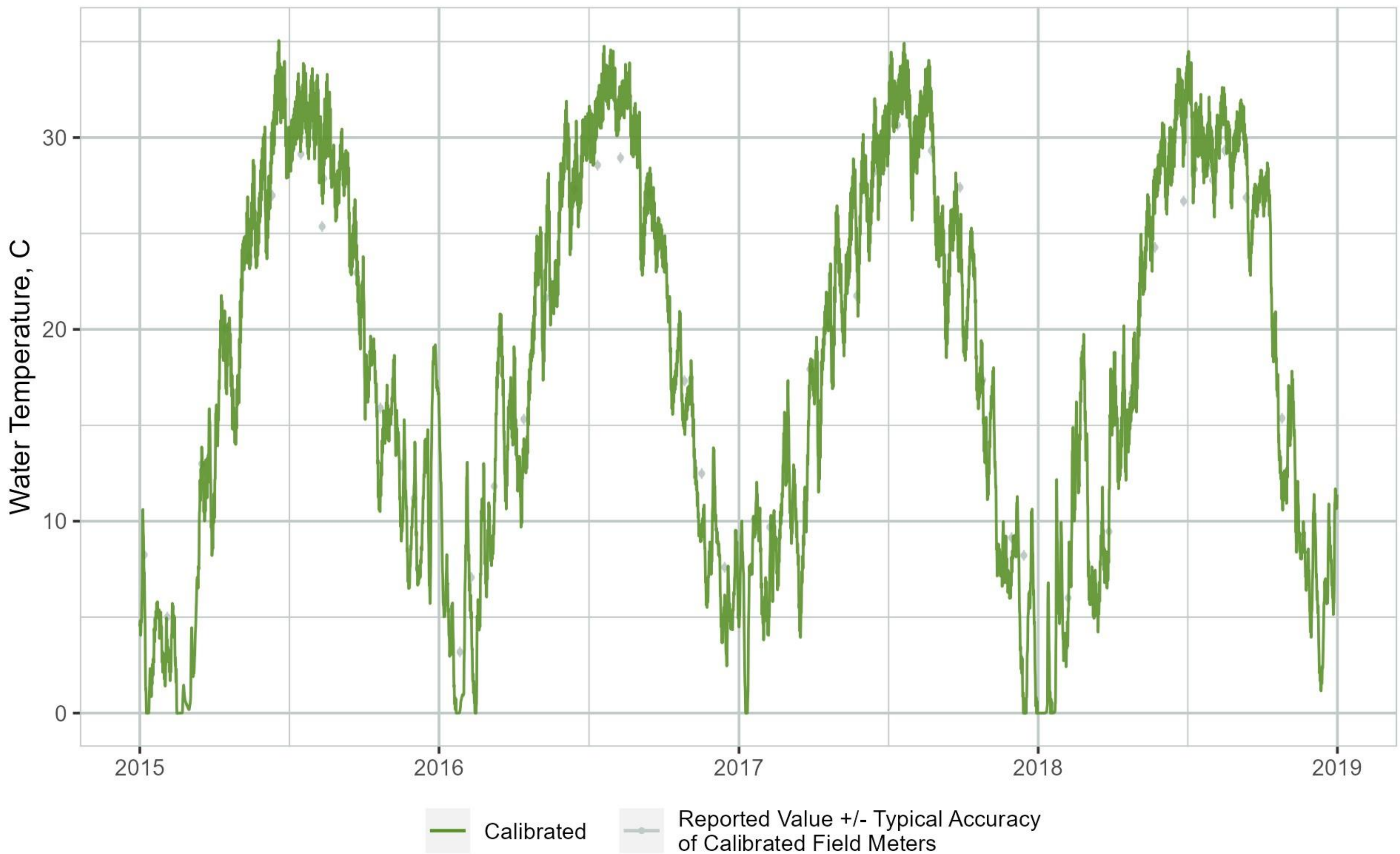

Figure B-9. Time Series Comparison of WARMF Lake Simulated Water Temperatures to Observations Collected at the Downstream End of Segment 1

Figure B-10. Time Series Comparison of WARMF Lake Simulated Water Temperatures to Observations Collected at the Downstream End of Segment 2

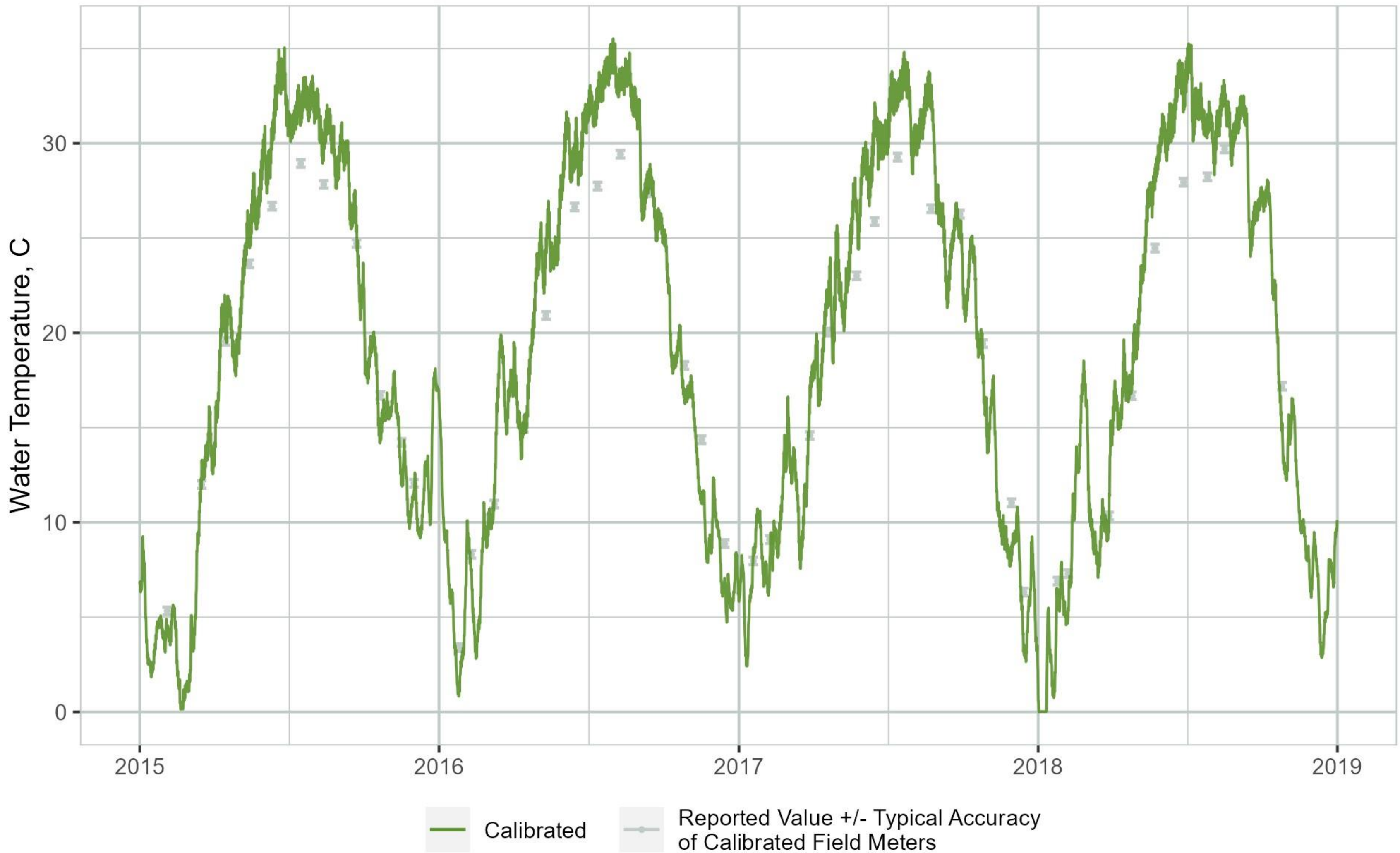

Figure B-11. Time Series Comparison of WARMF Lake Simulated Water Temperatures to Observations Collected at the Downstream End of Segment 3

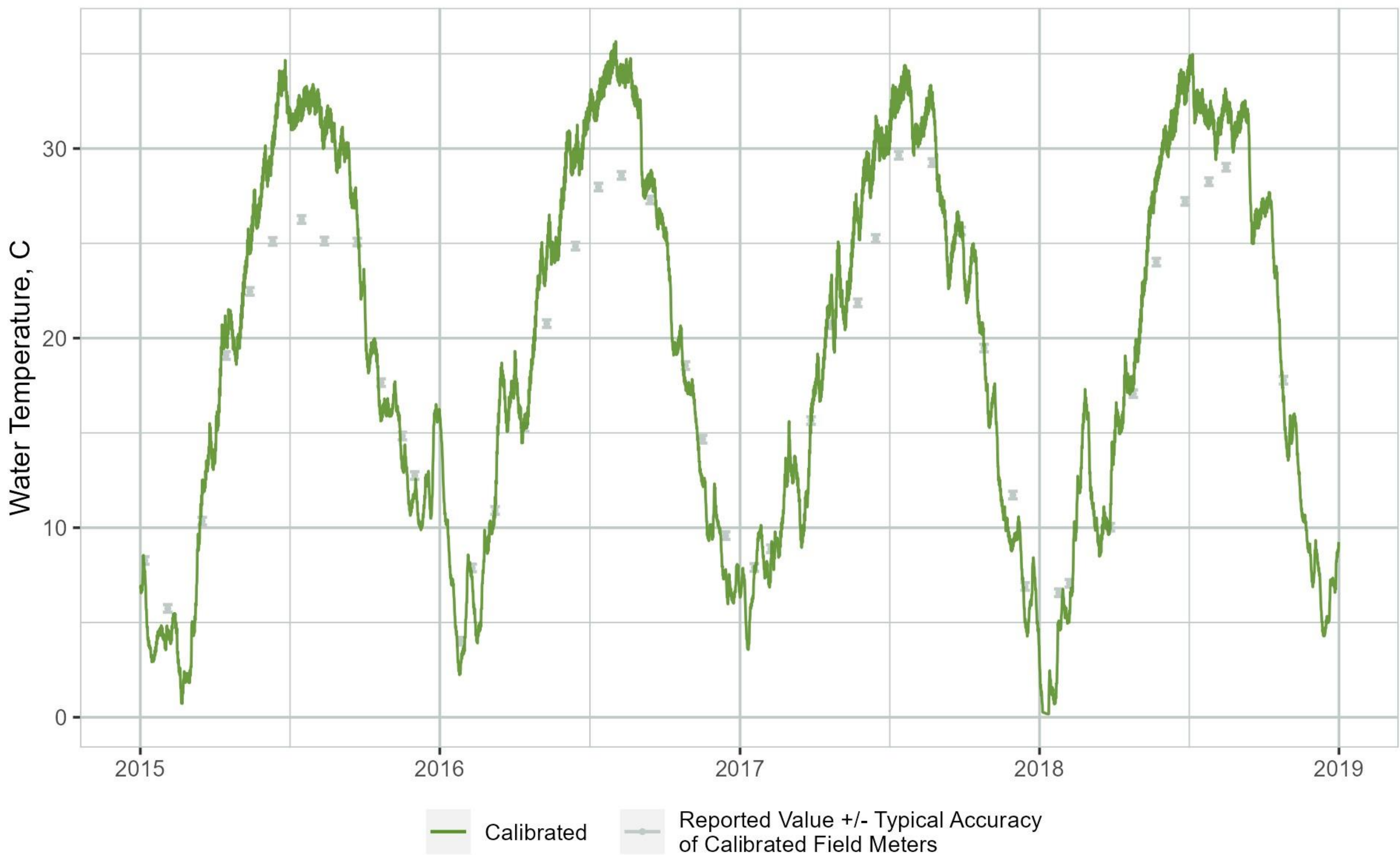

Figure B-12. Time Series Comparison of WARMF Lake Simulated Water Temperatures to Observations Collected at the Downstream End of Segment 4

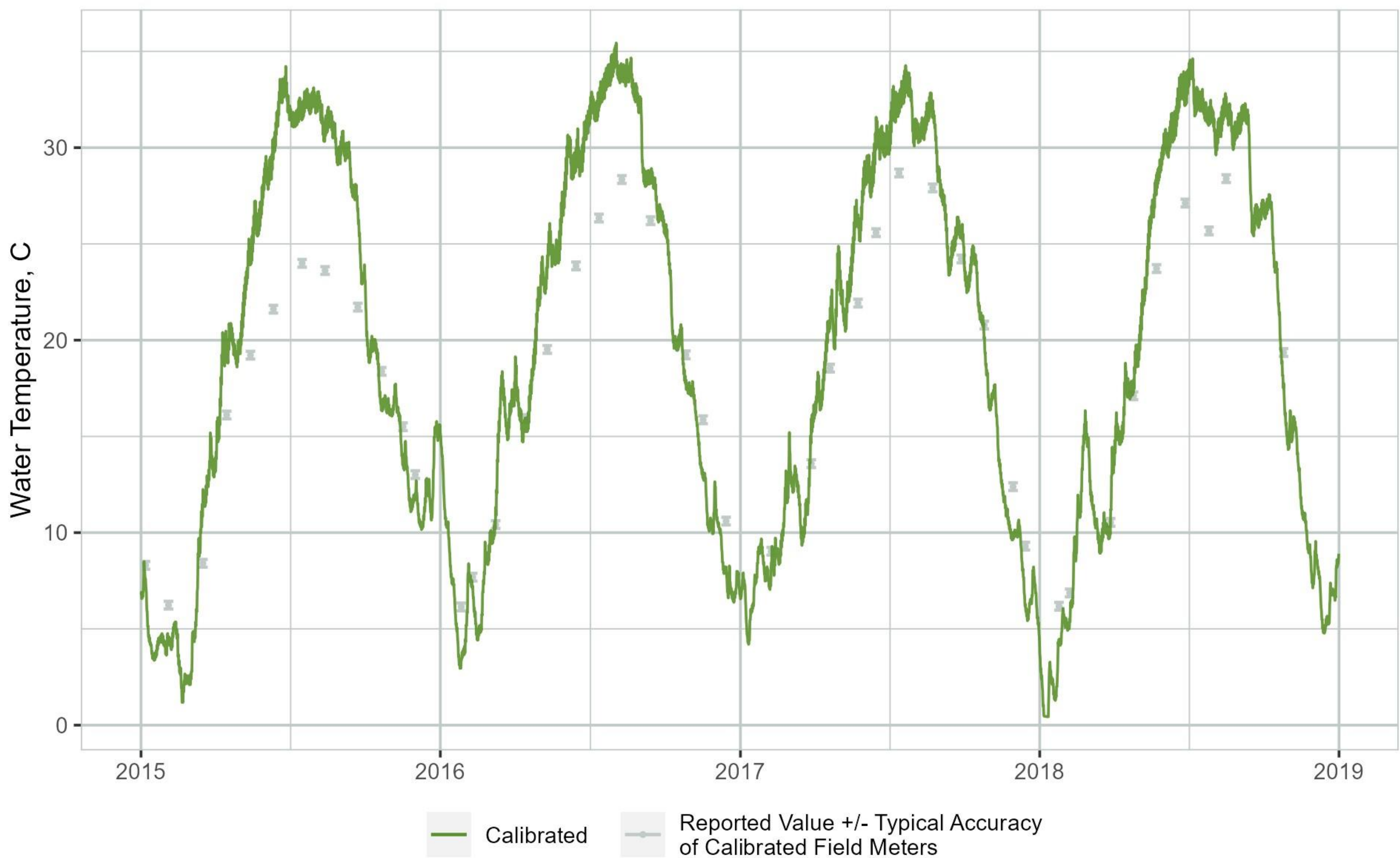

Figure B-13. Time Series Comparison of WARMF Lake Simulated Water Temperatures to Observations Collected at the Downstream End of Segment 5

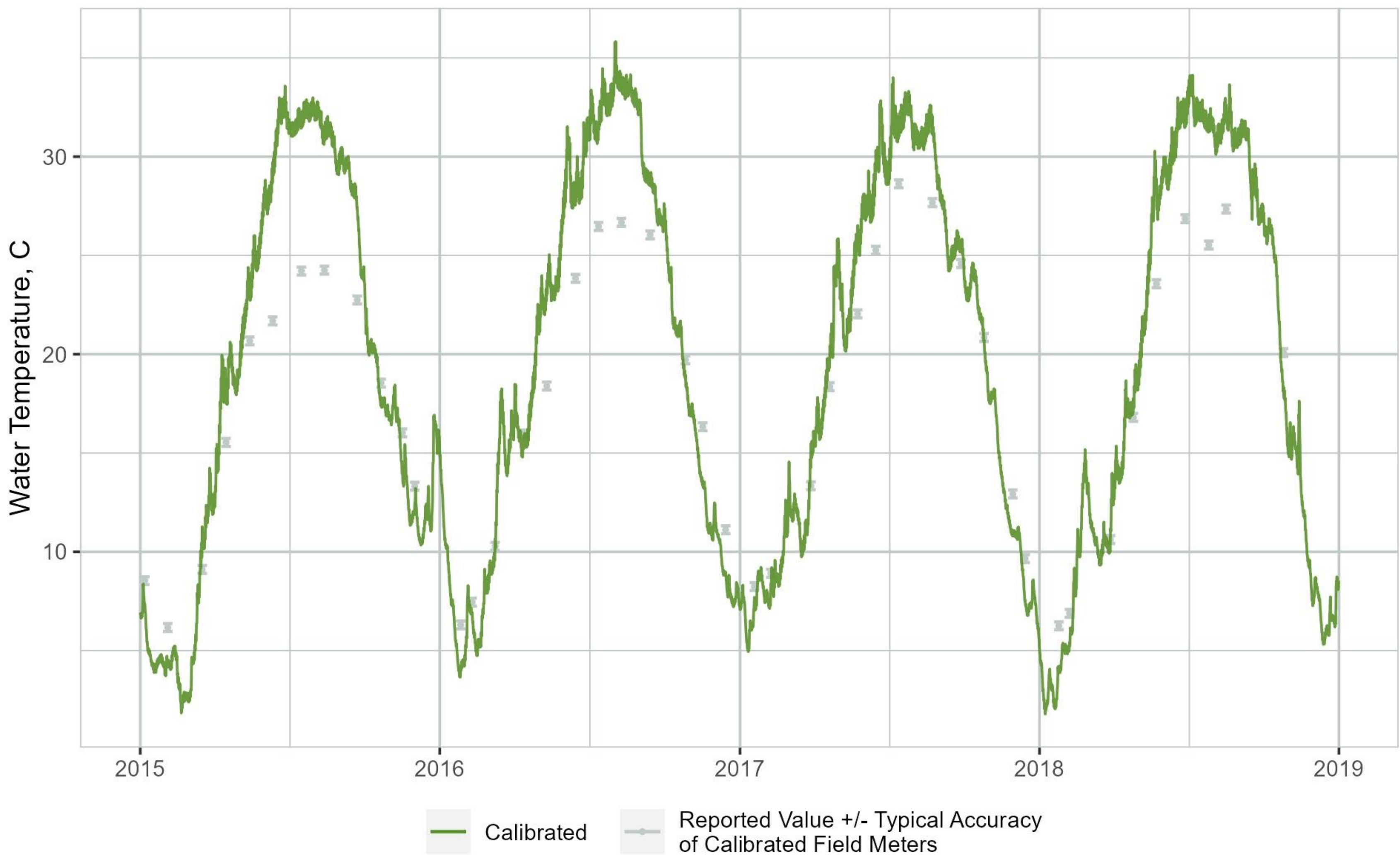

Figure B-14. Time Series Comparison of WARMF Lake Simulated Water Temperatures to Observations Collected at the Downstream End of Segment 6

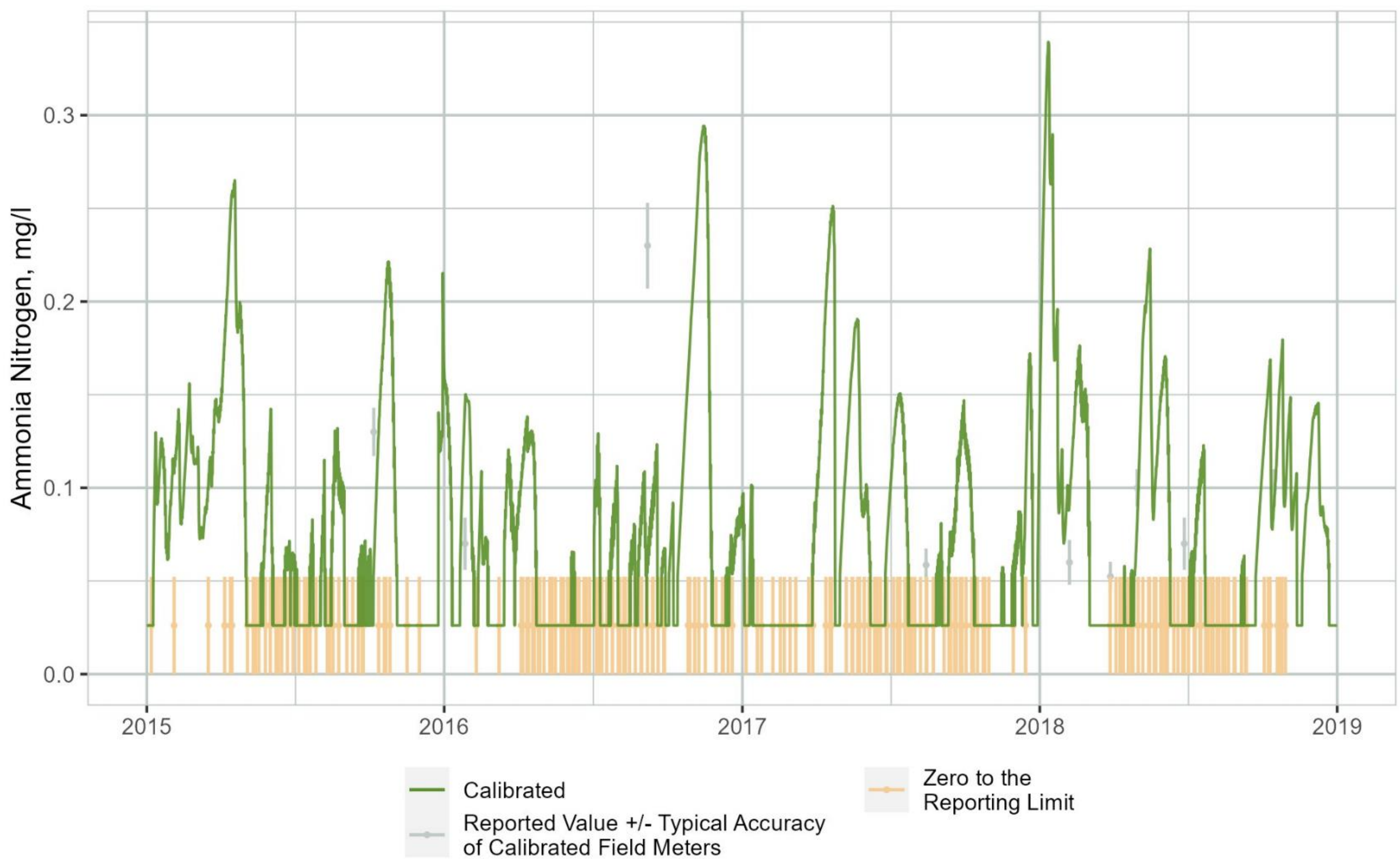

Figure B-15. Time Series Comparison of WARMF Lake Simulated Ammonia Concentrations to Observations Collected at the Downstream End of Segment 1

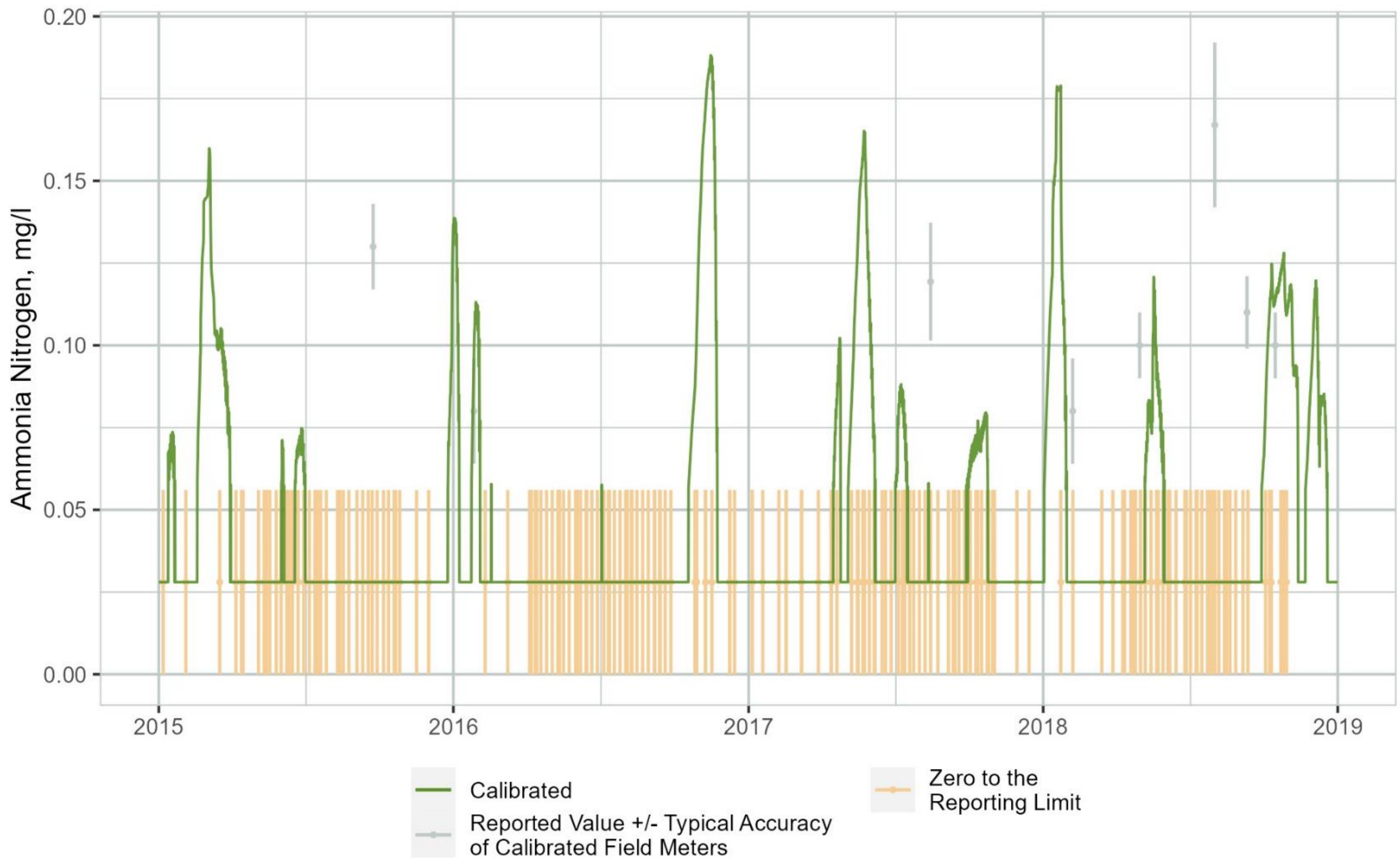

Figure B-16. Time Series Comparison of WARMF Lake Simulated Ammonia Concentrations to Observations Collected at the Downstream End of Segment 2

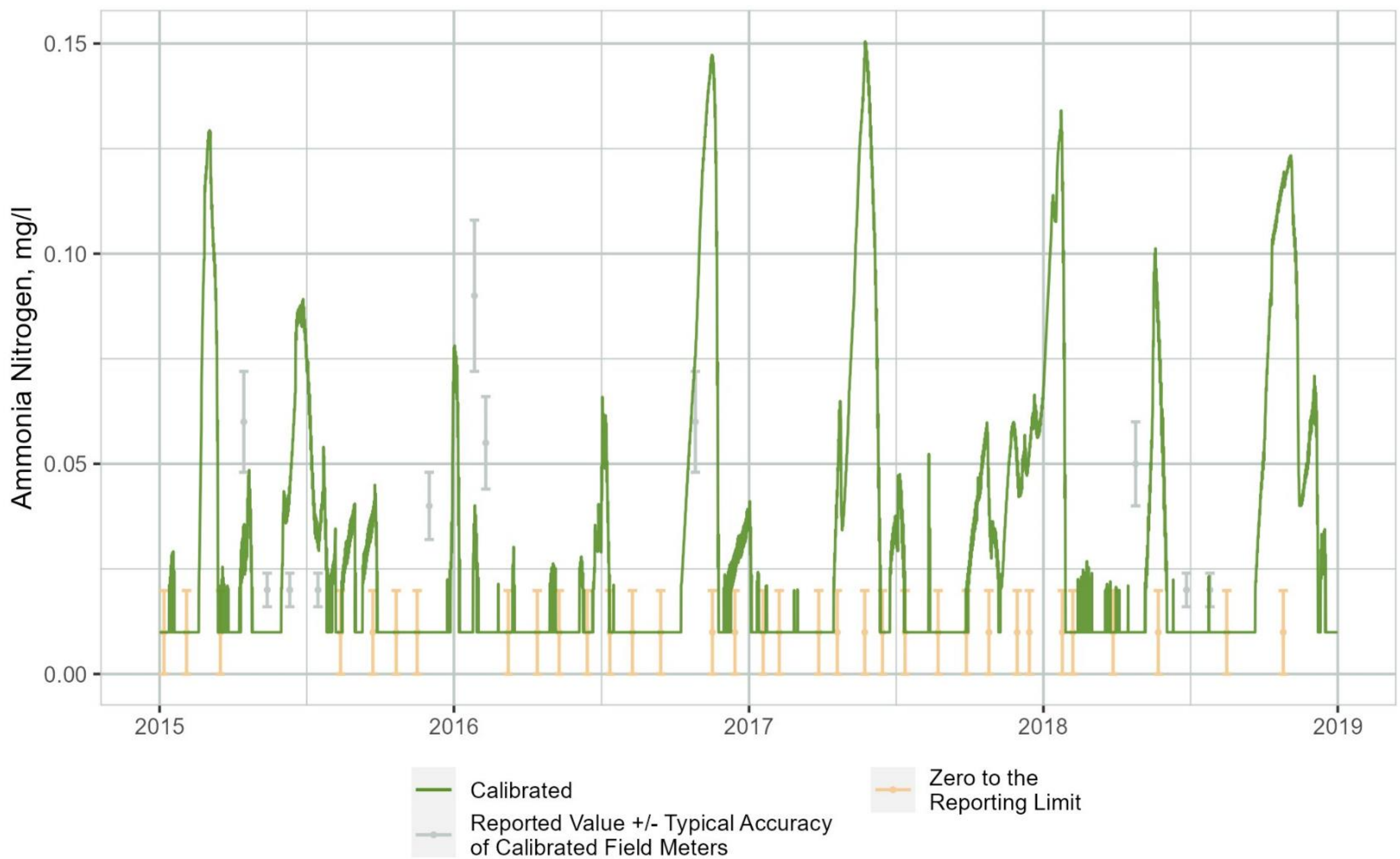

Figure B-17. Time Series Comparison of WARMF Lake Simulated Ammonia Concentrations to Observations Collected at the Downstream End of Segment 3

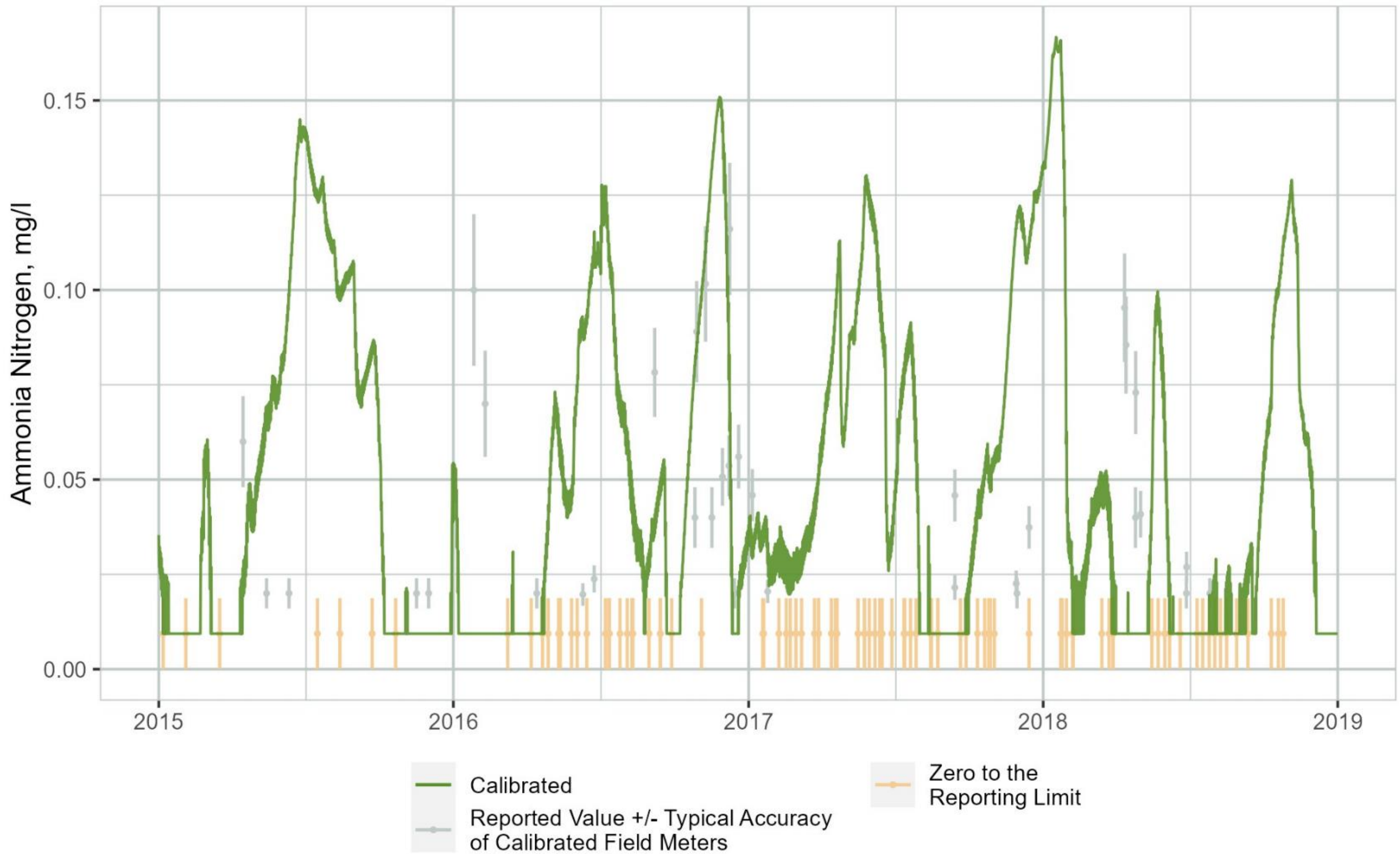

Figure B-18. Time Series Comparison of WARMF Lake Simulated Ammonia Concentrations to Observations Collected at the Downstream End of Segment 4

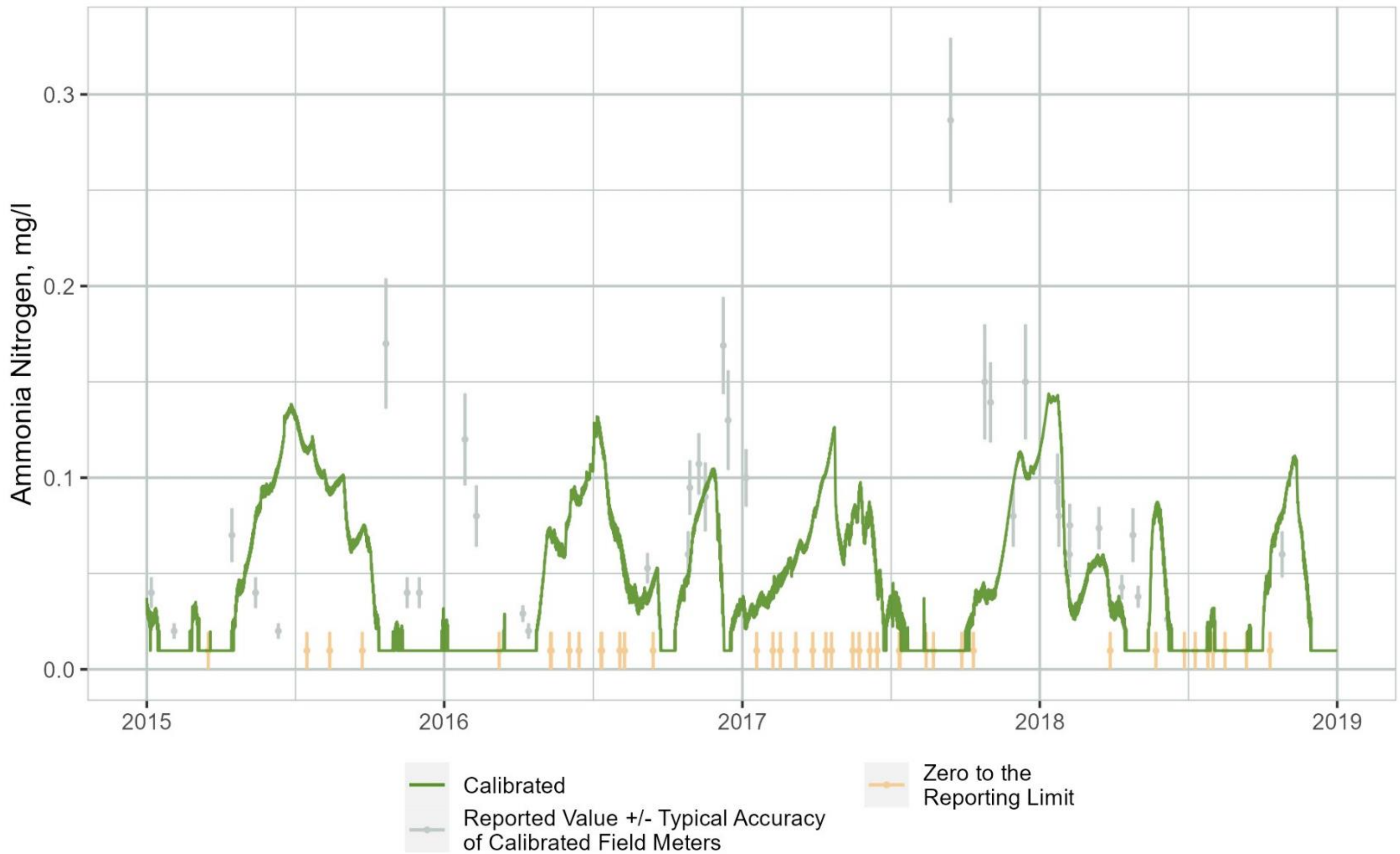

Figure B-19. Time Series Comparison of WARMF Lake Simulated Ammonia Concentrations to Observations Collected at the Downstream End of Segment 5

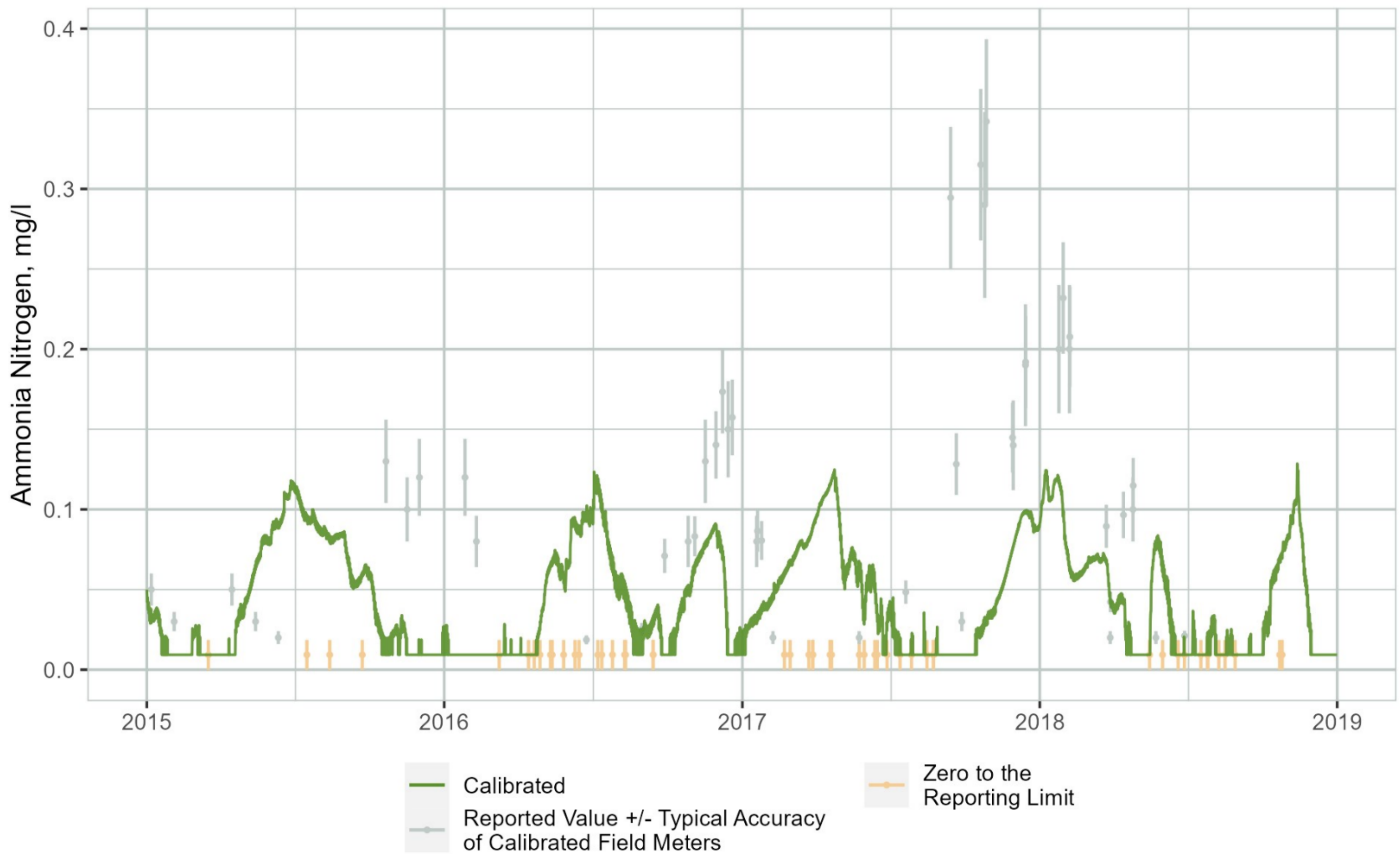

Figure B-20. Time Series Comparison of WARMF Lake Simulated Ammonia Concentrations to Observations Collected at the Downstream End of Segment 6

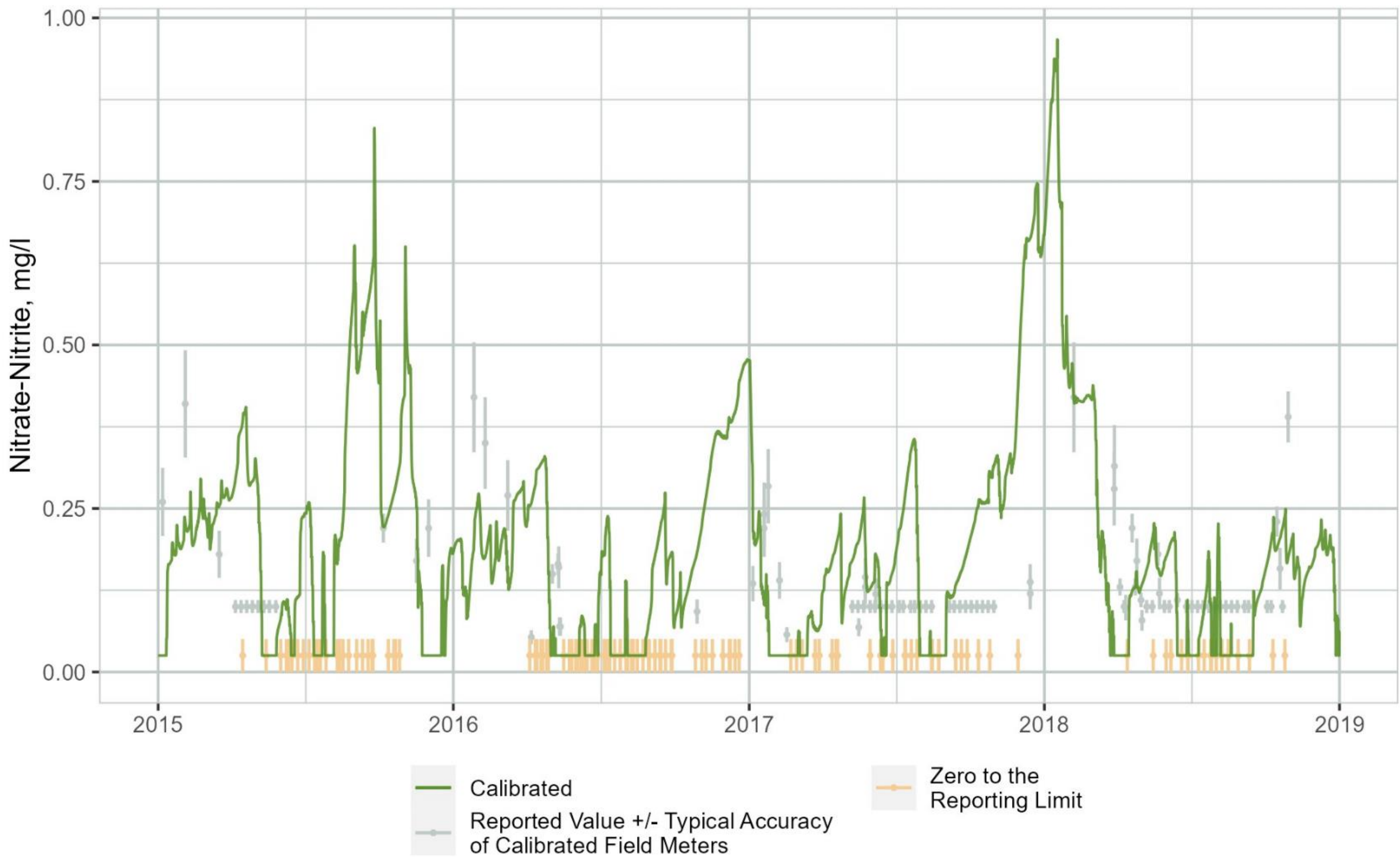

Figure B-21. Time Series Comparison of WARMF Lake Simulated Nitrate plus Nitrite Concentrations to Observations Collected at the Downstream End of Segment 1

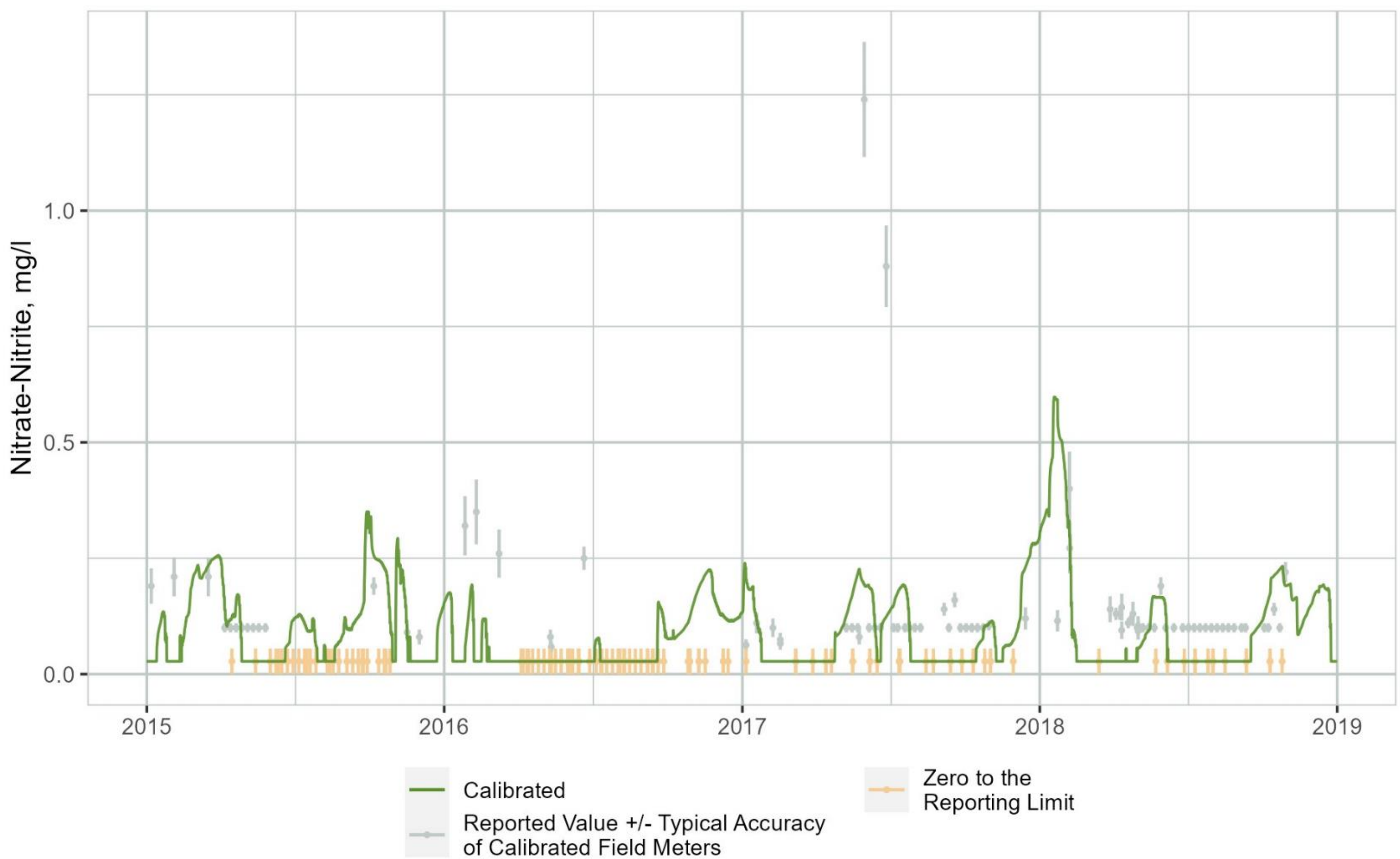

Figure B-22. Time Series Comparison of WARMF Lake Simulated Nitrate plus Nitrite Concentrations to Observations Collected at the Downstream End of Segment 2

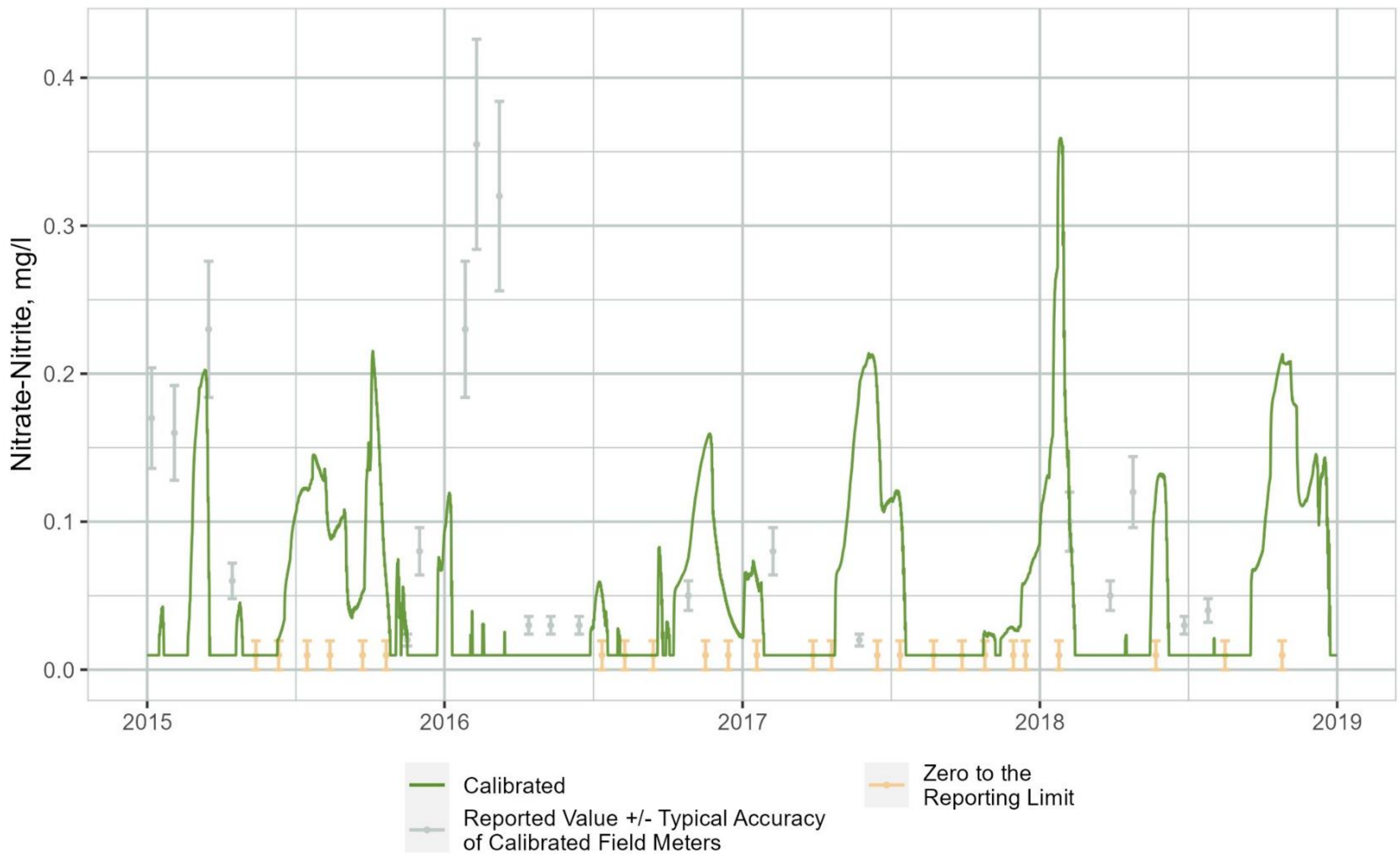

Figure B-23. Time Series Comparison of WARMF Lake Simulated Nitrate plus Nitrite Concentrations to Observations Collected at the Downstream End of Segment 3

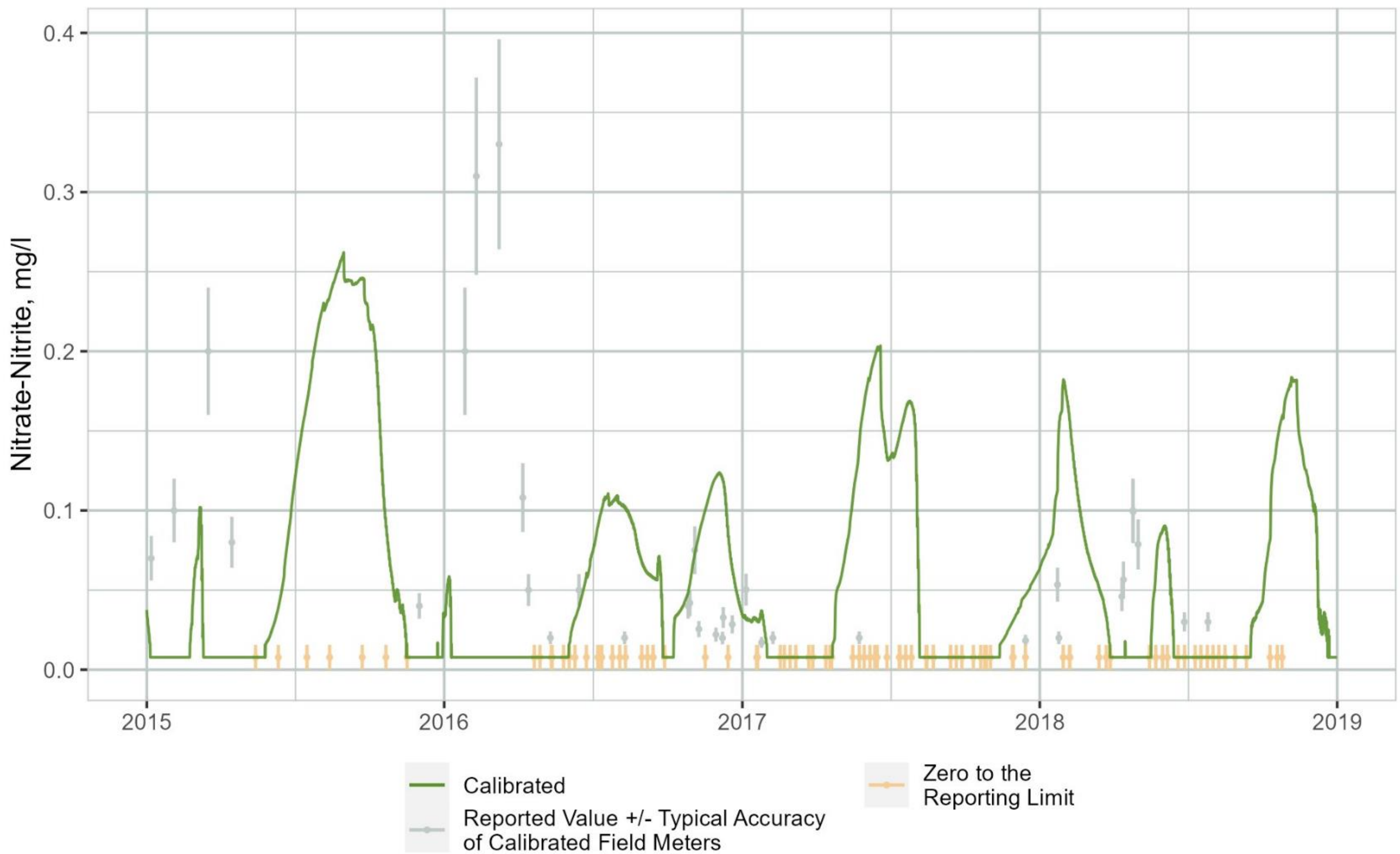

Figure B-24. Time Series Comparison of WARMF Lake Simulated Nitrate plus Nitrite Concentrations to Observations Collected at the Downstream End of Segment 4

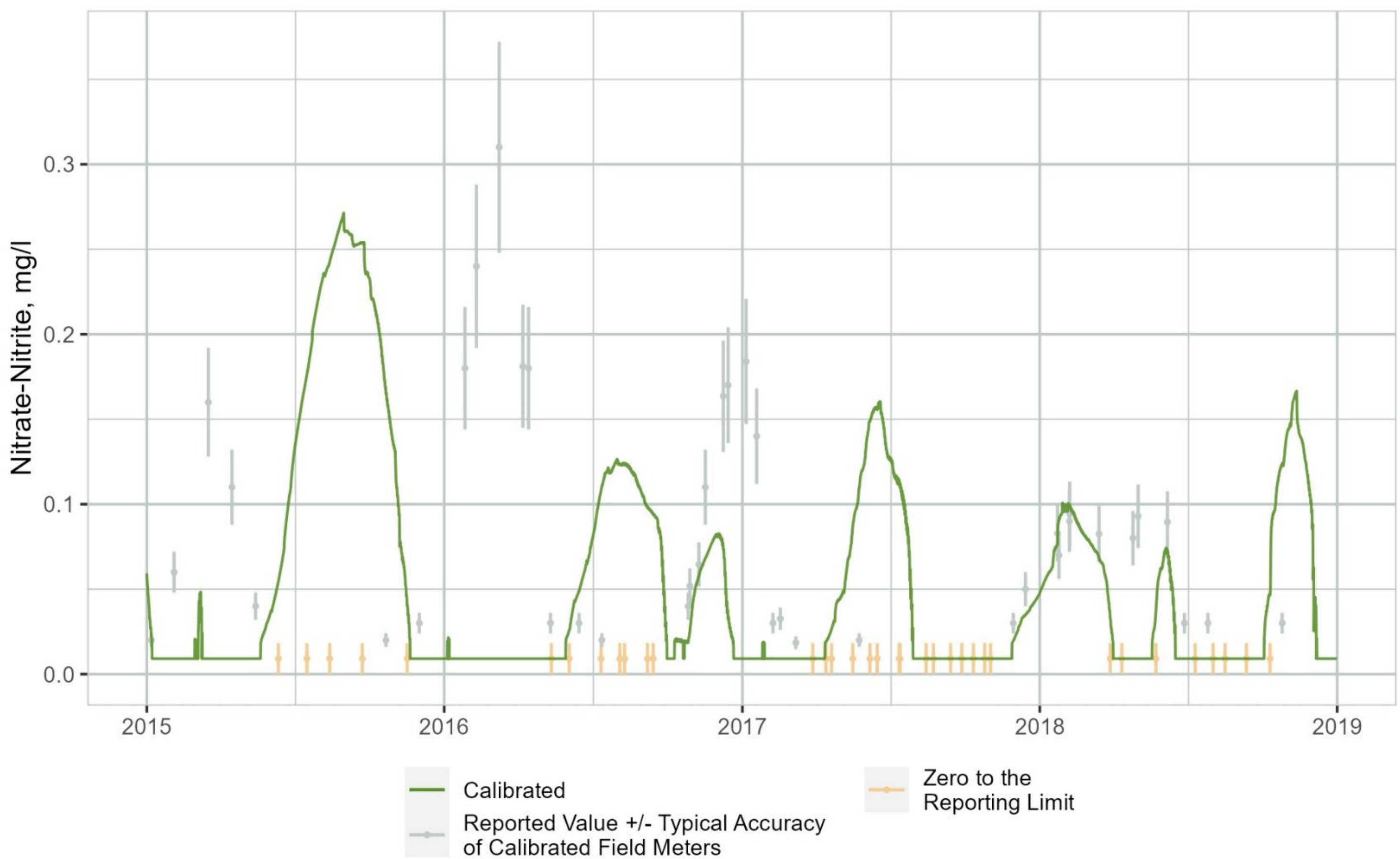

Figure B-25. Time Series Comparison of WARMF Lake Simulated Nitrate plus Nitrite Concentrations to Observations Collected at the Downstream End of Segment 5

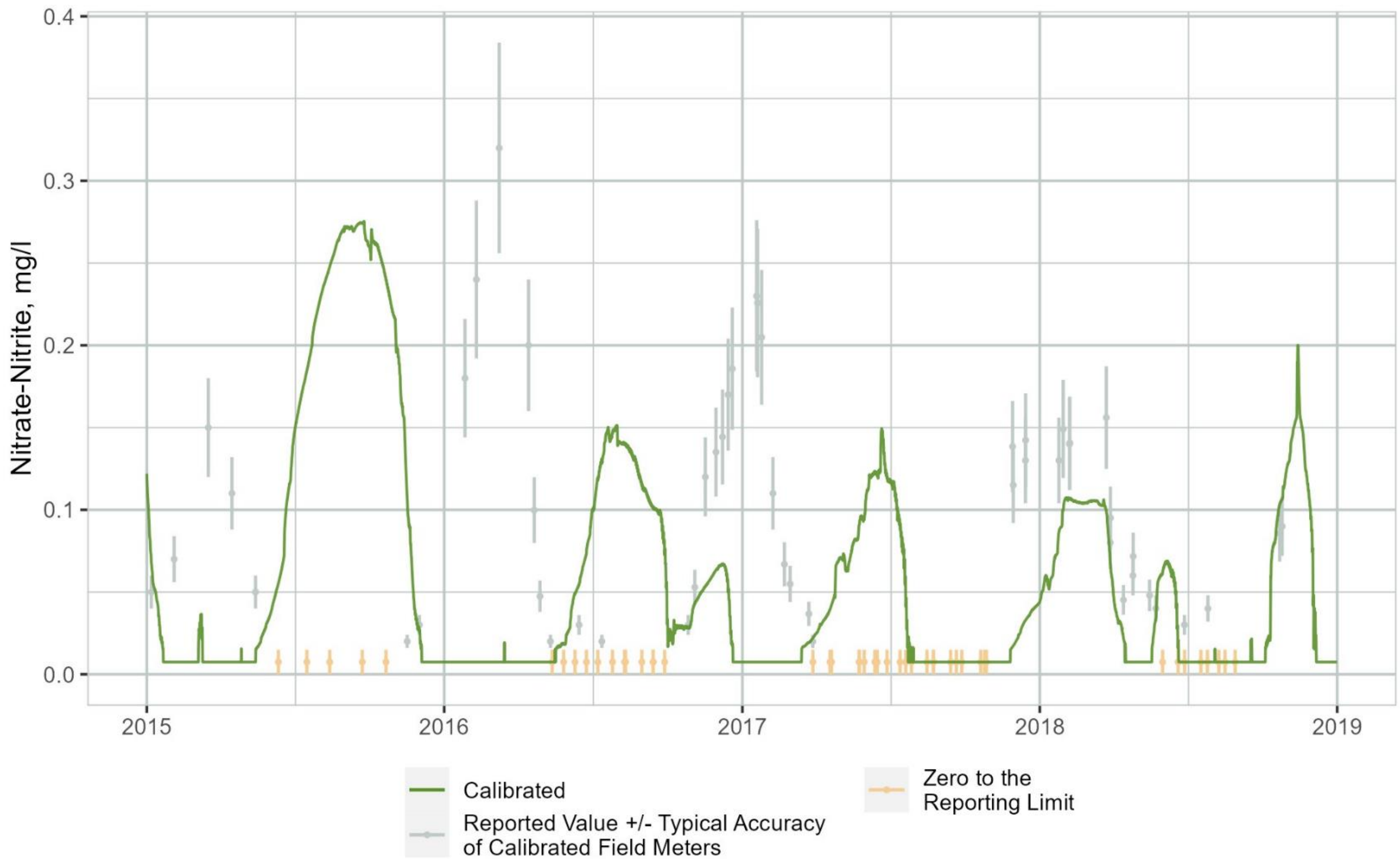

Figure B-26. Time Series Comparison of WARMF Lake Simulated Nitrate plus Nitrite Concentrations to Observations Collected at the Downstream End of Segment 6

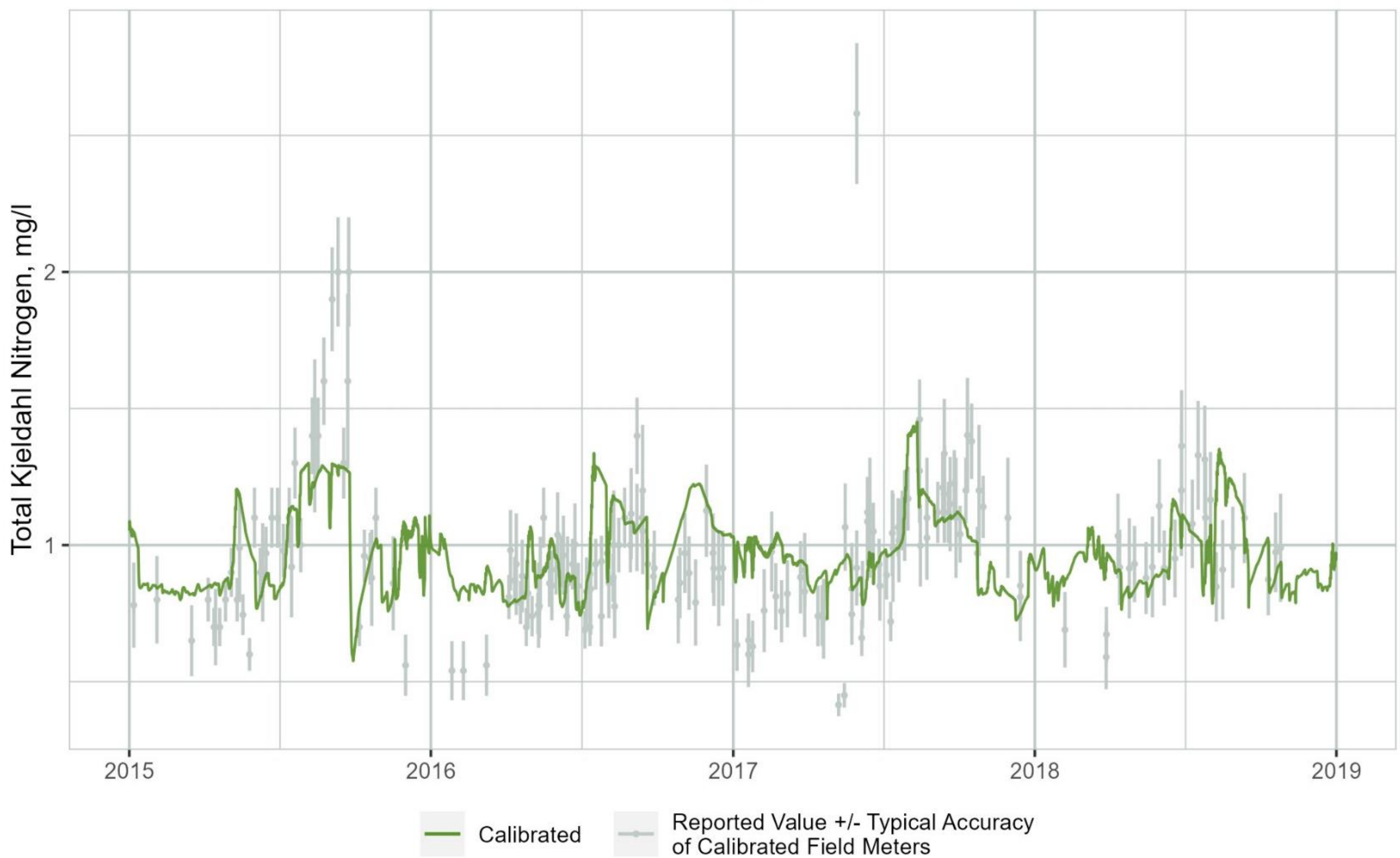

Figure B-27. Time Series Comparison of WARMF Lake Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations Collected at the Downstream End of Segment 1

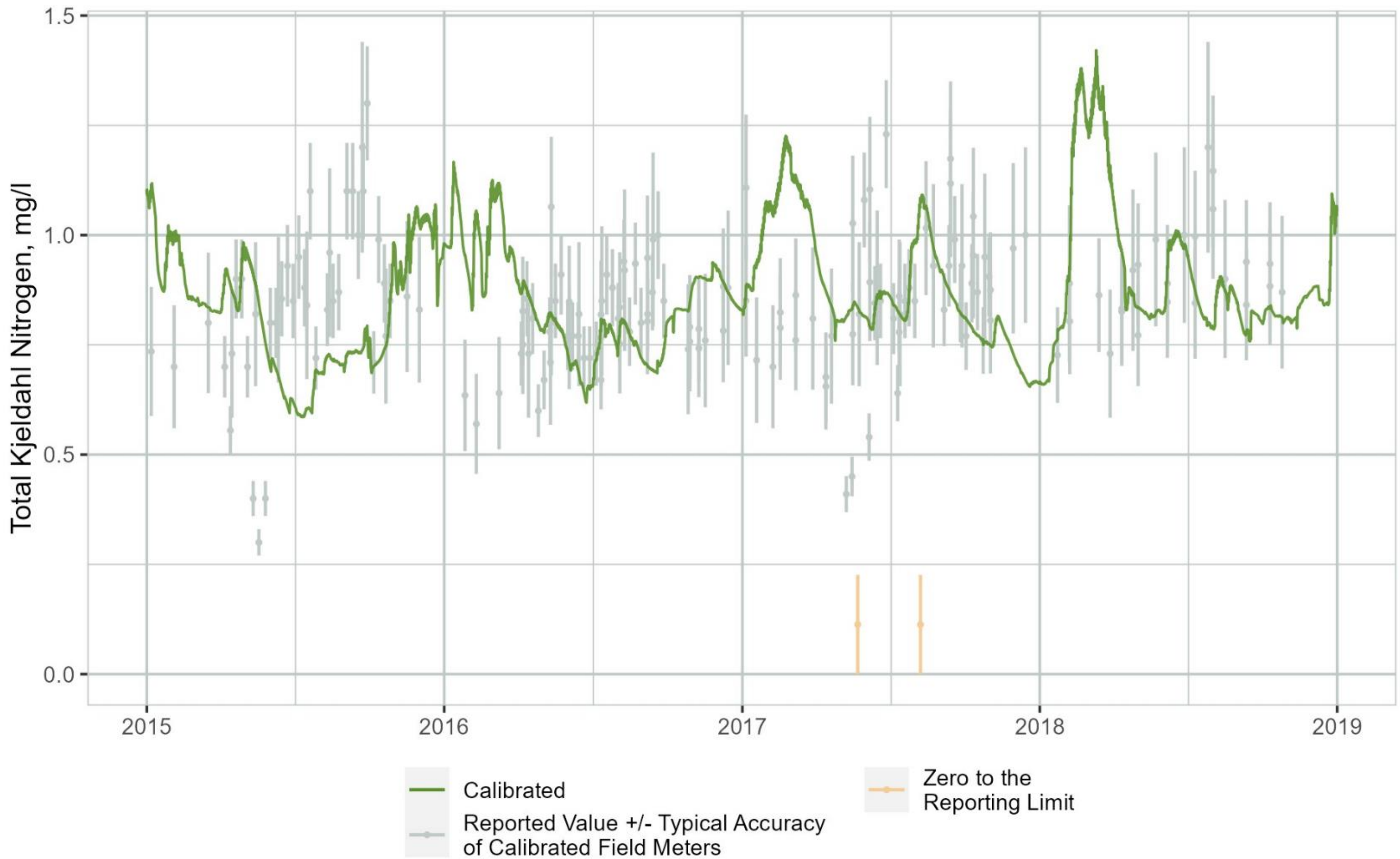

Figure B-28. Time Series Comparison of WARMF Lake Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations Collected at the Downstream End of Segment 2

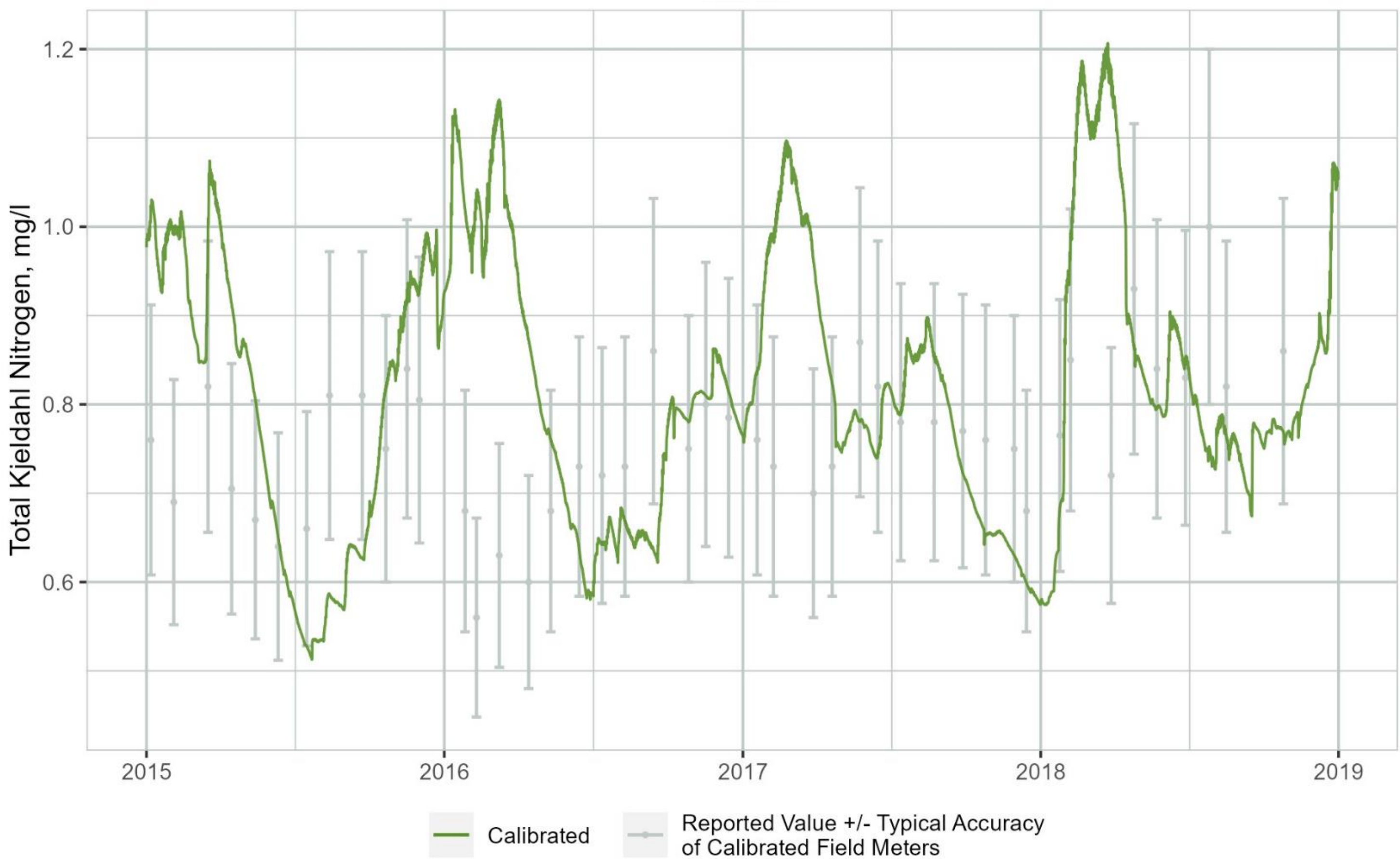

Figure B-29. Time Series Comparison of WARMF Lake Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations Collected at the Downstream End of Segment 3

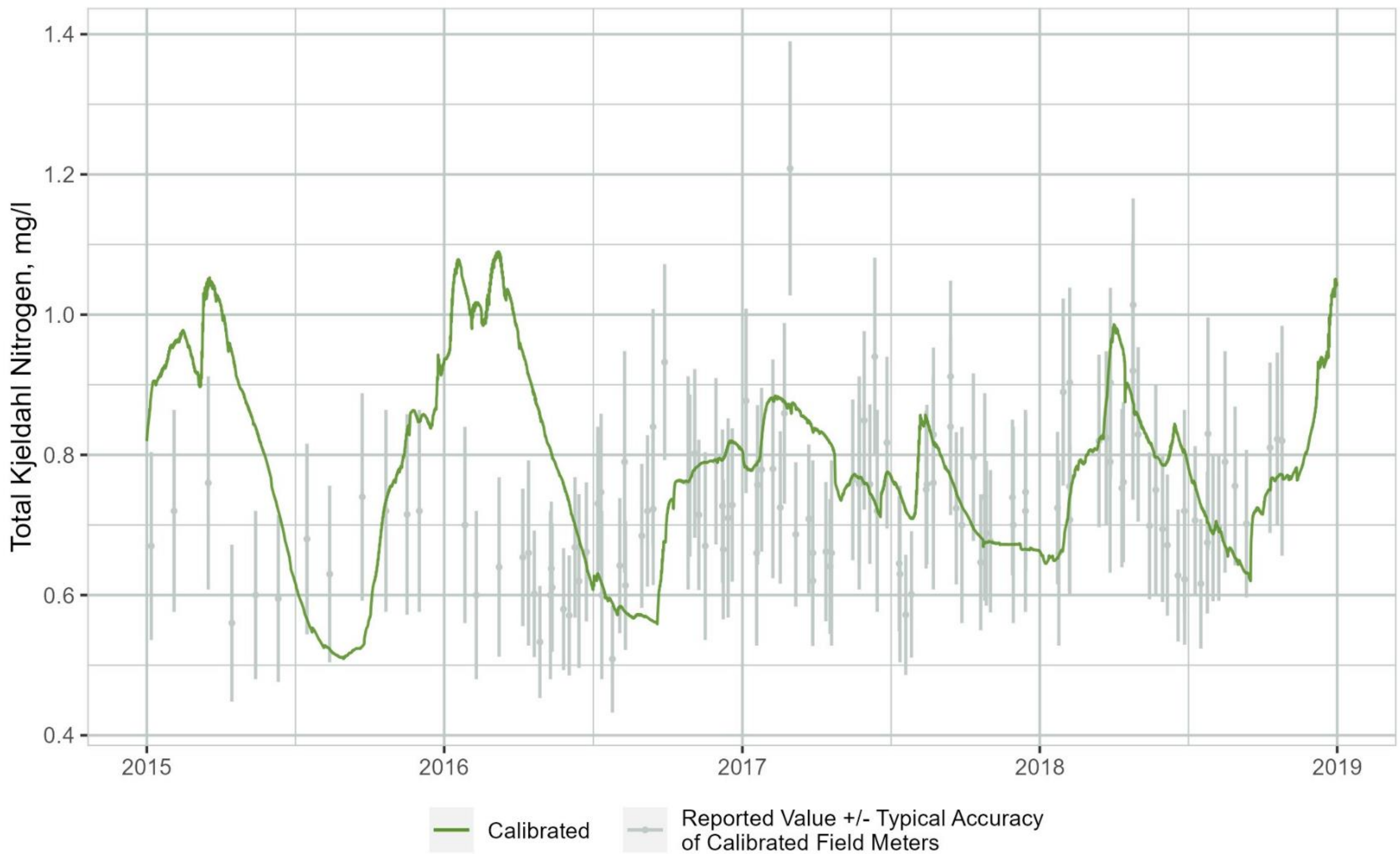

Figure B-30. Time Series Comparison of WARMF Lake Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations Collected at the Downstream End of Segment 4

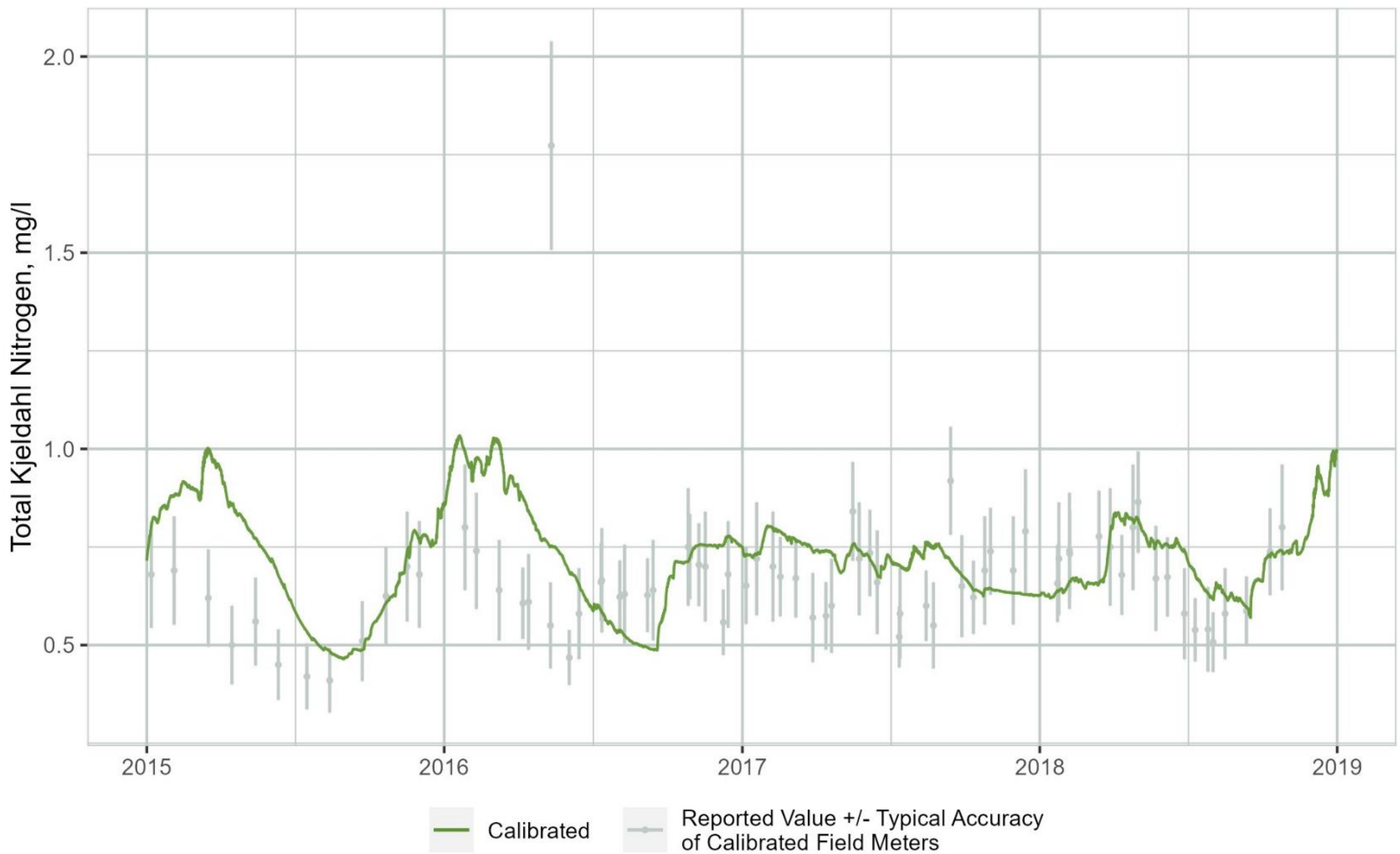

Figure B-31. Time Series Comparison of WARMF Lake Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations Collected at the Downstream End of Segment 5

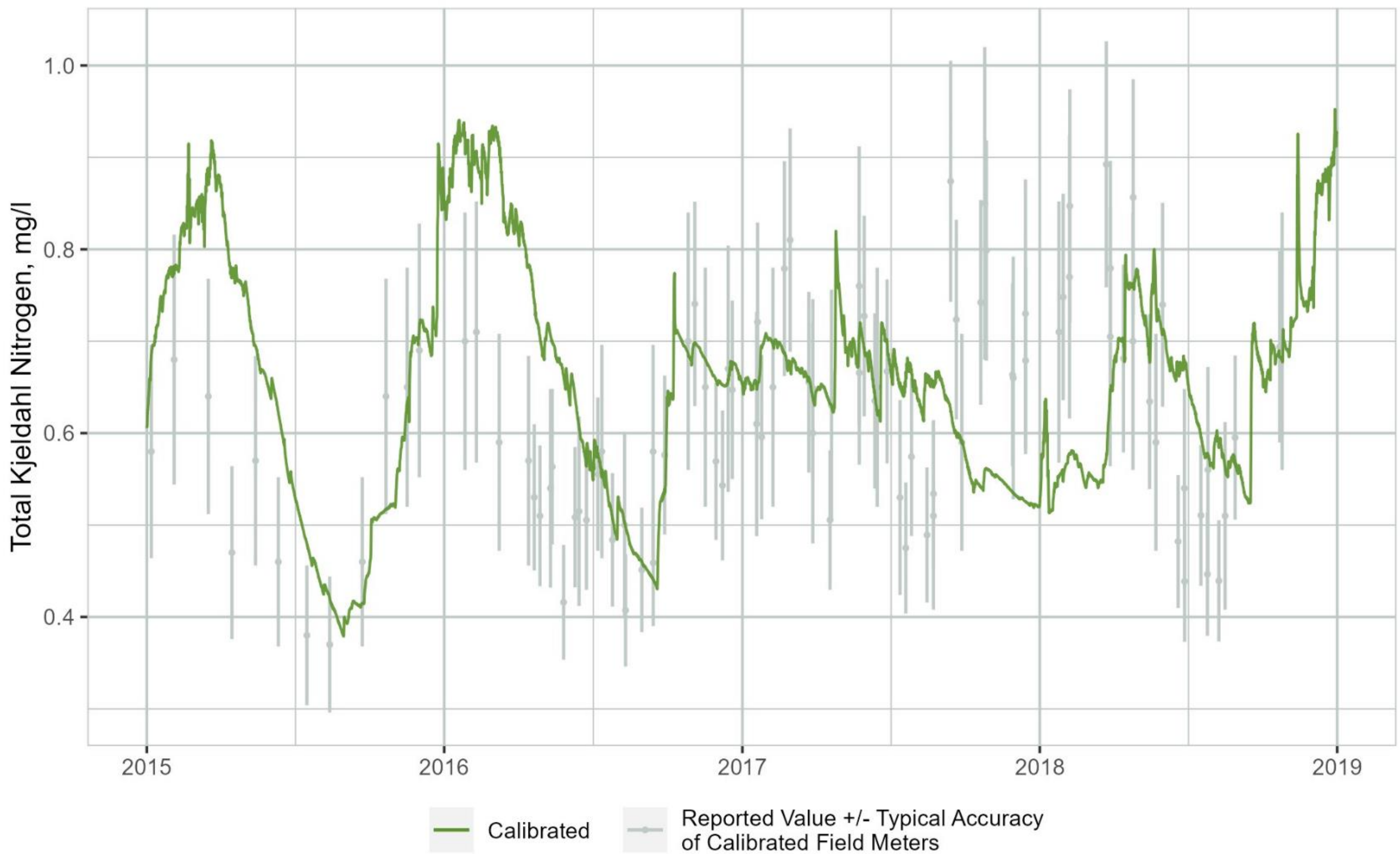

Figure B-32. Time Series Comparison of WARMF Lake Simulated Total Kjeldahl Nitrogen (TKN) Concentrations to Observations Collected at the Downstream End of Segment 6

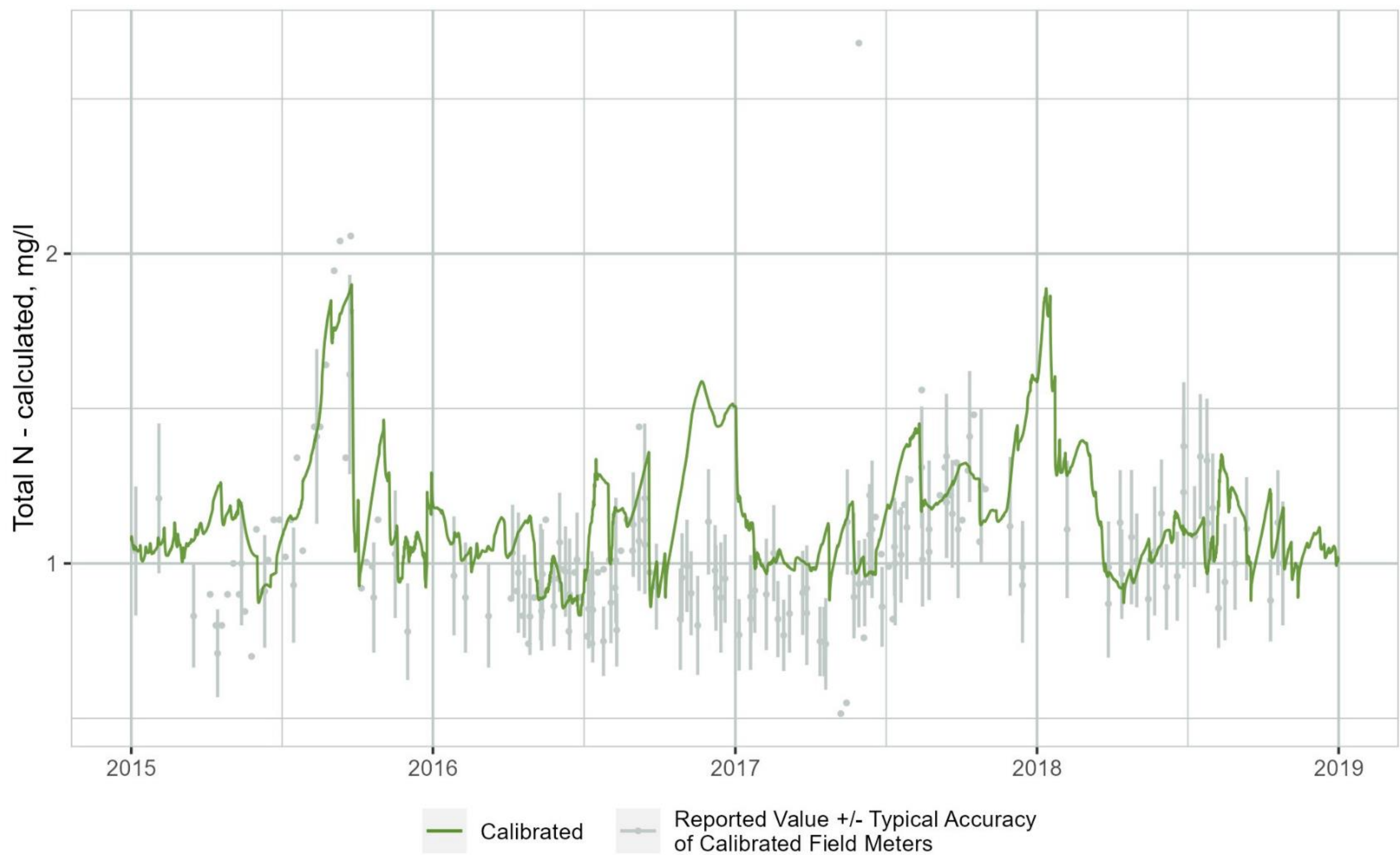

Figure B-33. Time Series Comparison of WARMF Lake Simulated Total Nitrogen (TN) Concentrations to Observations Collected at the Downstream End of Segment 1

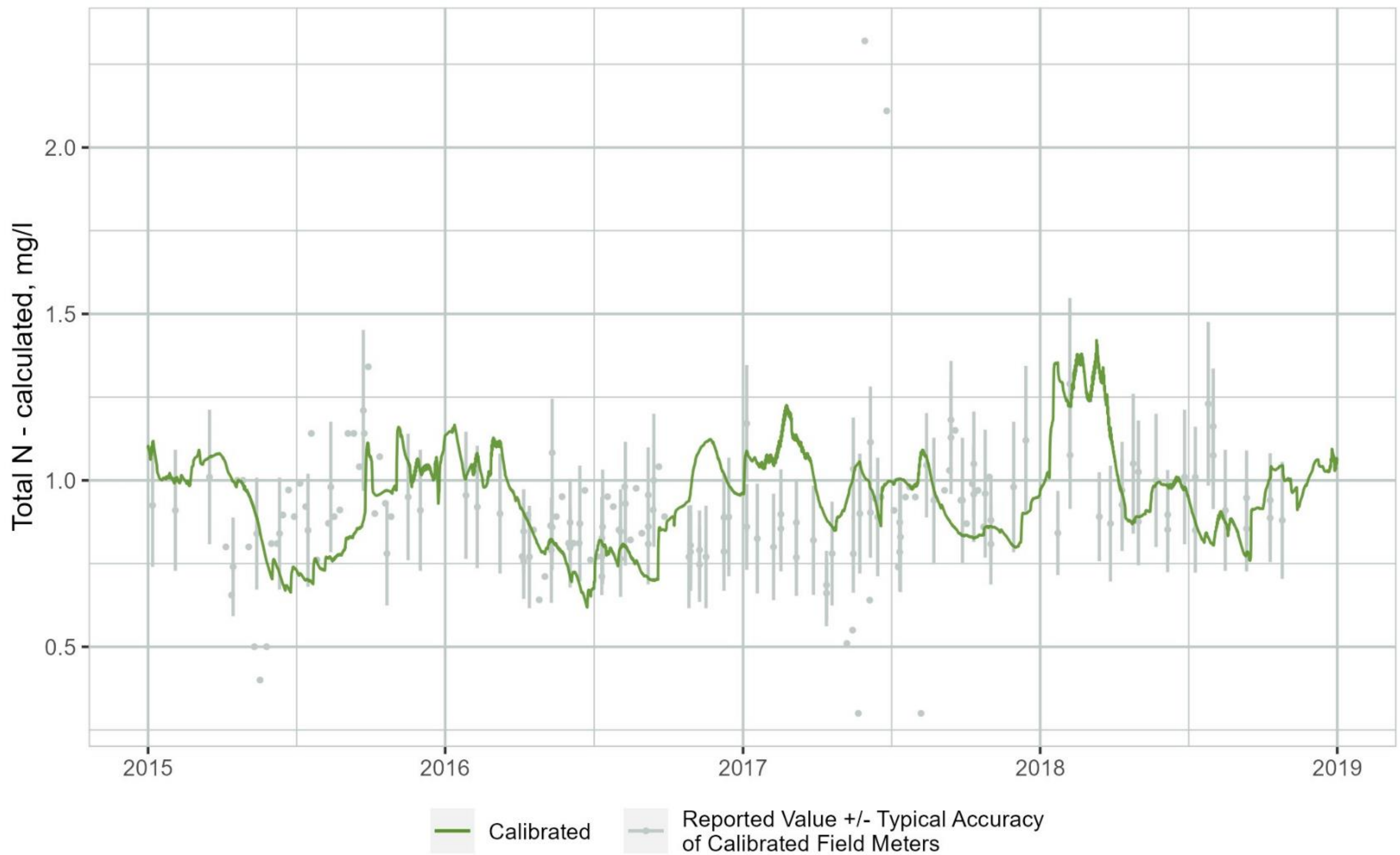

Figure B-34. Time Series Comparison of WARMF Lake Simulated Total Nitrogen (TN) Concentrations to Observations Collected at the Downstream End of Segment 2

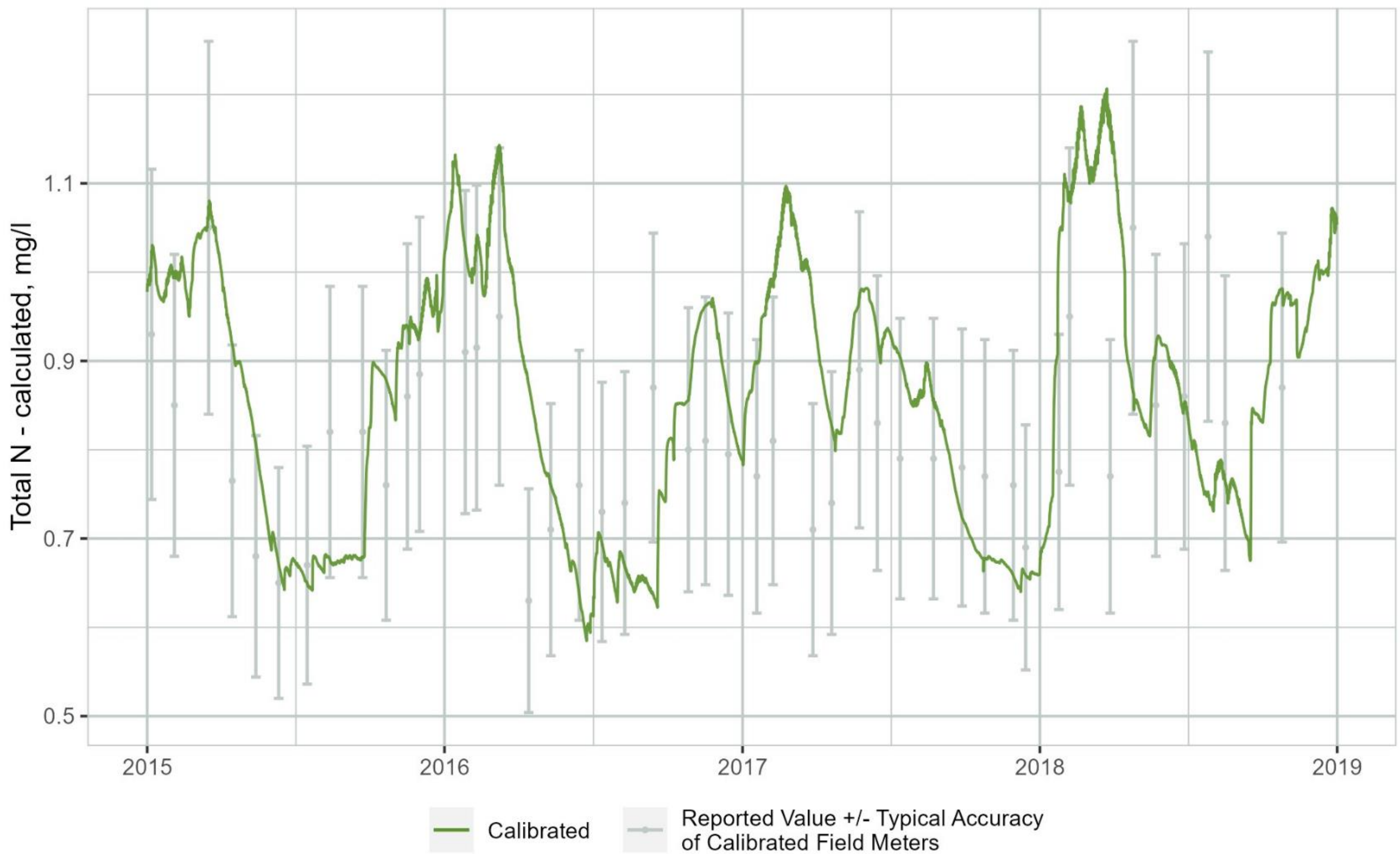

Figure B-35. Time Series Comparison of WARMF Lake Simulated Total Nitrogen (TN) Concentrations to Observations Collected at the Downstream End of Segment 3

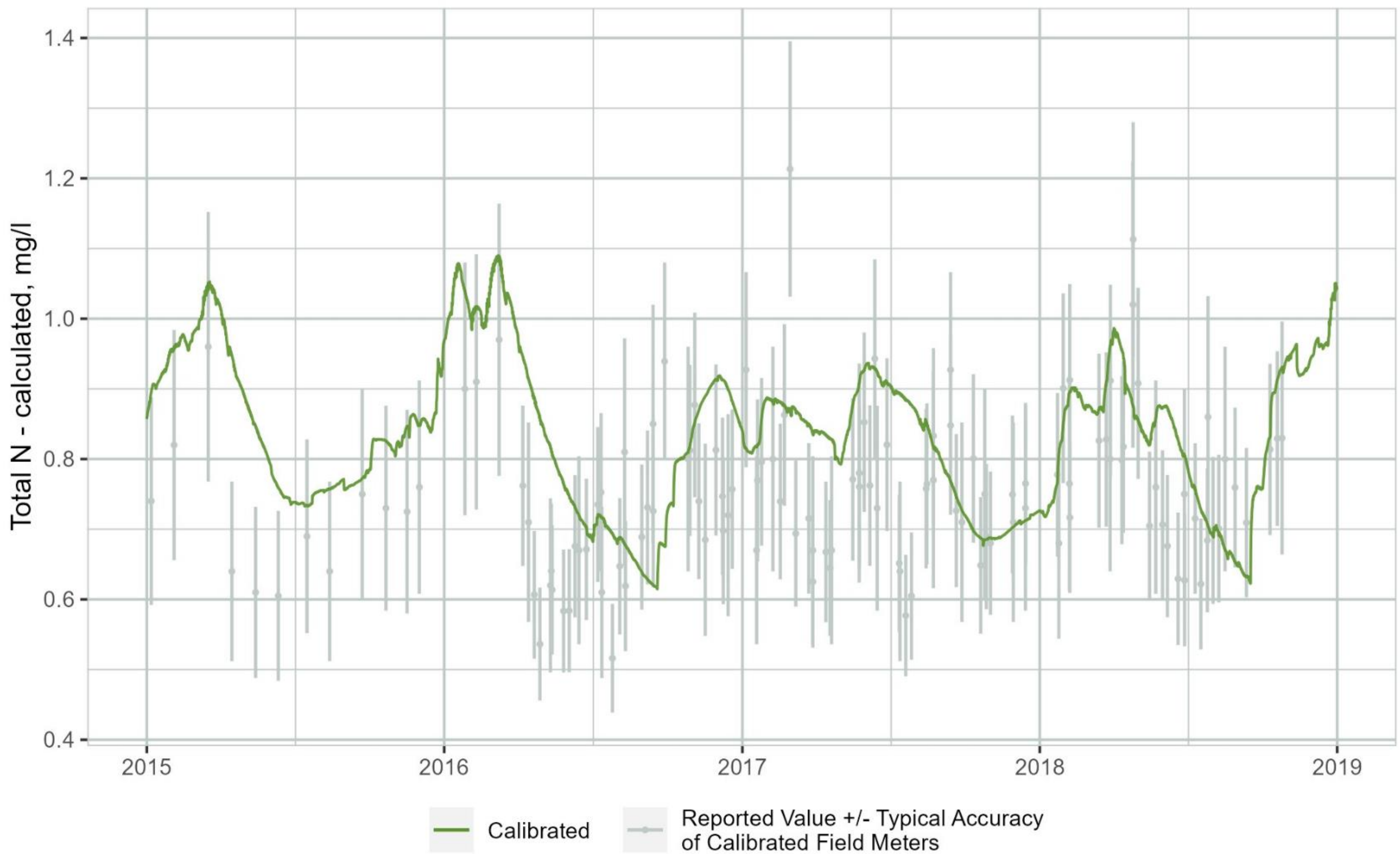

Figure B-36. Time Series Comparison of WARMF Lake Simulated Total Nitrogen (TN) Concentrations to Observations Collected at the Downstream End of Segment 4

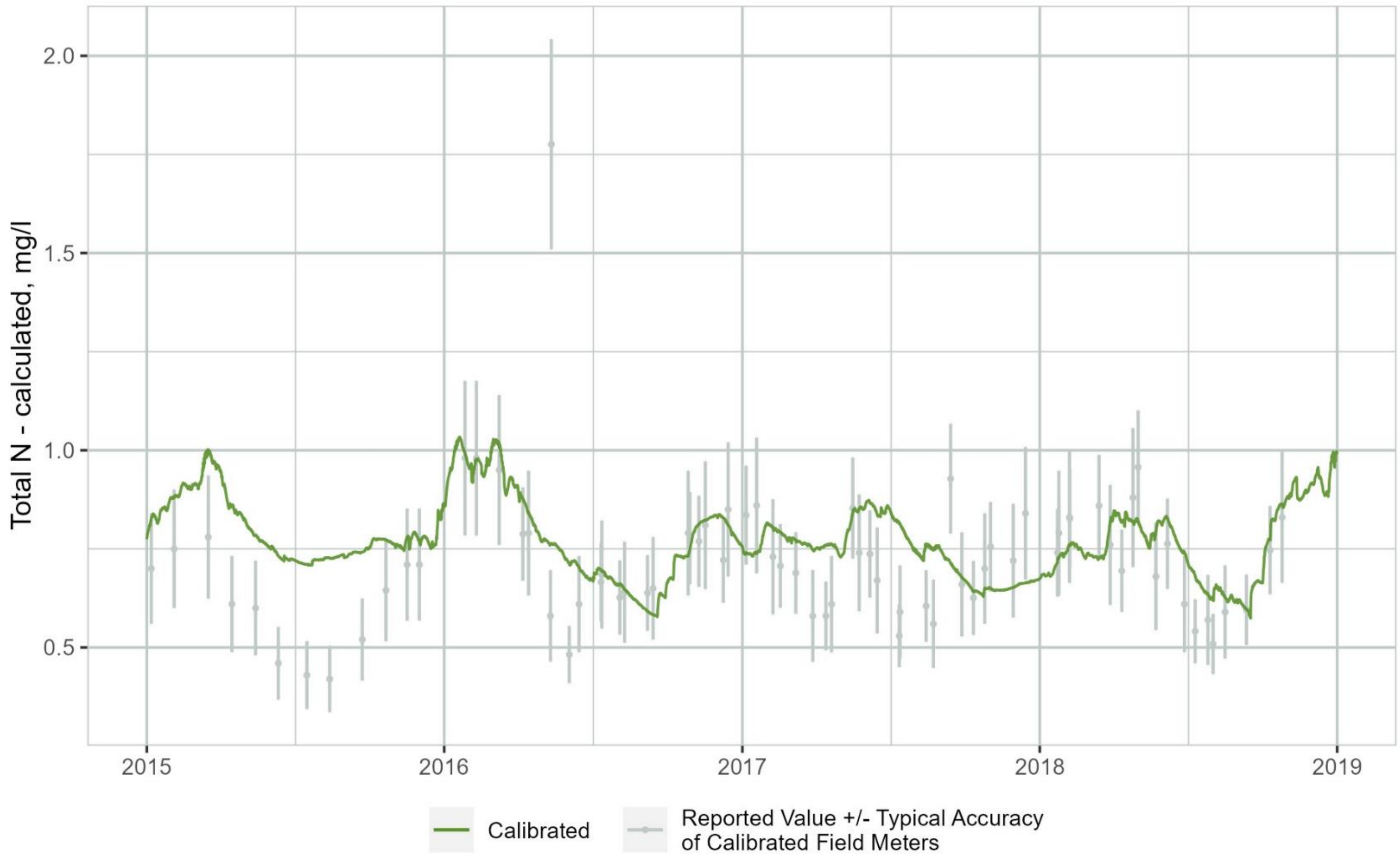

Figure B-37. Time Series Comparison of WARMF Lake Simulated Total Nitrogen (TN) Concentrations to Observations Collected at the Downstream End of Segment 5

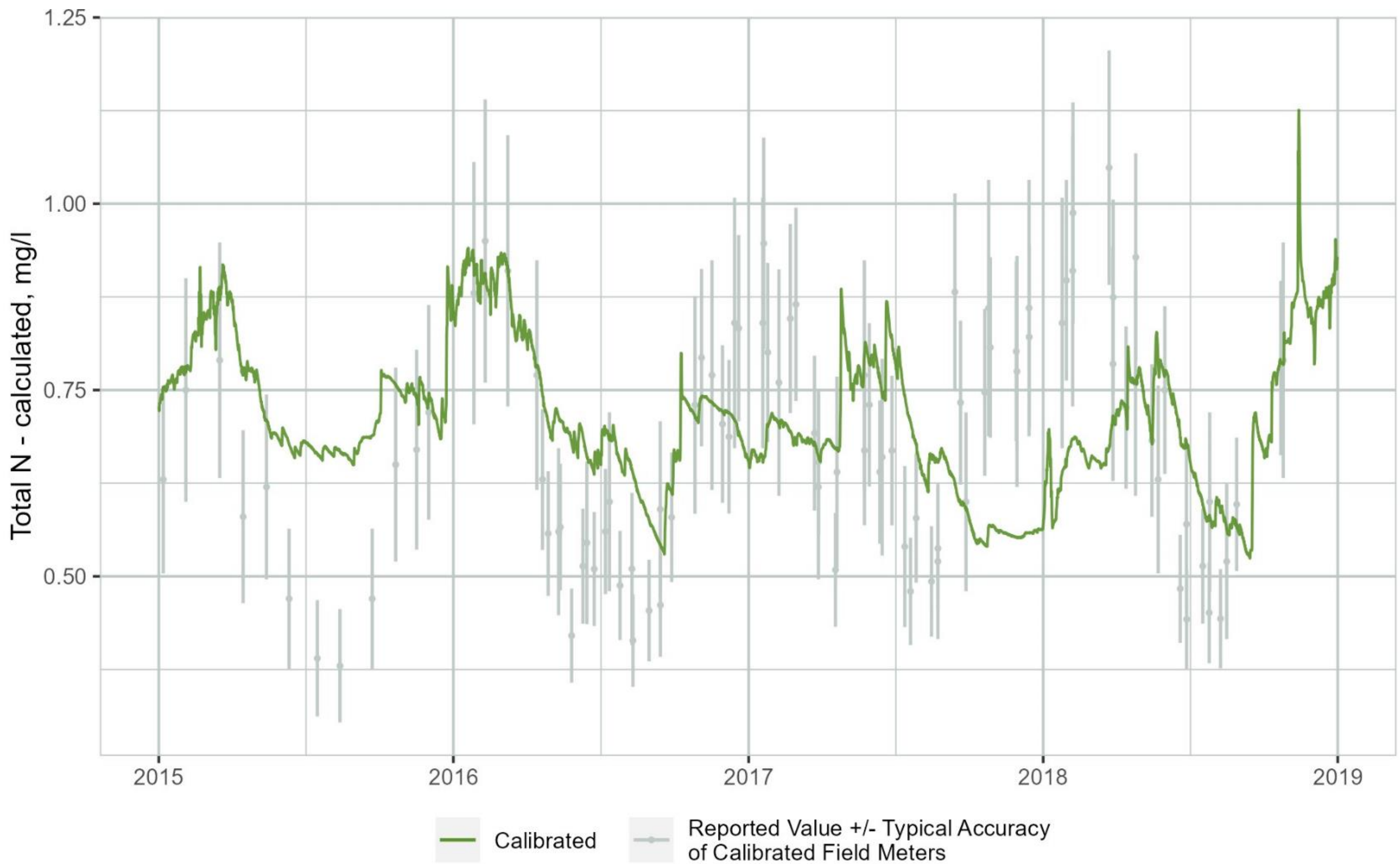

Figure B-38. Time Series Comparison of WARMF Lake Simulated Total Nitrogen (TN) Concentrations to Observations Collected at the Downstream End of Segment 6

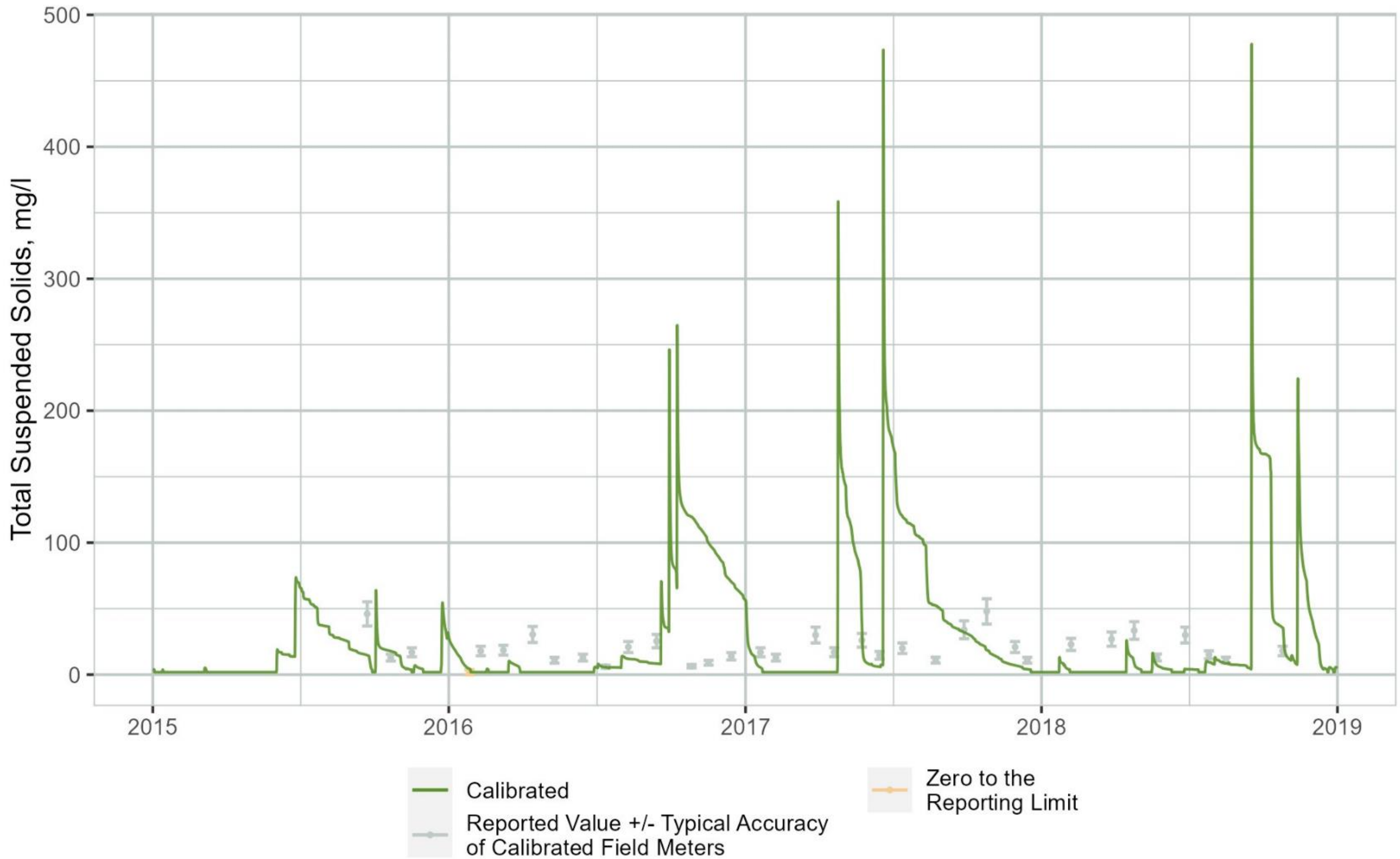

Figure B-39. Time Series Comparison of WARMF Lake Simulated Total Suspended Sediment (TSS) Concentrations to Observations Collected at the Downstream End of Segment 1

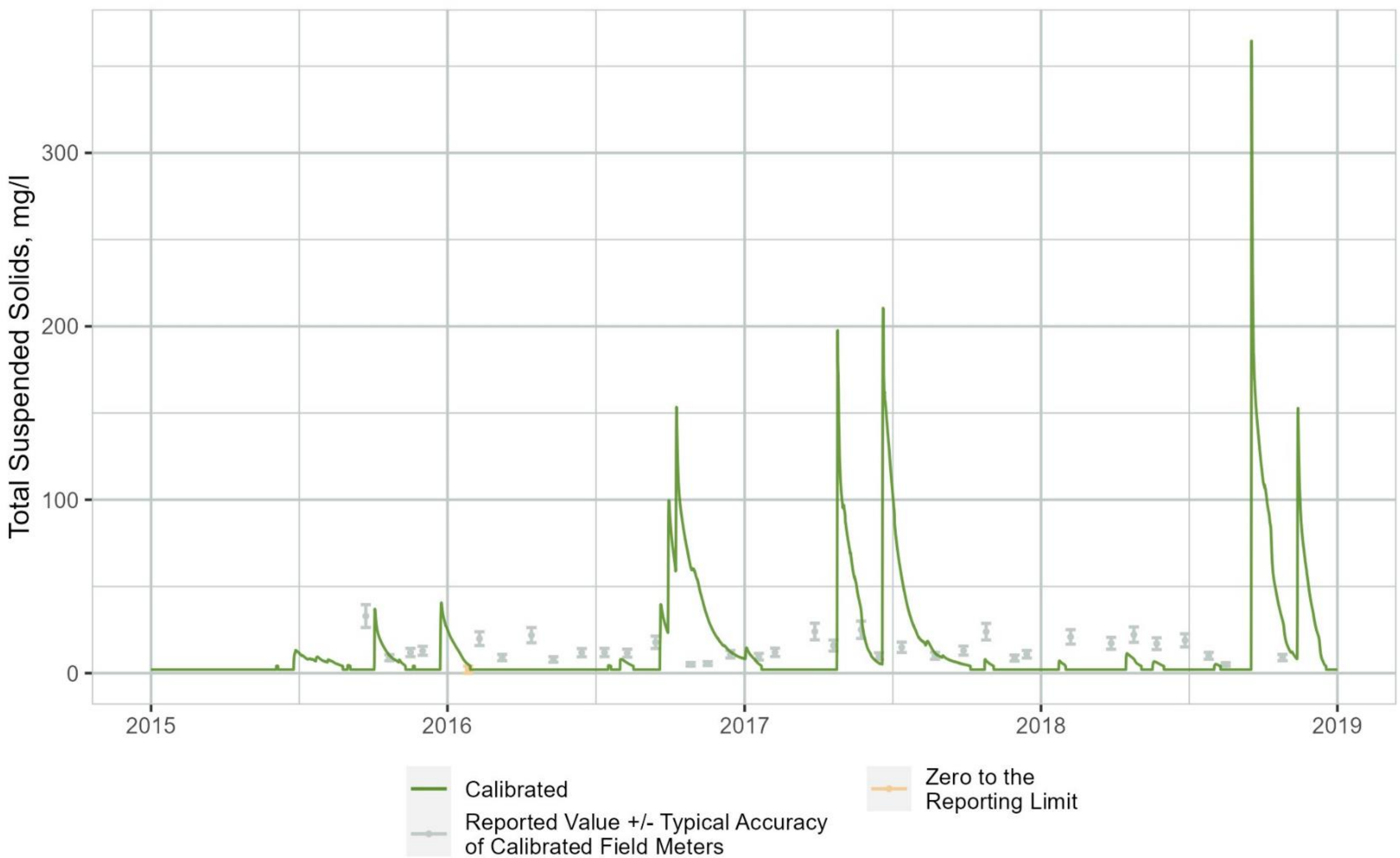

Figure B-40. Time Series Comparison of WARMF Lake Simulated Total Suspended Sediment (TSS) Concentrations to Observations Collected at the Downstream End of Segment 2

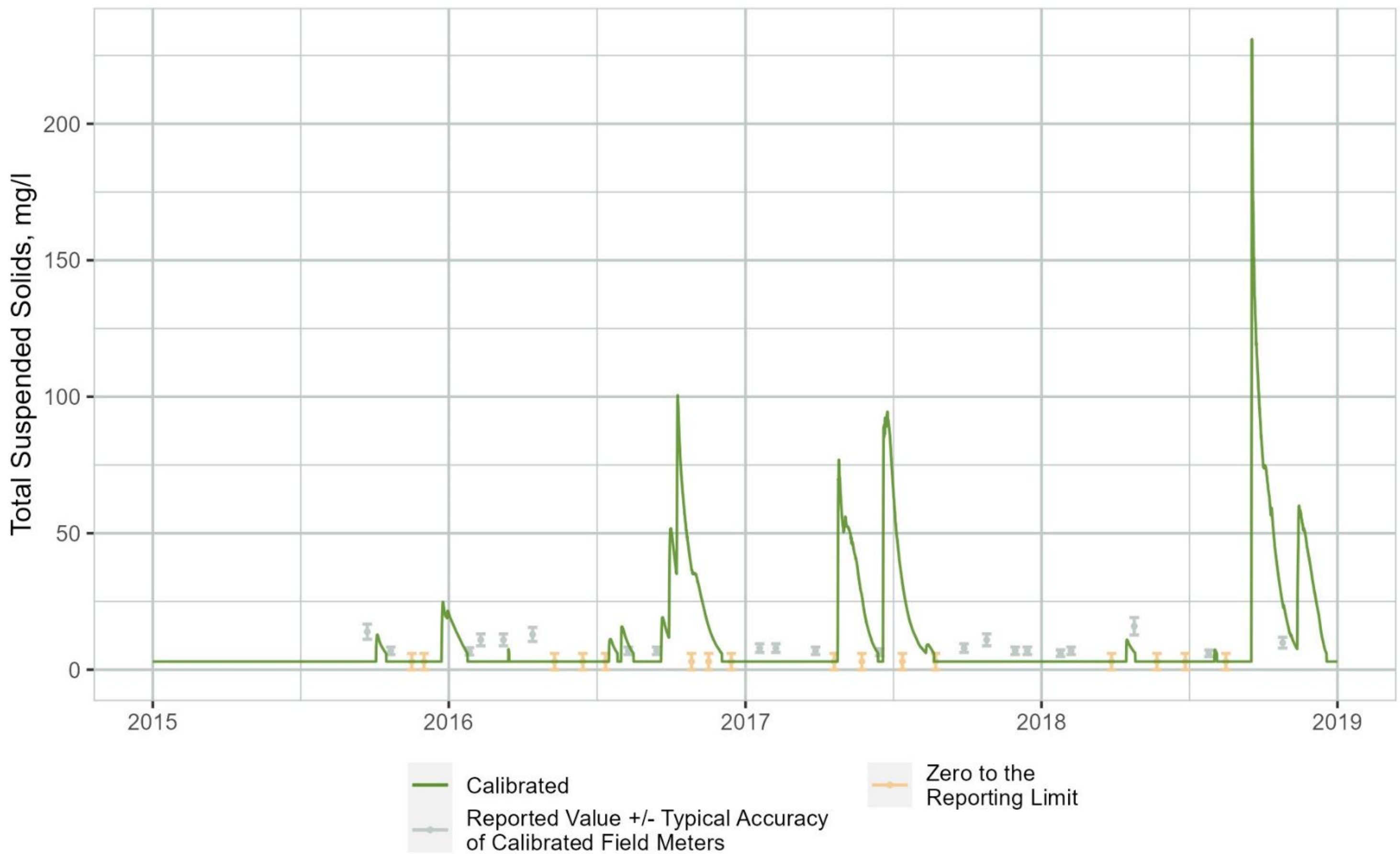

Figure B-41. Time Series Comparison of WARMF Lake Simulated Total Suspended Sediment (TSS) Concentrations to Observations Collected at the Downstream End of Segment 3

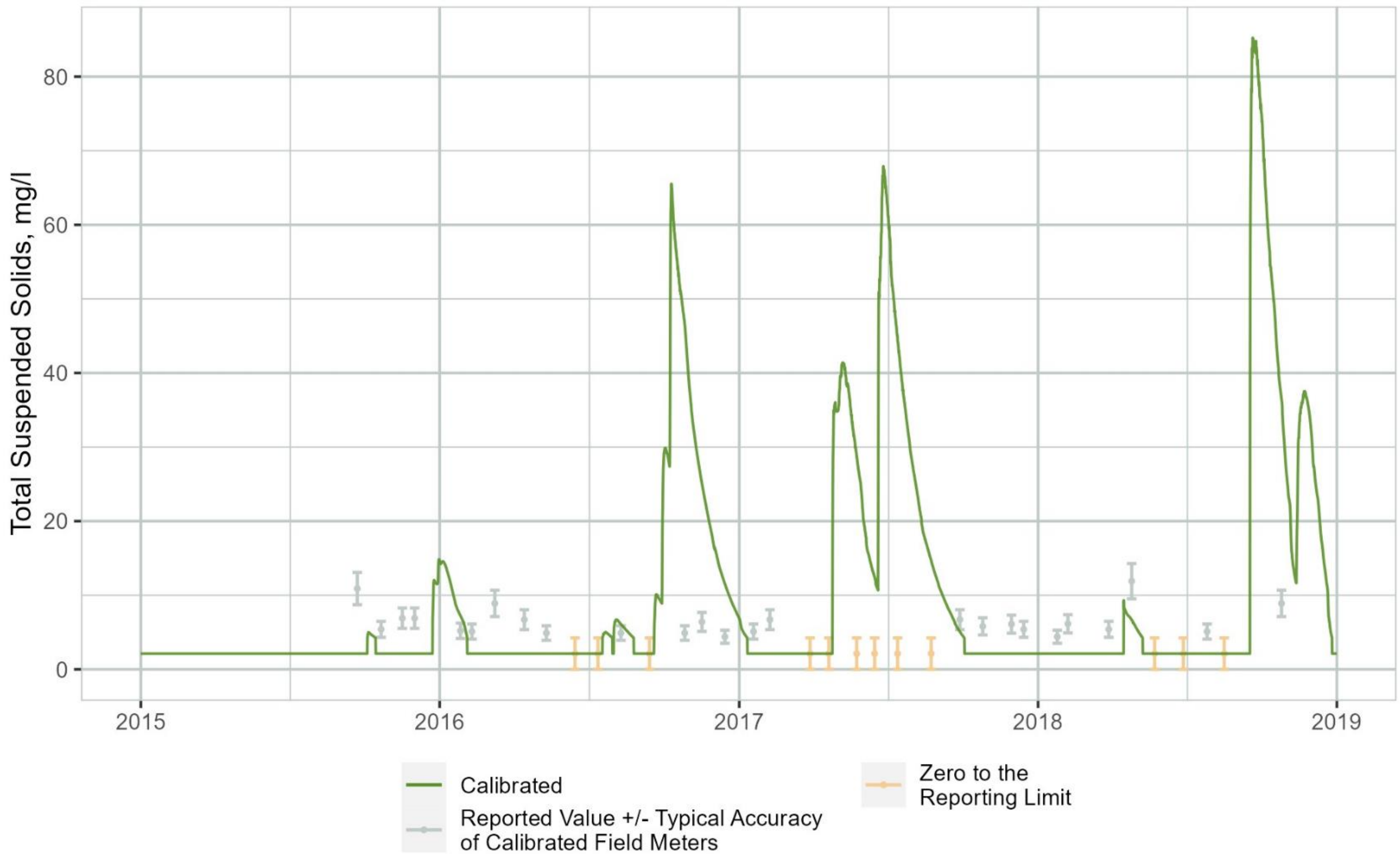

Figure B-42. Time Series Comparison of WARMF Lake Simulated Total Suspended Sediment (TSS) Concentrations to Observations Collected at the Downstream End of Segment 4

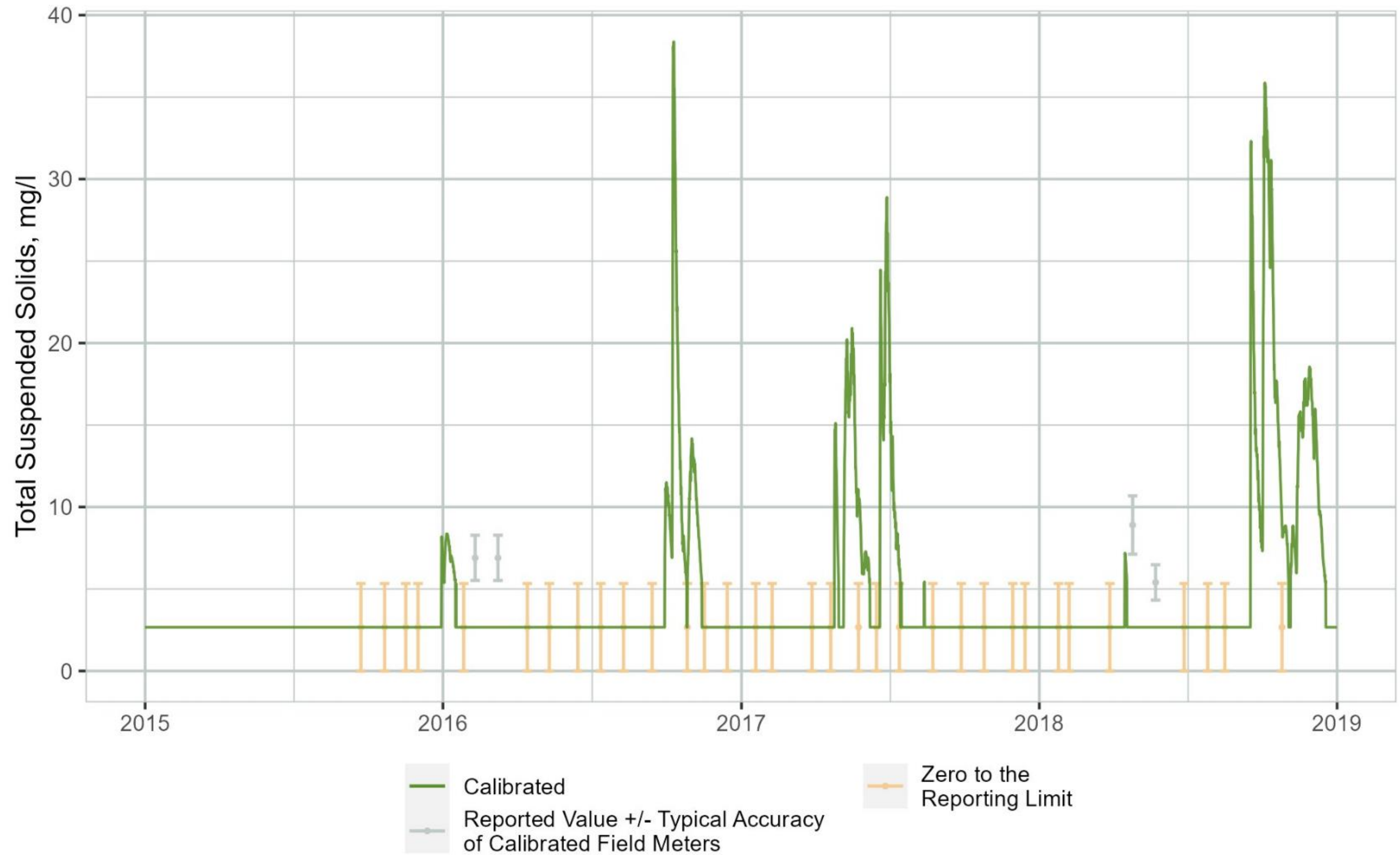

Figure B-43. Time Series Comparison of WARMF Lake Simulated Total Suspended Sediment (TSS) Concentrations to Observations Collected at the Downstream End of Segment 5

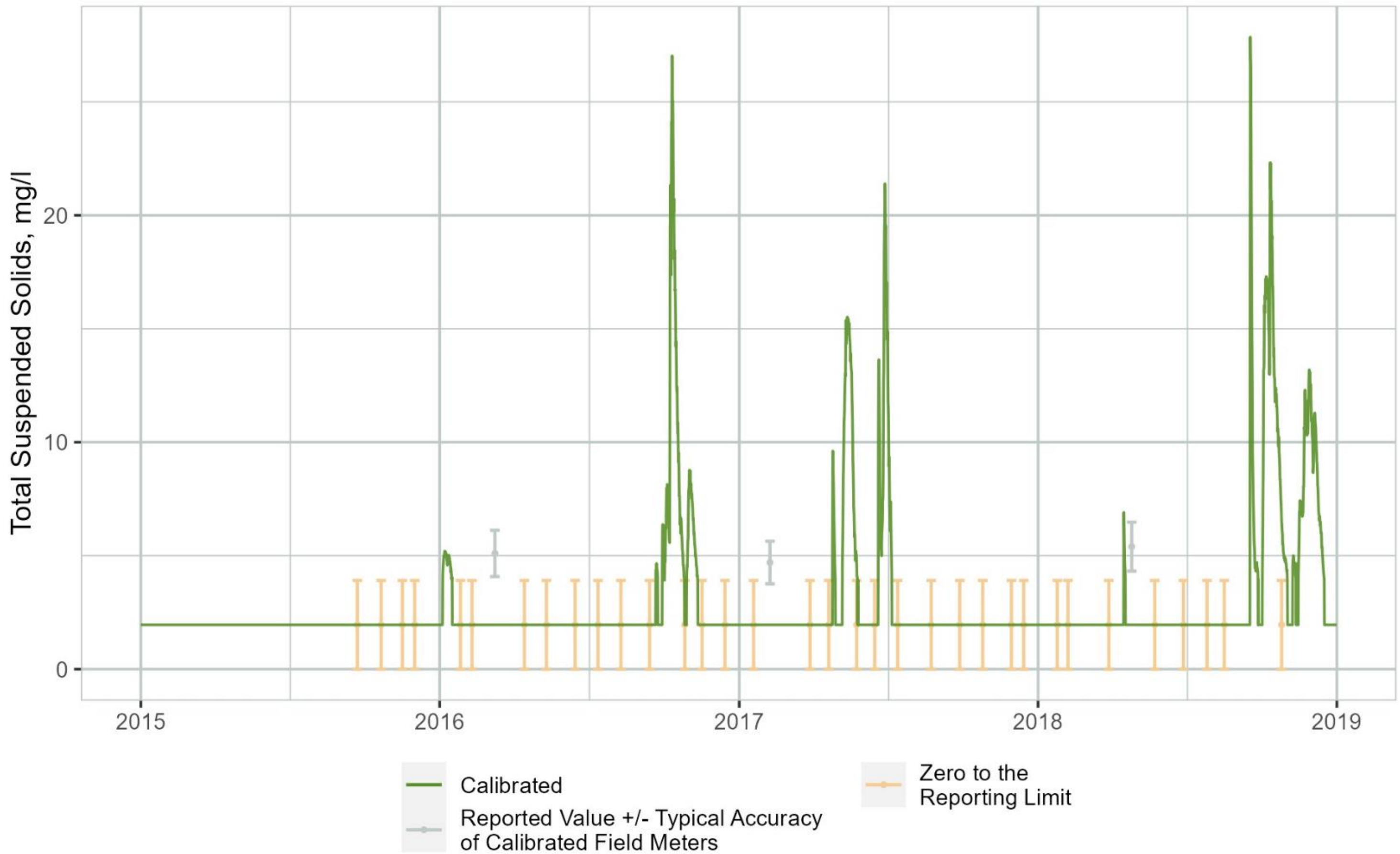

Figure B-44. Time Series Comparison of WARMF Lake Simulated Total Suspended Sediment (TSS) Concentrations to Observations Collected at the Downstream End of Segment 6

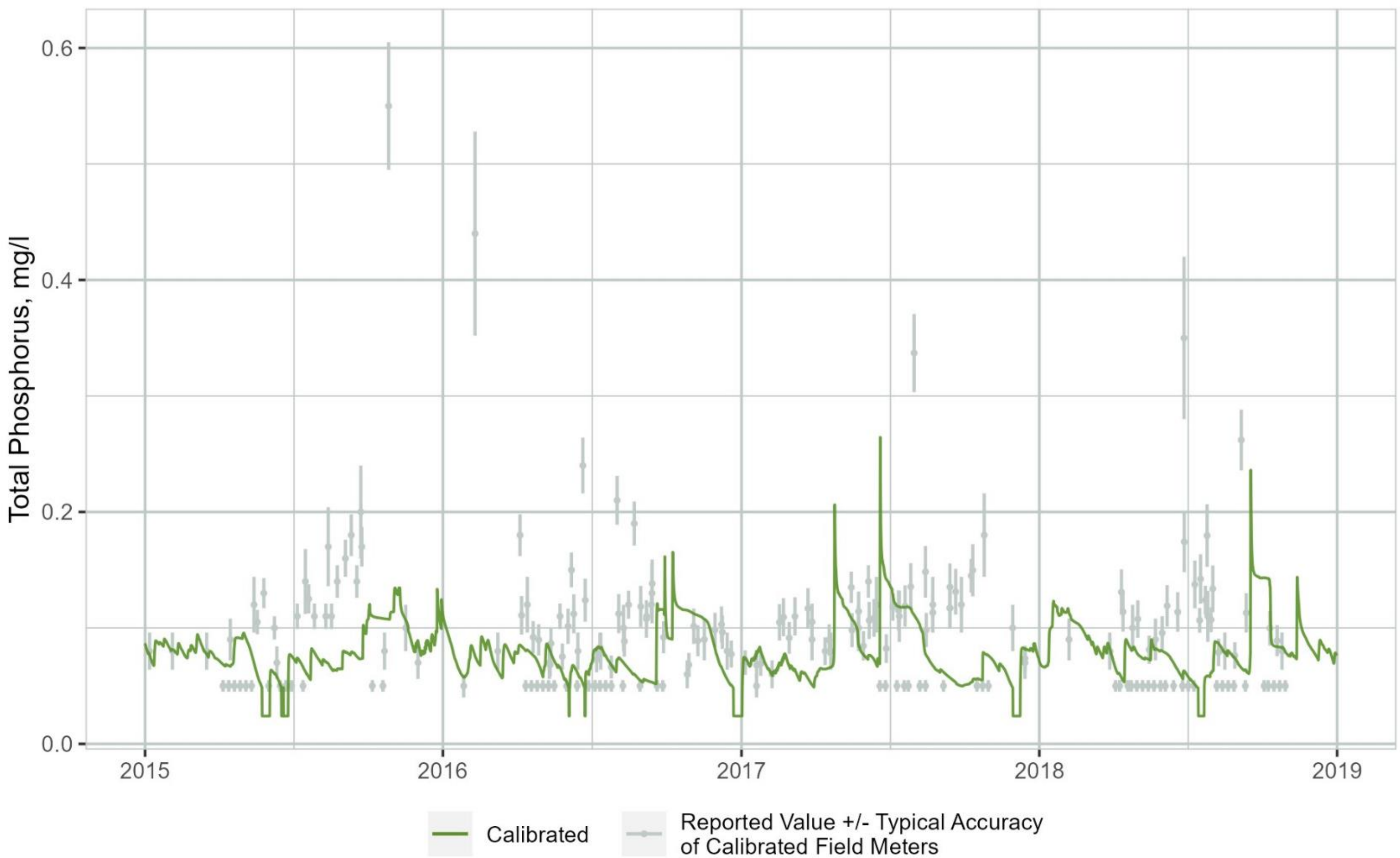

Figure B-45. Time Series Comparison of WARMF Lake Simulated Total Phosphorus (TP) Concentrations to Observations Collected at the Downstream End of Segment 1

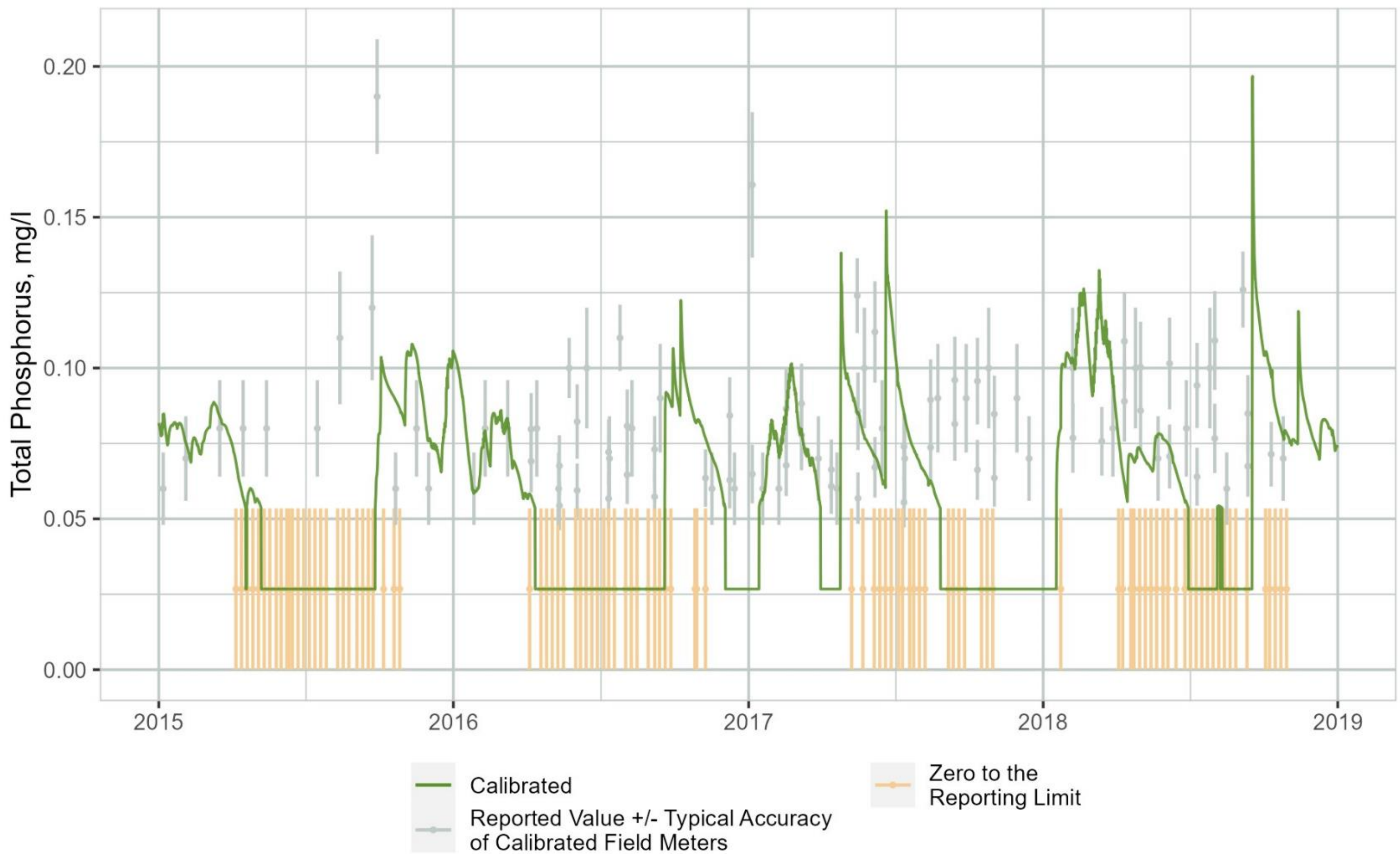

Figure B-46. Time Series Comparison of WARMF Lake Simulated Total Phosphorus (TP) Concentrations to Observations Collected at the Downstream End of Segment 2

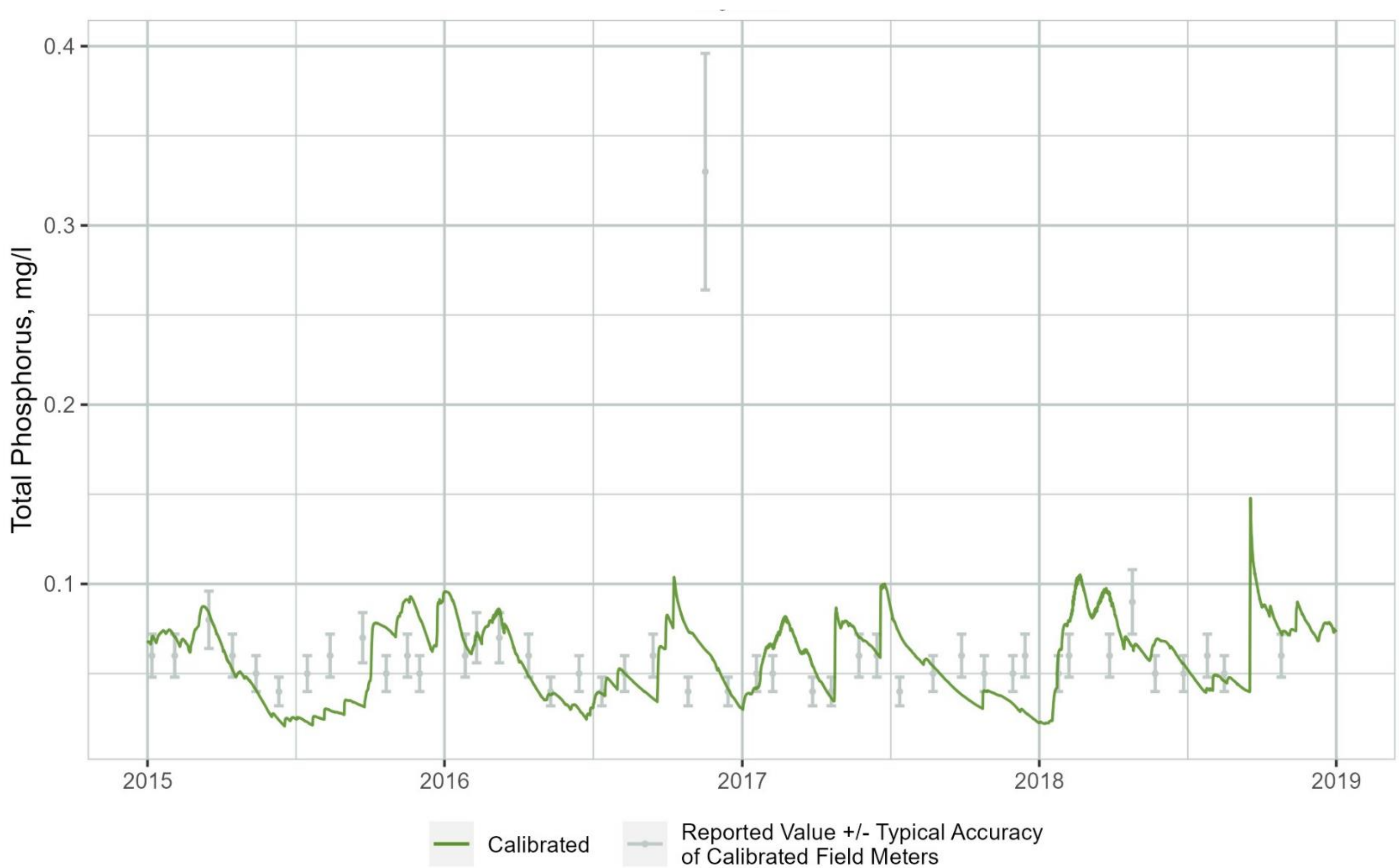

Figure B-47. Time Series Comparison of WARMF Lake Simulated Total Phosphorus (TP) Concentrations to Observations Collected at the Downstream End of Segment 3

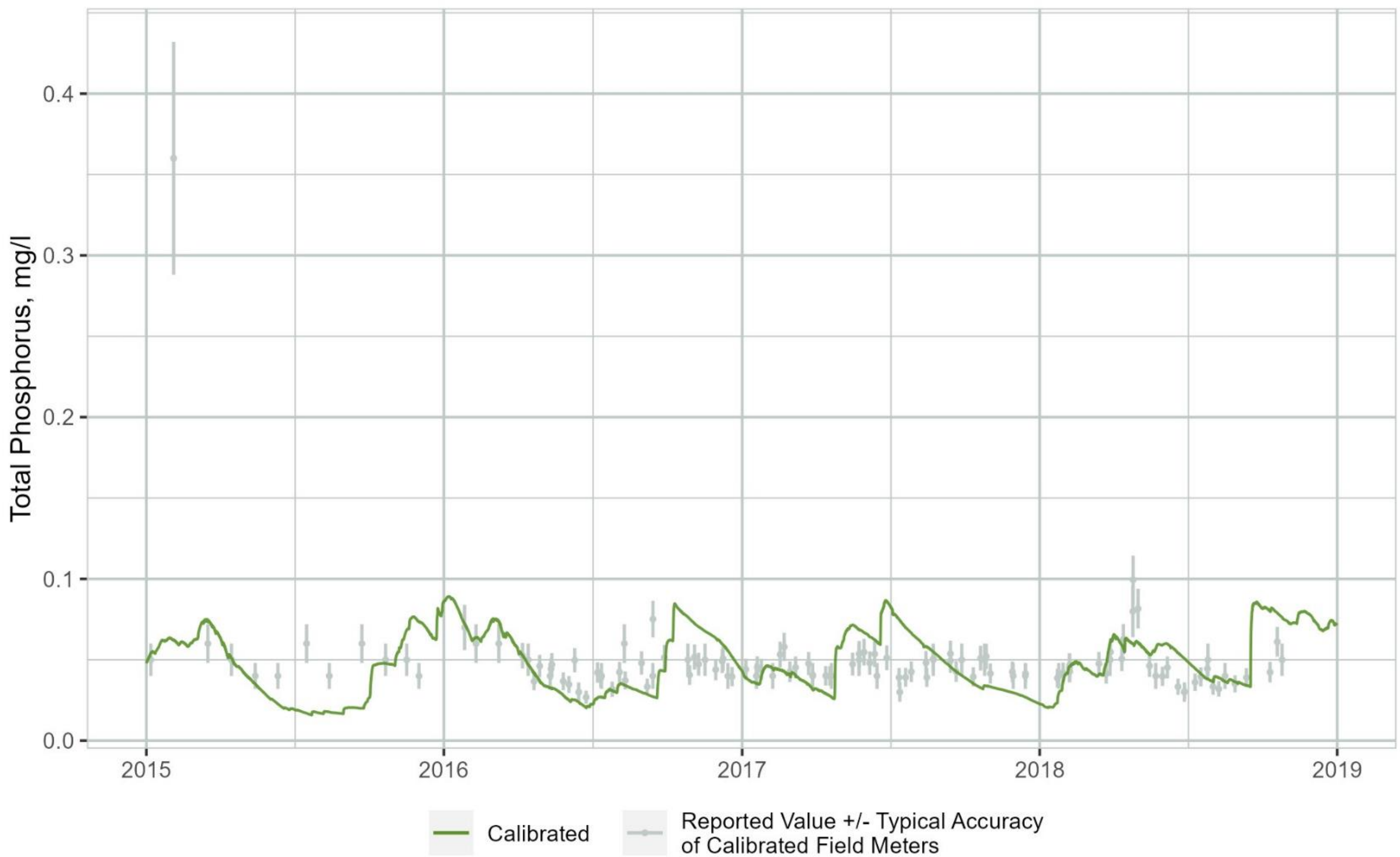

Figure B-48. Time Series Comparison of WARMF Lake Simulated Total Phosphorus (TP) Concentrations to Observations Collected at the Downstream End of Segment 4

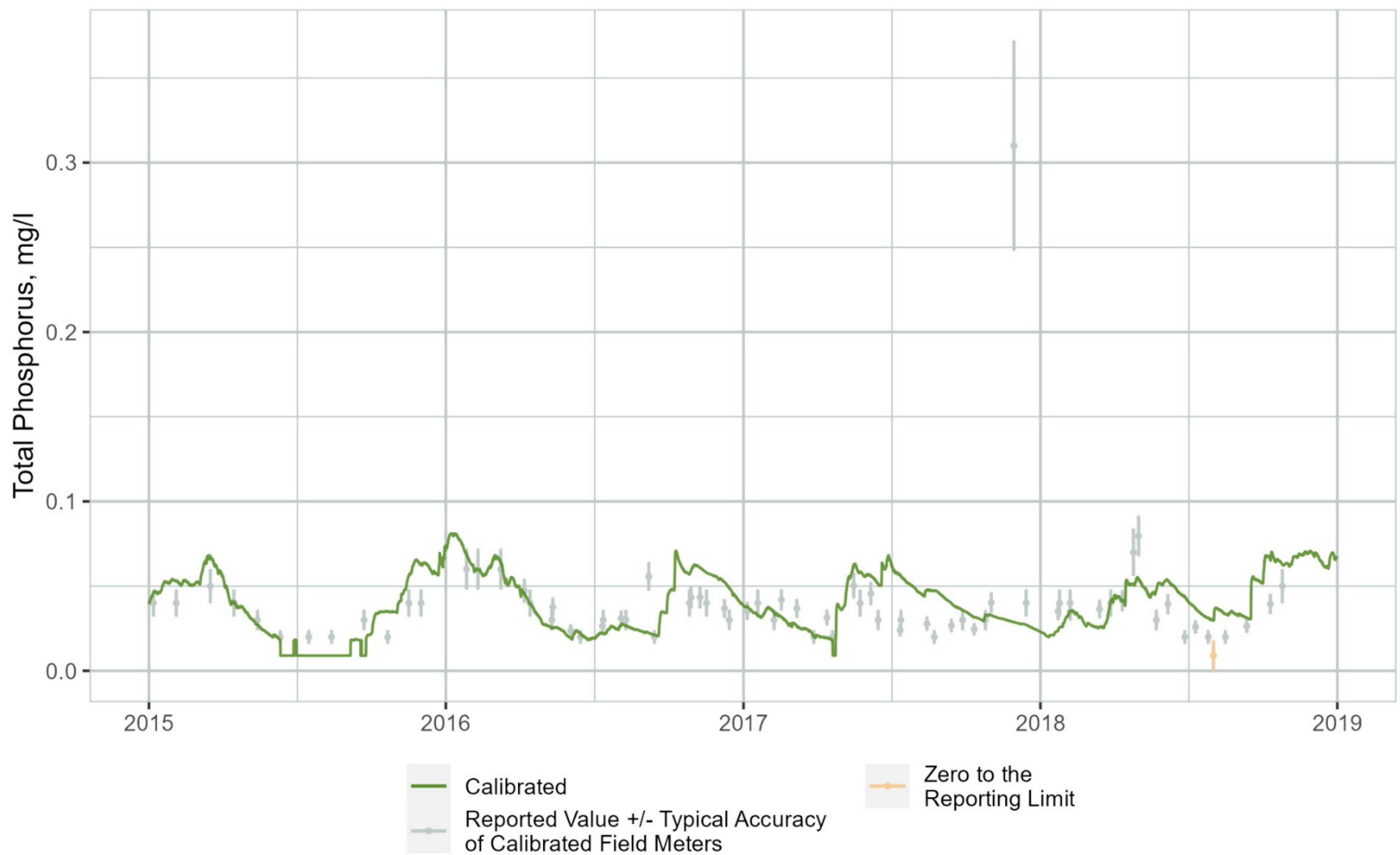

Figure B-49. Time Series Comparison of WARMF Lake Simulated Total Phosphorus (TP) Concentrations to Observations Collected at the Downstream End of Segment 5

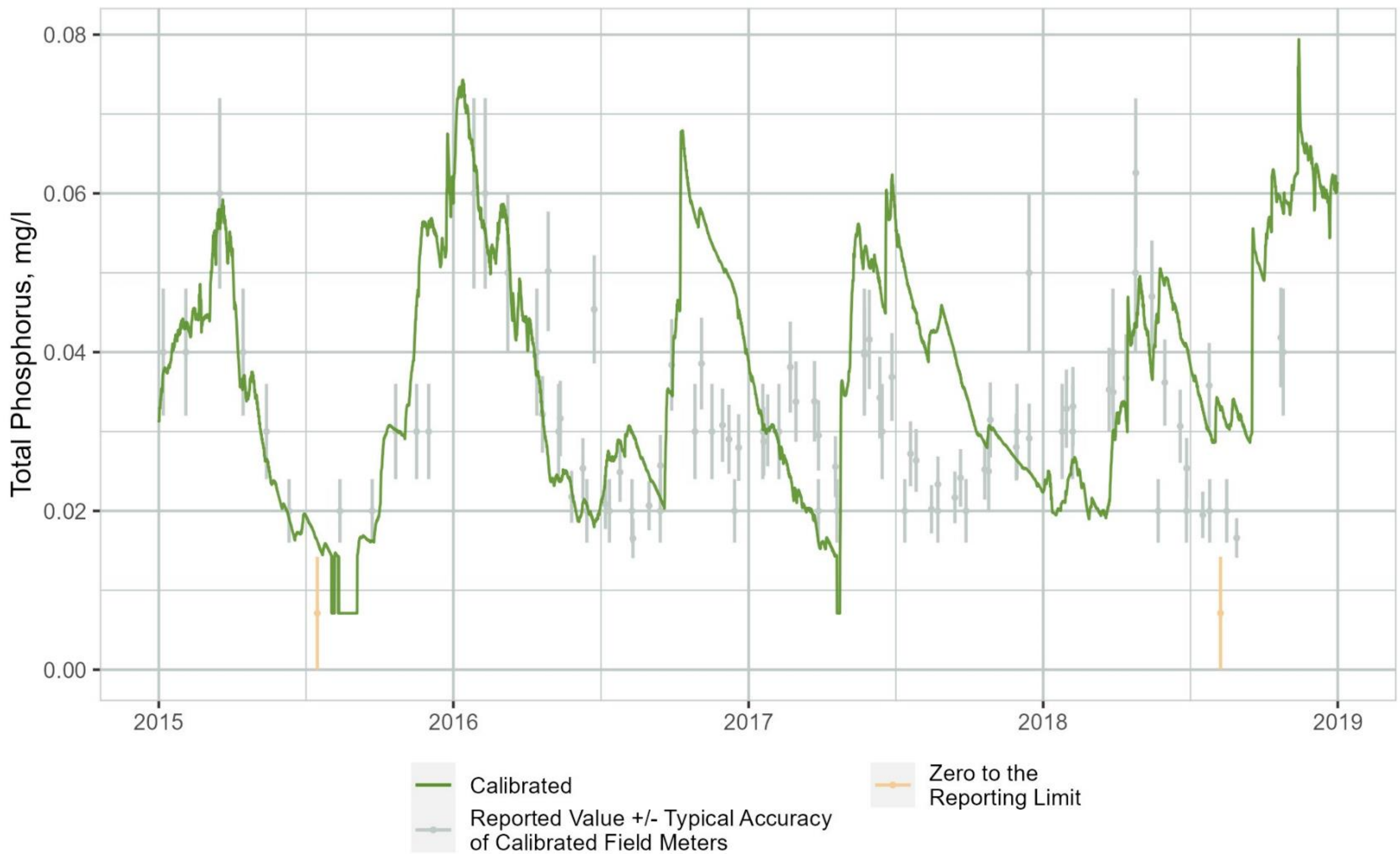

Figure B-50. Time Series Comparison of WARMF Lake Simulated Total Phosphorus (TP) Concentrations to Observations Collected at the Downstream End of Segment 6

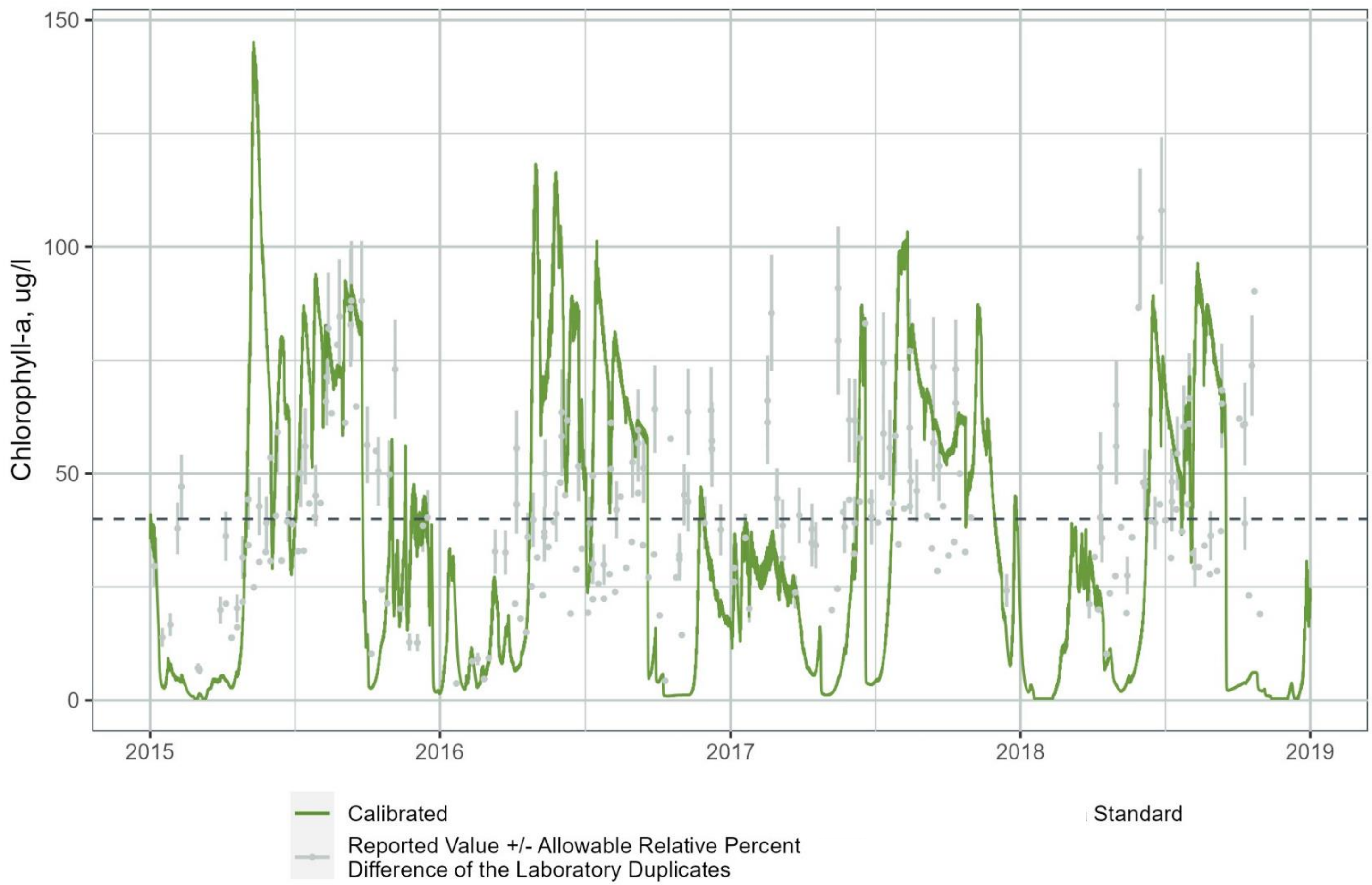

Figure B-51. Time Series Comparison of WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected at the Downstream End of Segment 1

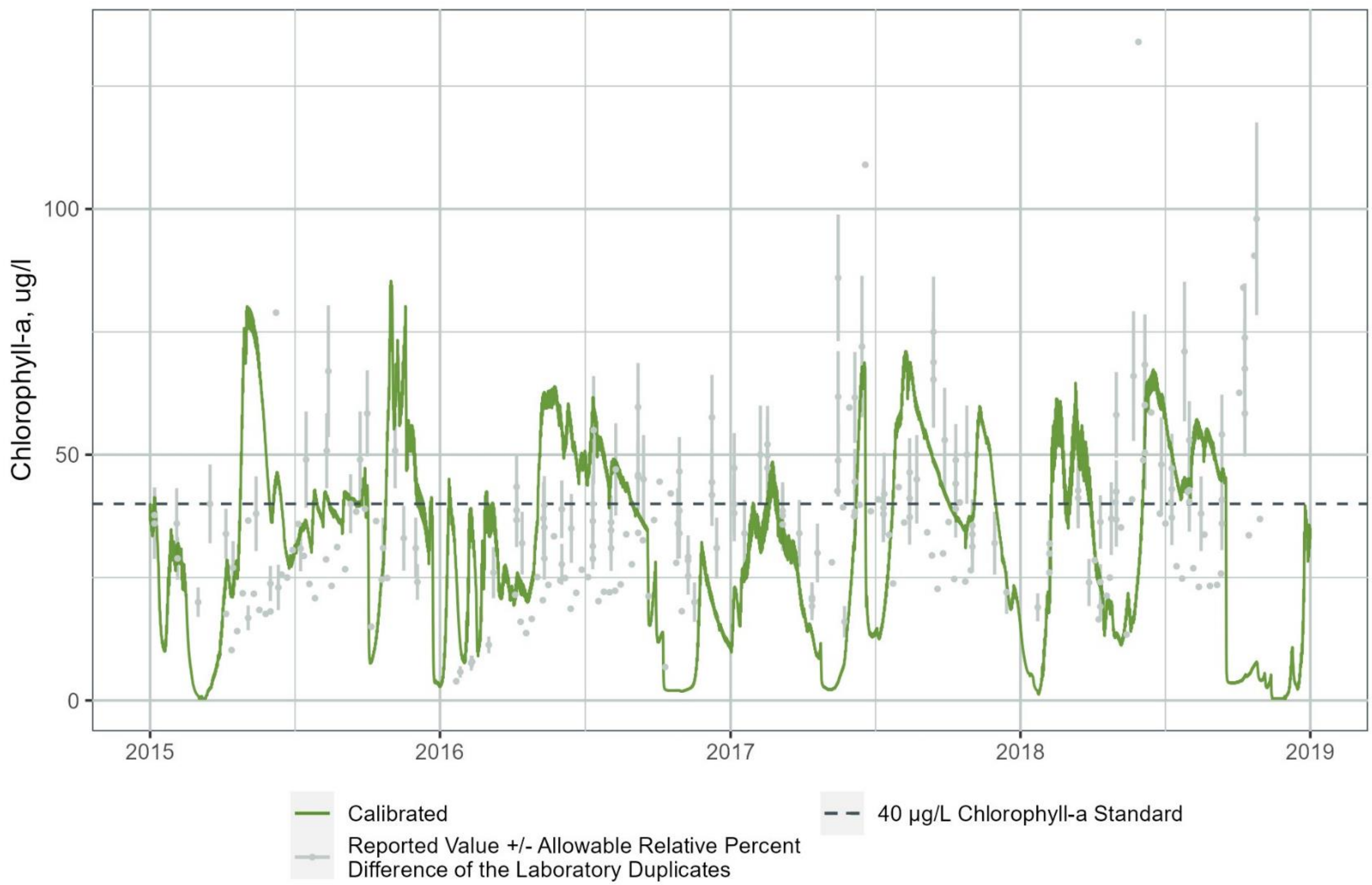

Figure B-52. Time Series Comparison of WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected at the Downstream End of Segment 2

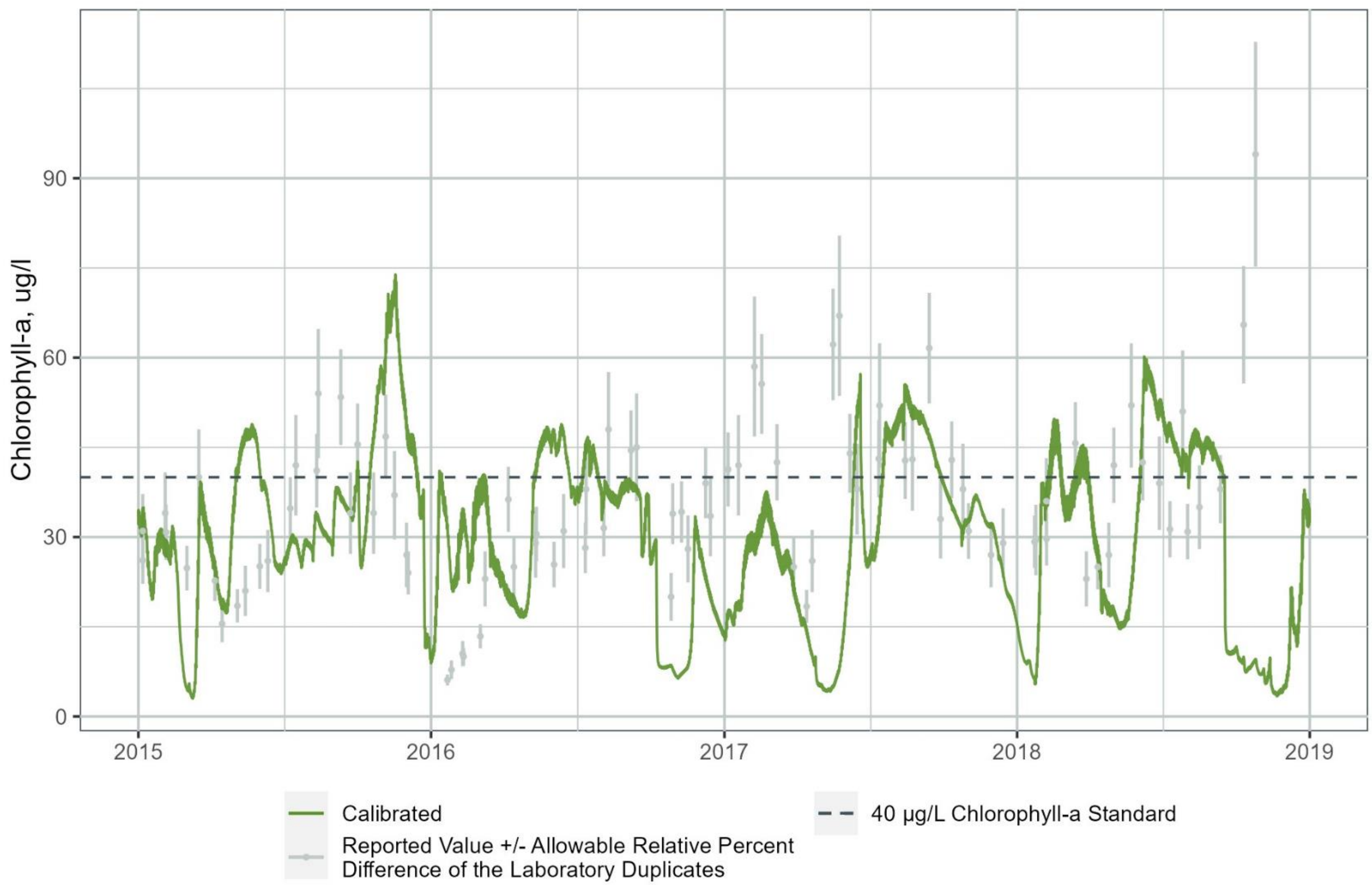

Figure B-53. Time Series Comparison of WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected at the Downstream End of Segment 3

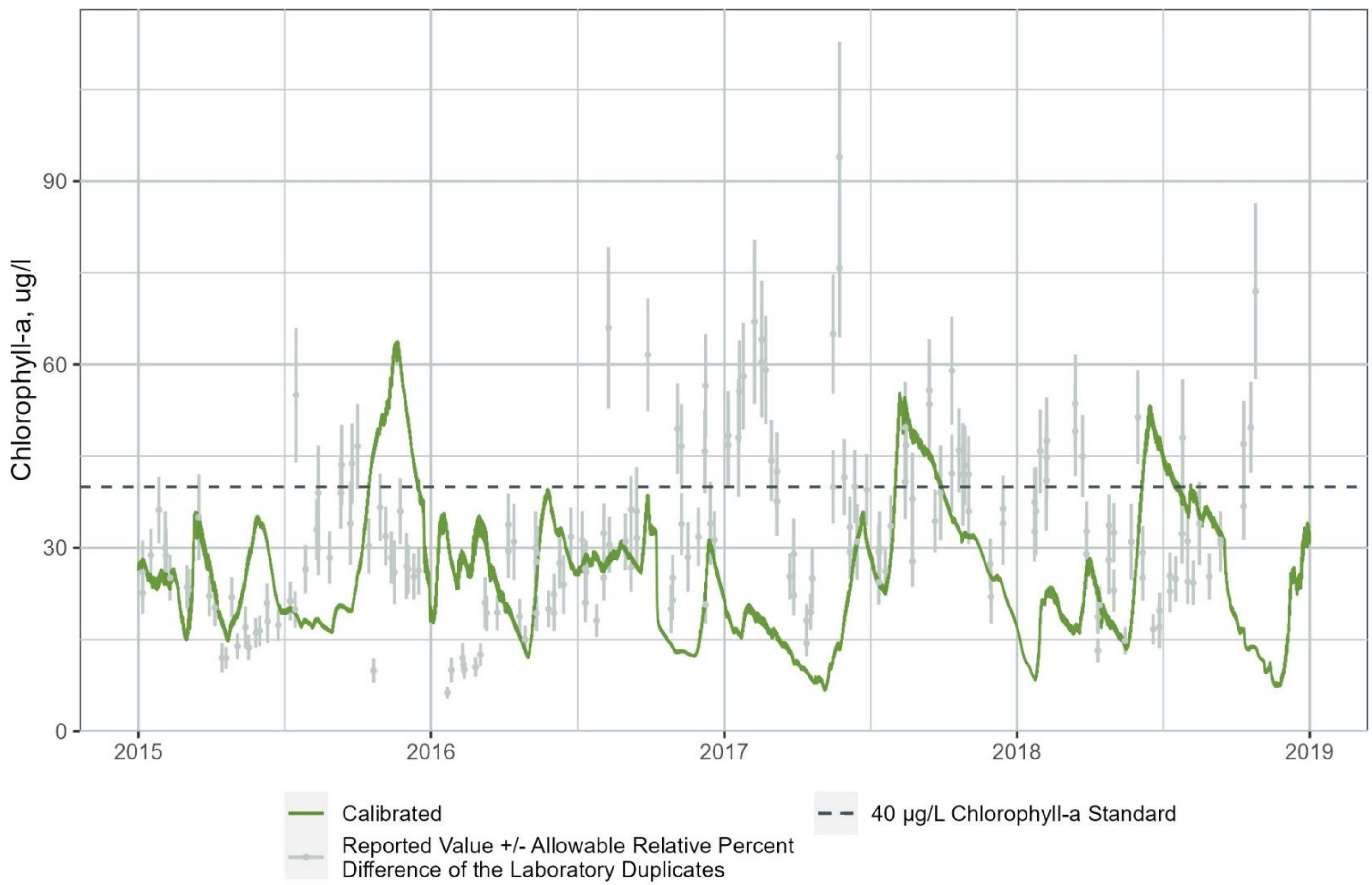

Figure B-54. Time Series Comparison of WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected at the Downstream End of Segment 4

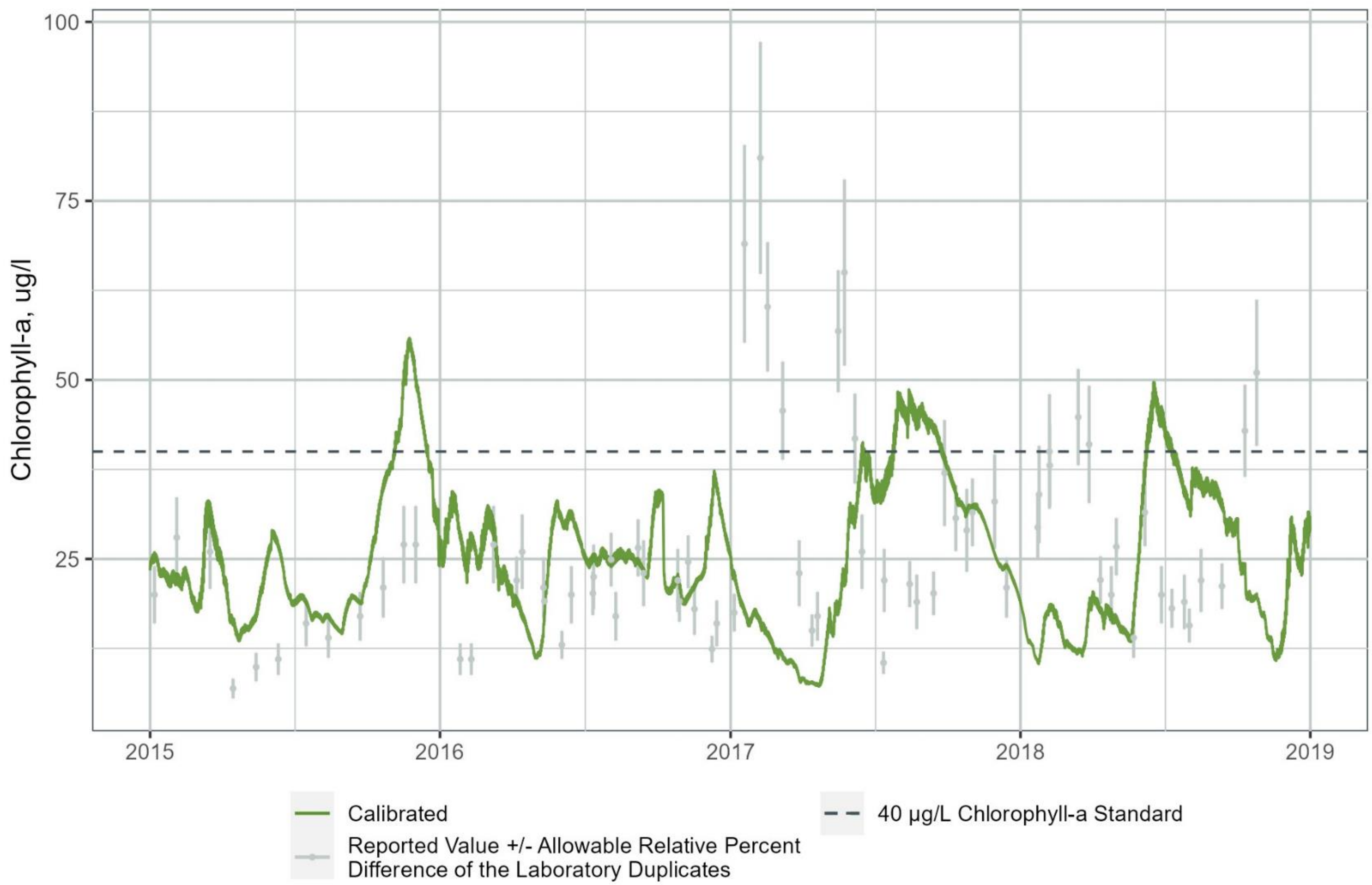

Figure B-55. Time Series Comparison of WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected at the Downstream End of Segment 5

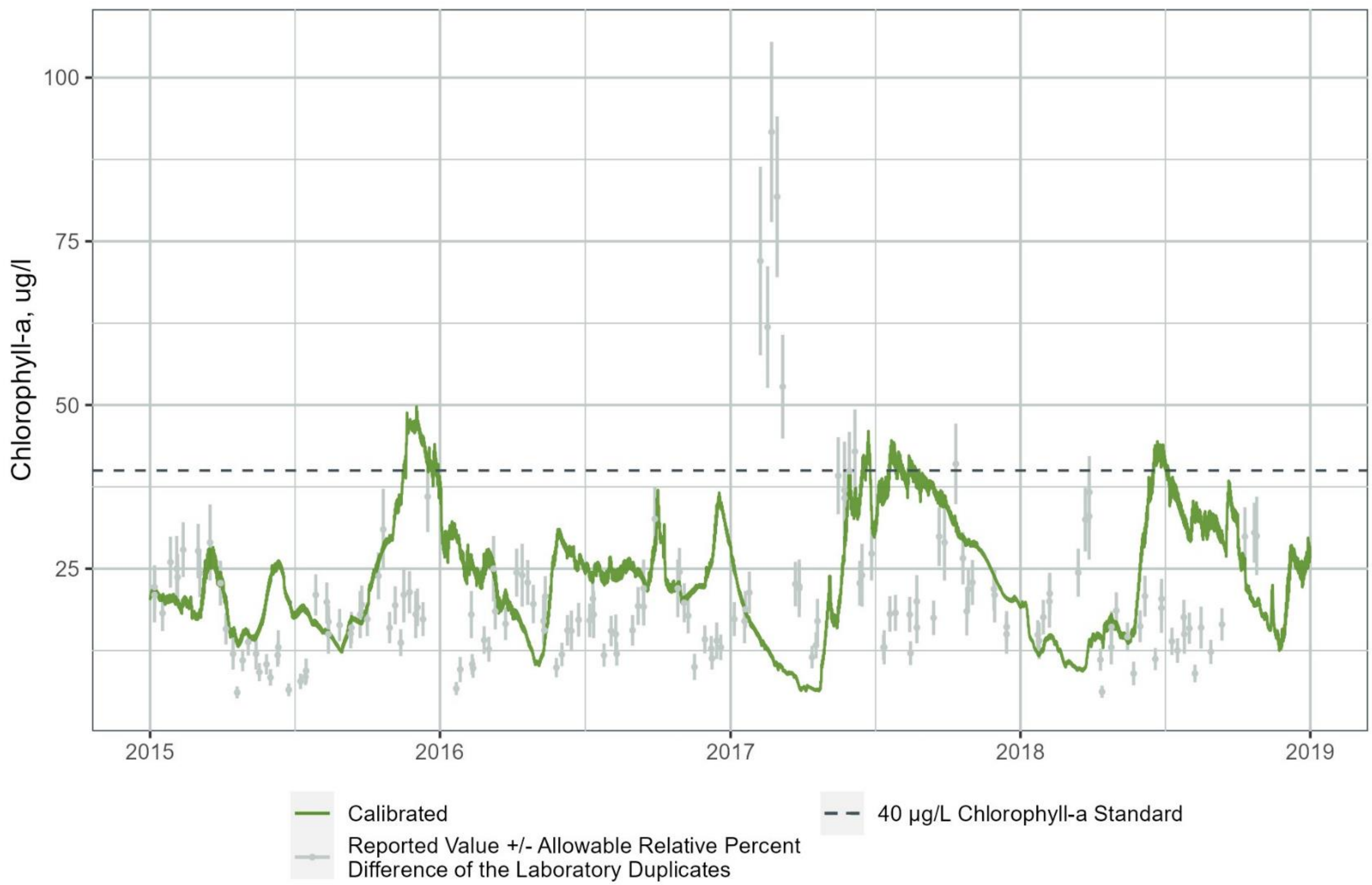

Figure B-56. Time Series Comparison of WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected at the Downstream End of Segment 6

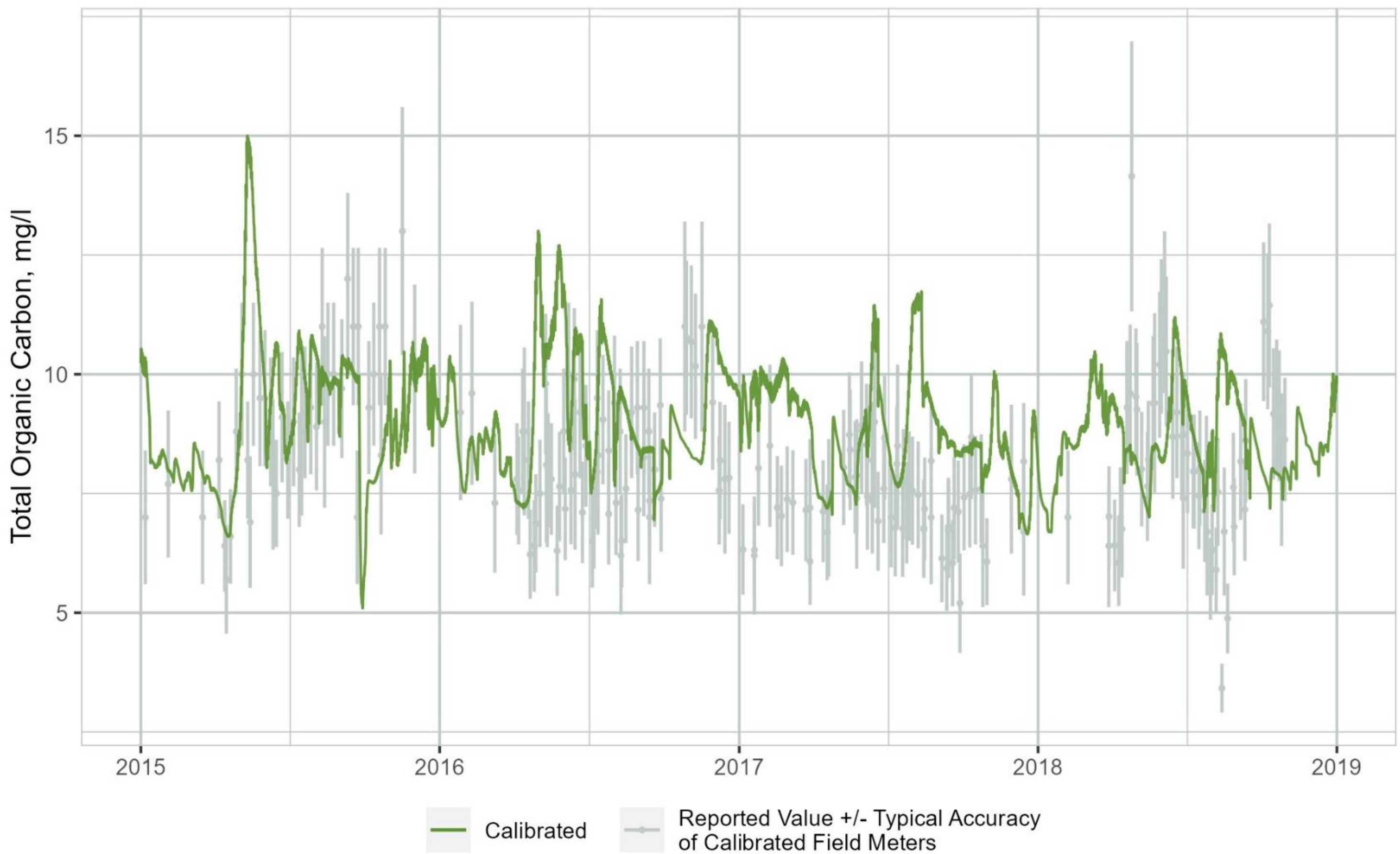

Figure B-57. Time Series Comparison of WARMF Lake Simulated Total Organic Carbon (TOC) Concentrations to Observations Collected at the Downstream End of Segment 1

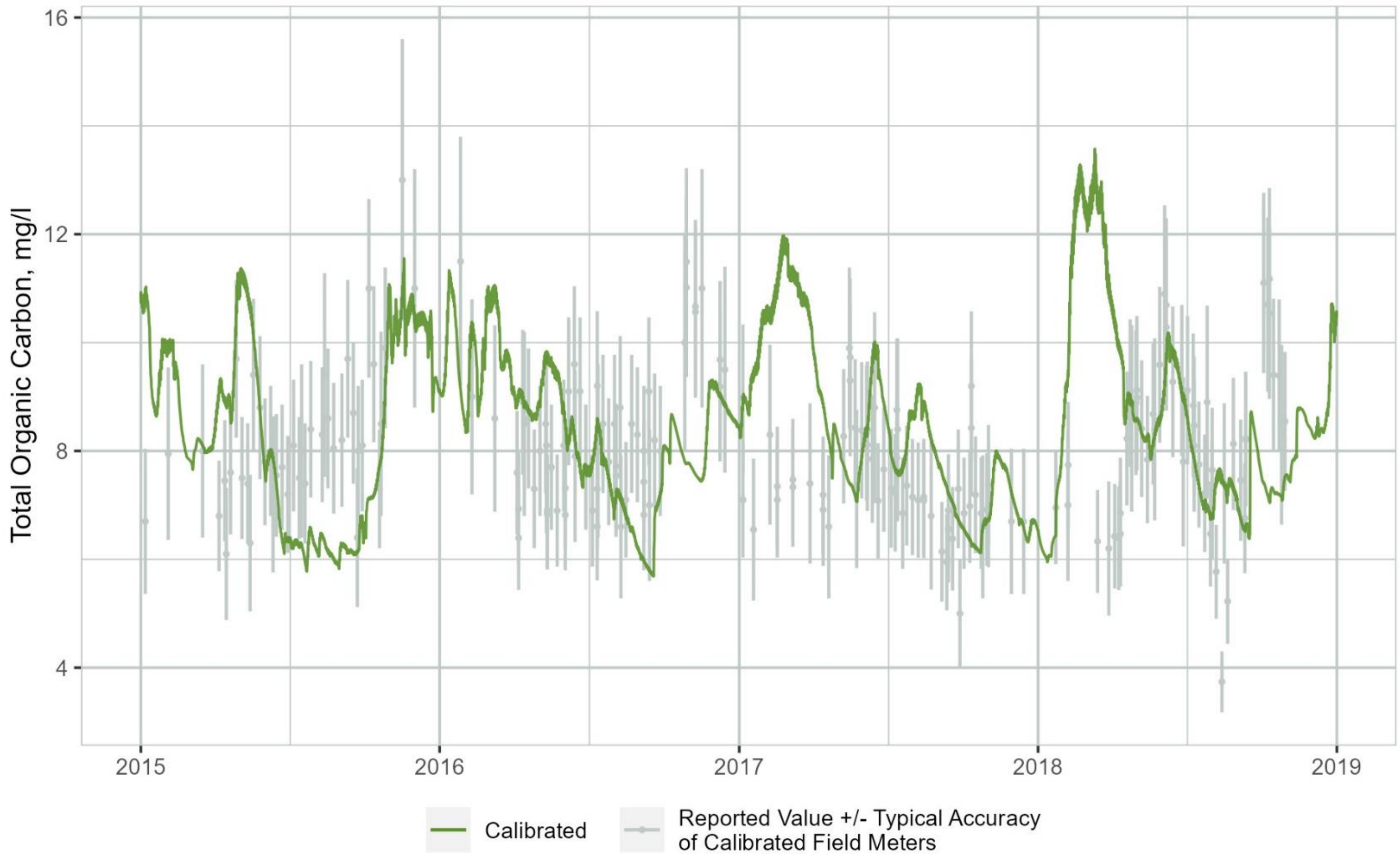

Figure B-58. Time Series Comparison of WARMF Lake Simulated Total Organic Carbon (TOC) Concentrations to Observations Collected at the Downstream End of Segment 2

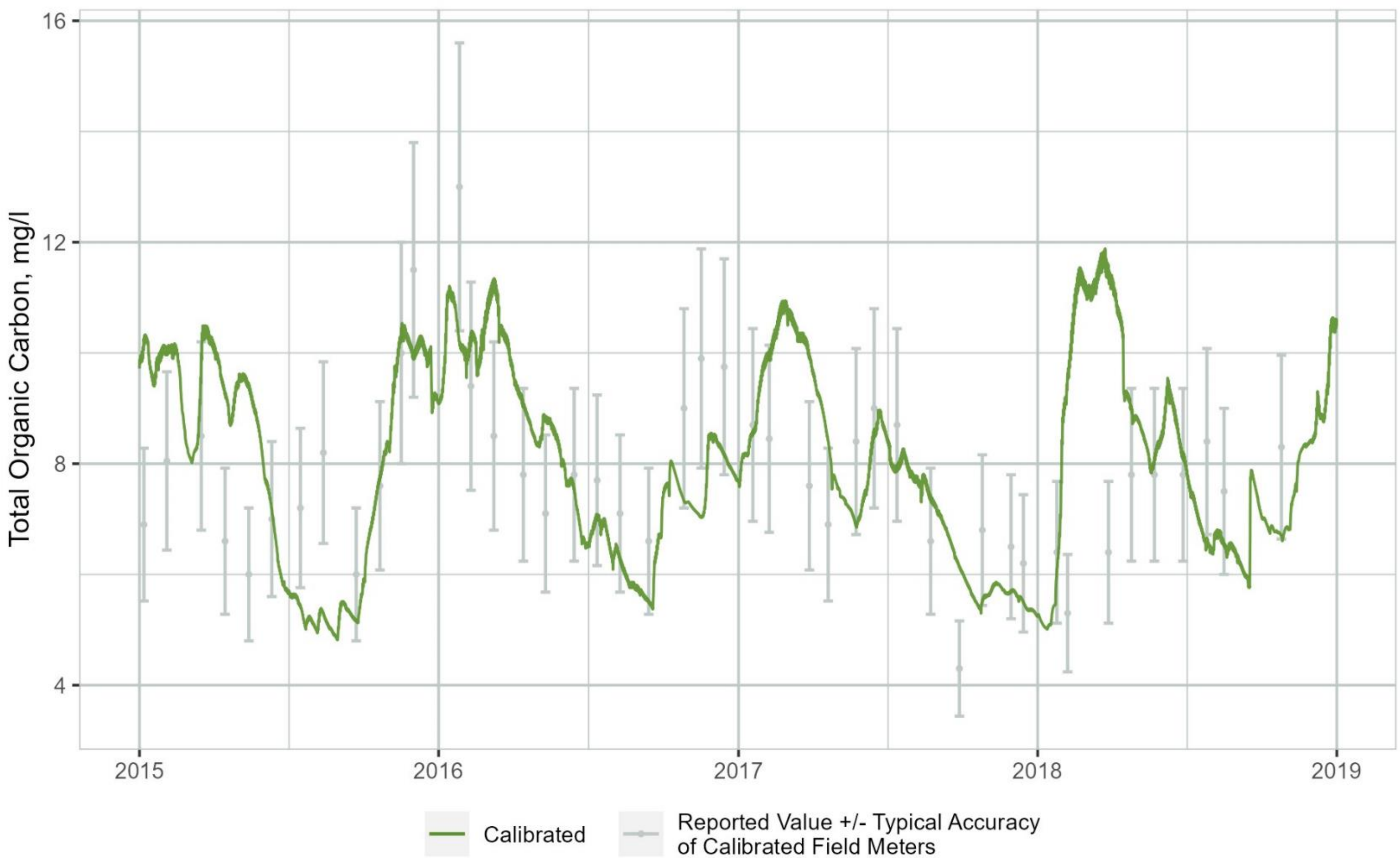

Figure B-59. Time Series Comparison of WARMF Lake Simulated Total Organic Carbon (TOC) Concentrations to Observations Collected at the Downstream End of Segment 3

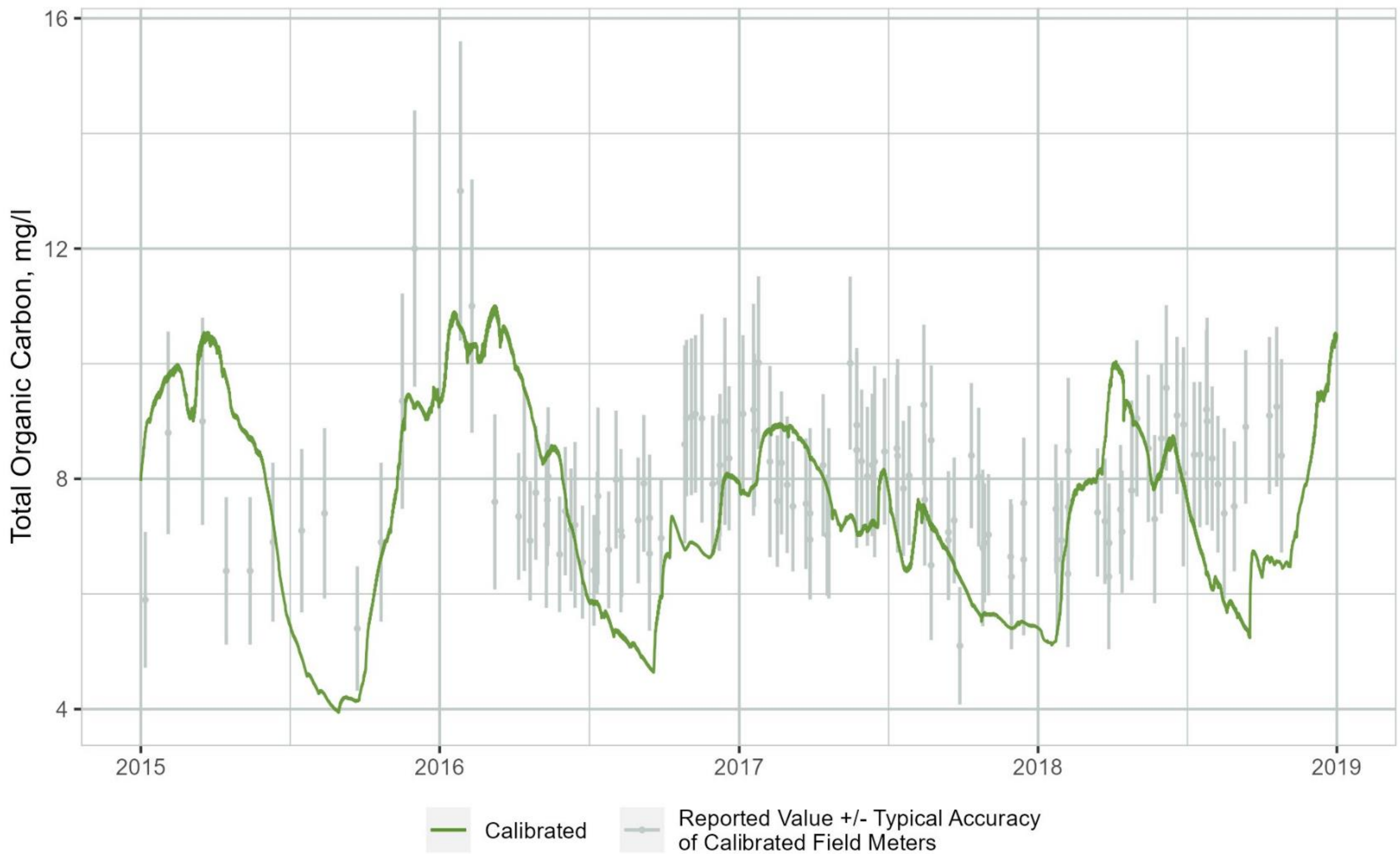

Figure B-60. Time Series Comparison of WARMF Lake Simulated Total Organic Carbon (TOC) Concentrations to Observations Collected at the Downstream End of Segment 4

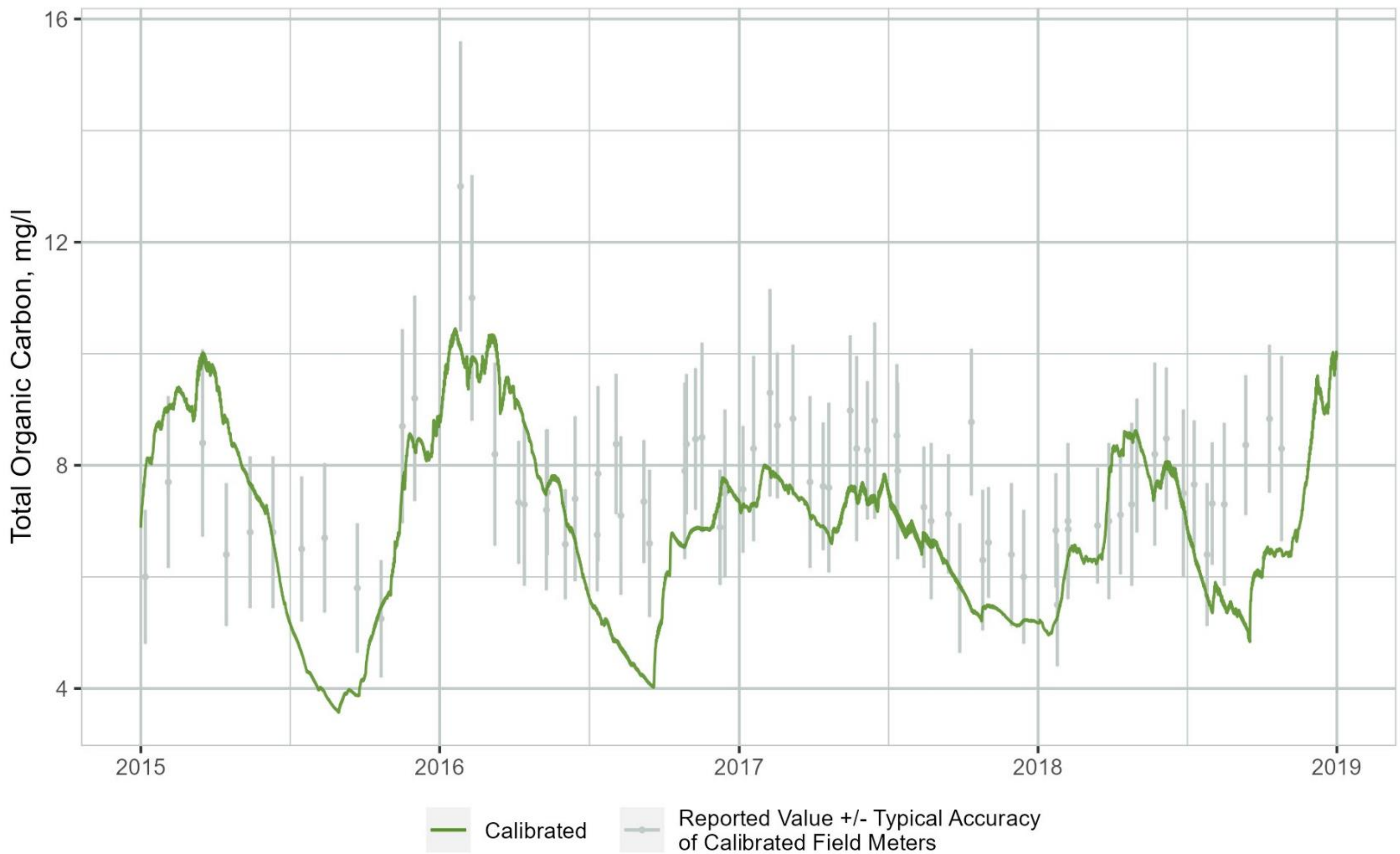

Figure B-61. Time Series Comparison of WARMF Lake Simulated Total Organic Carbon (TOC) Concentrations to Observations Collected at the Downstream End of Segment 5

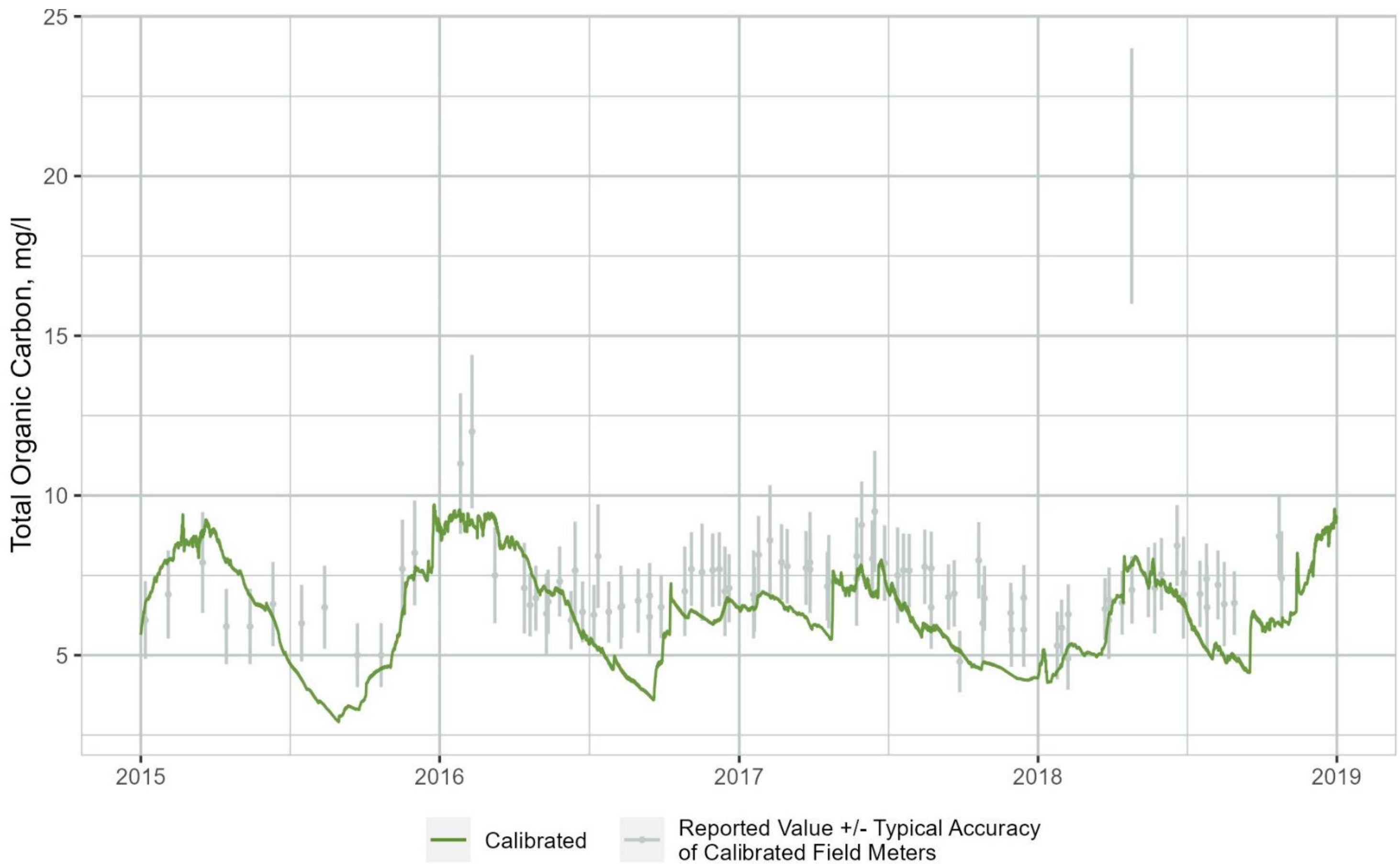

Figure B-62. Time Series Comparison of WARMF Lake Simulated Total Organic Carbon (TOC) Concentrations to Observations Collected at the Downstream End of Segment 6

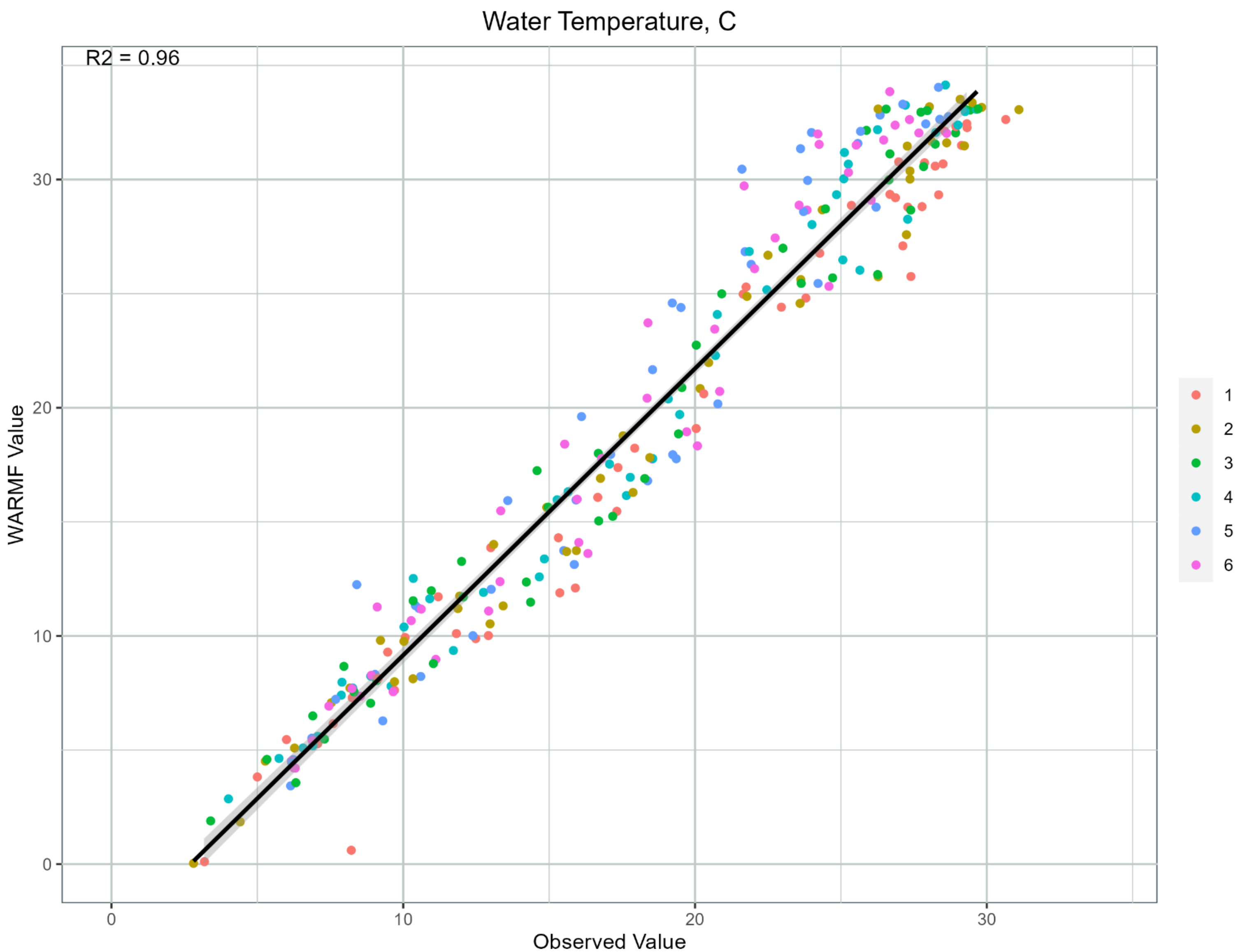

Figure B-63. Scatter Plot Comparing WARMF Lake Simulated Water Temperatures to Observations Collected in Falls Lake for Six Mainstem Segments

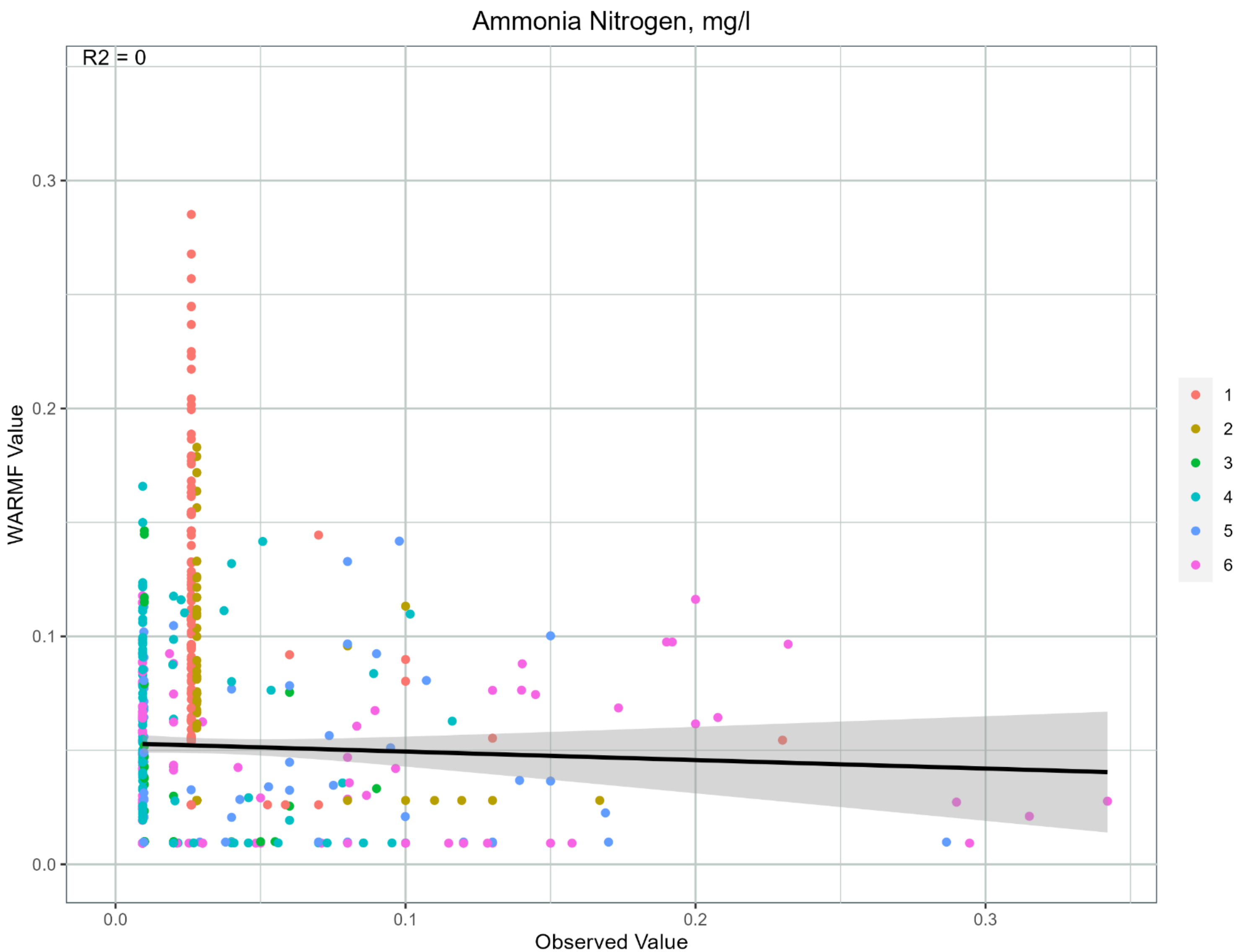

Figure B-64. Scatter Plot Comparing WARMF Lake Simulated Ammonia Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

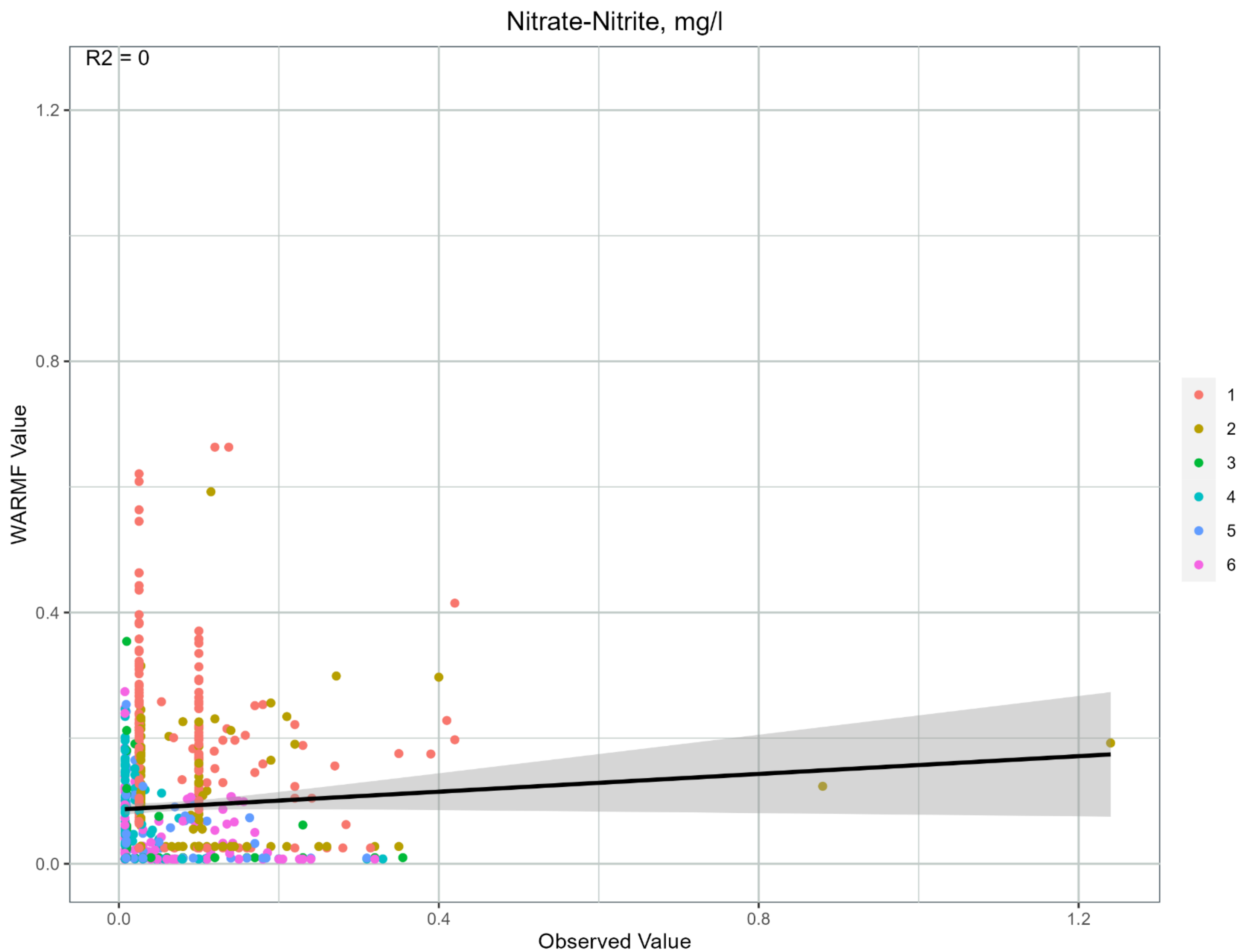

Figure B-65. Scatter Plot Comparing of WARMF Lake Simulated Nitrate plus Nitrite Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

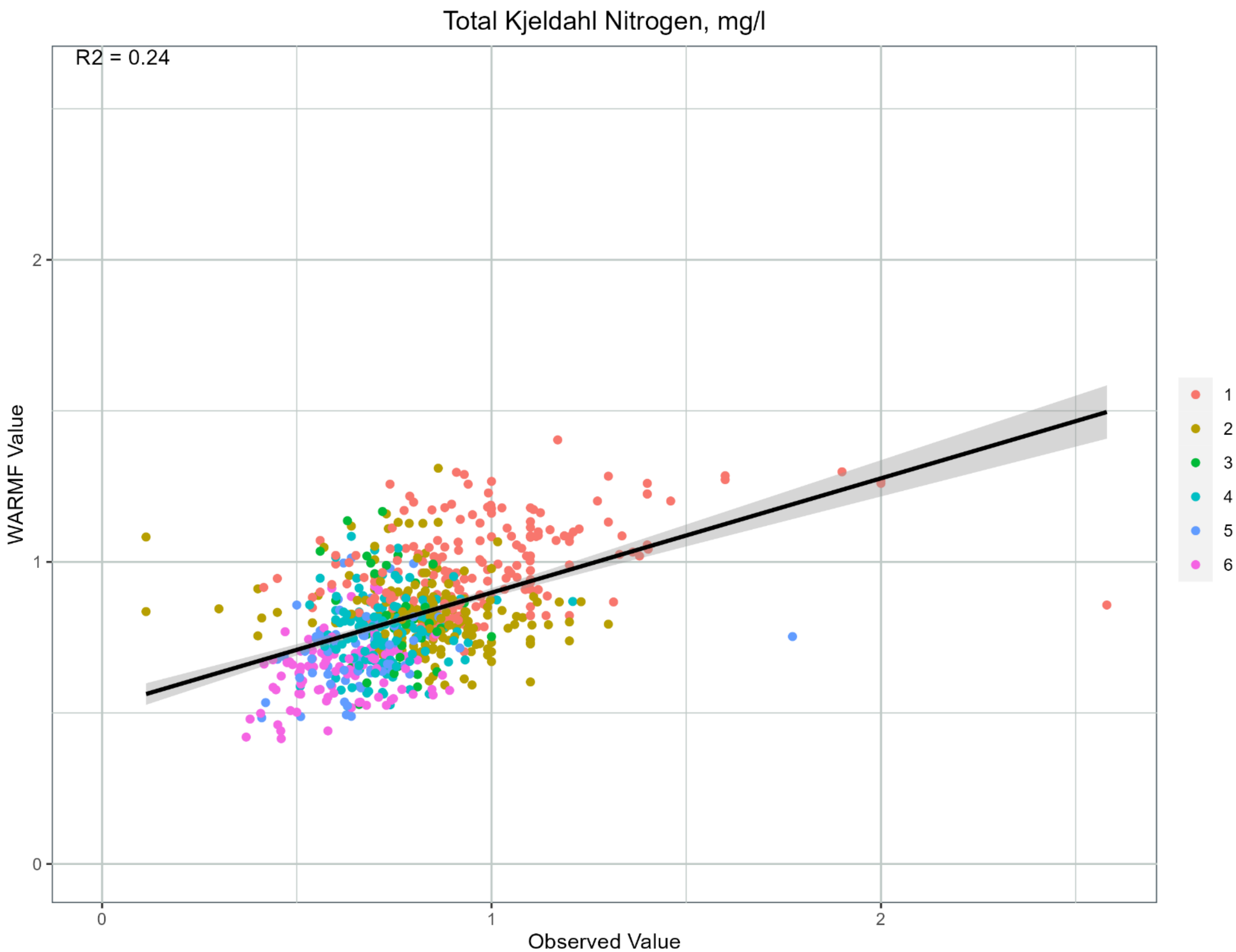

Figure B-66. Scatter Plot Comparing WARMF Lake Simulated TKN Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

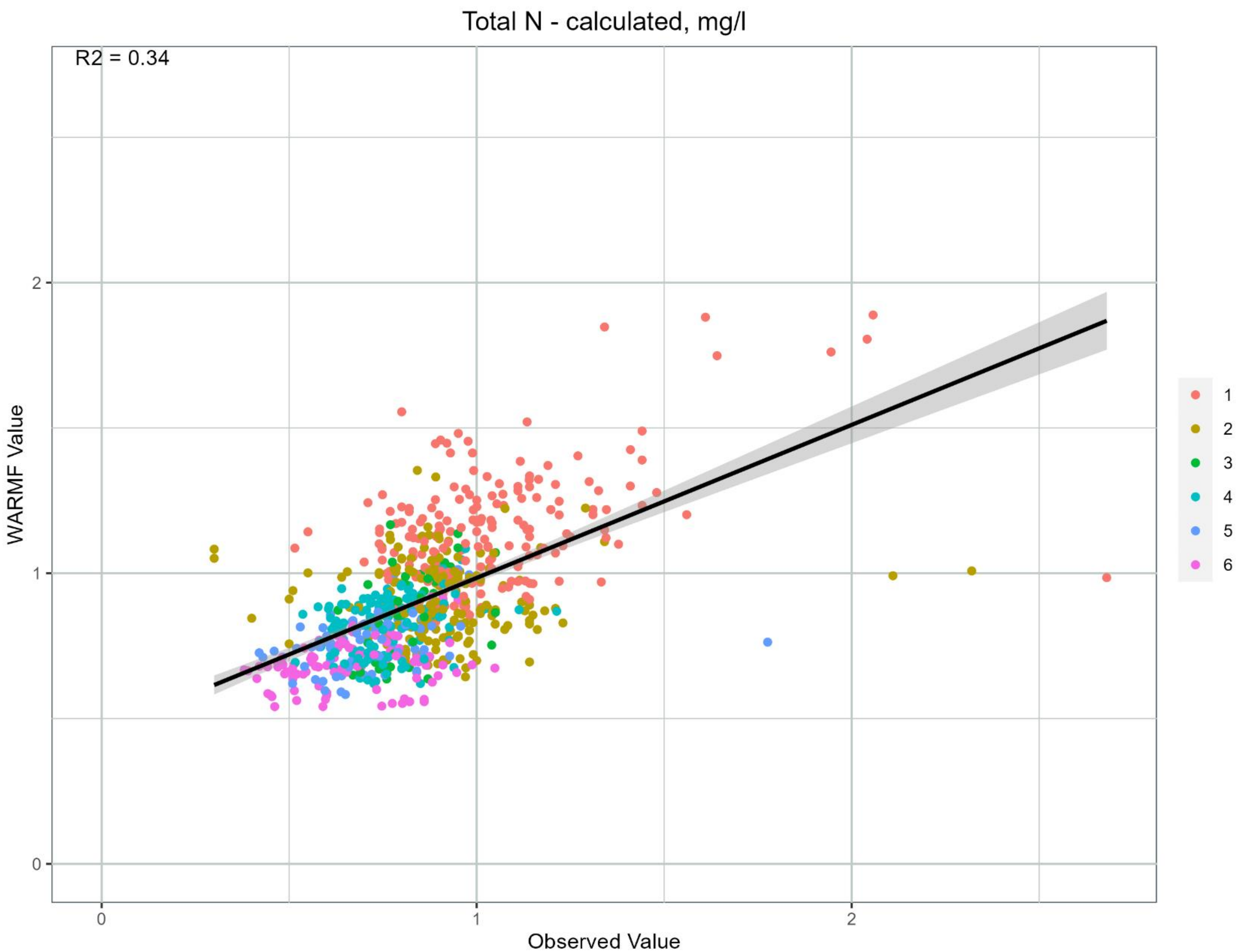

Figure B-67. Scatter Plot Comparing WARMF Lake Simulated TN Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

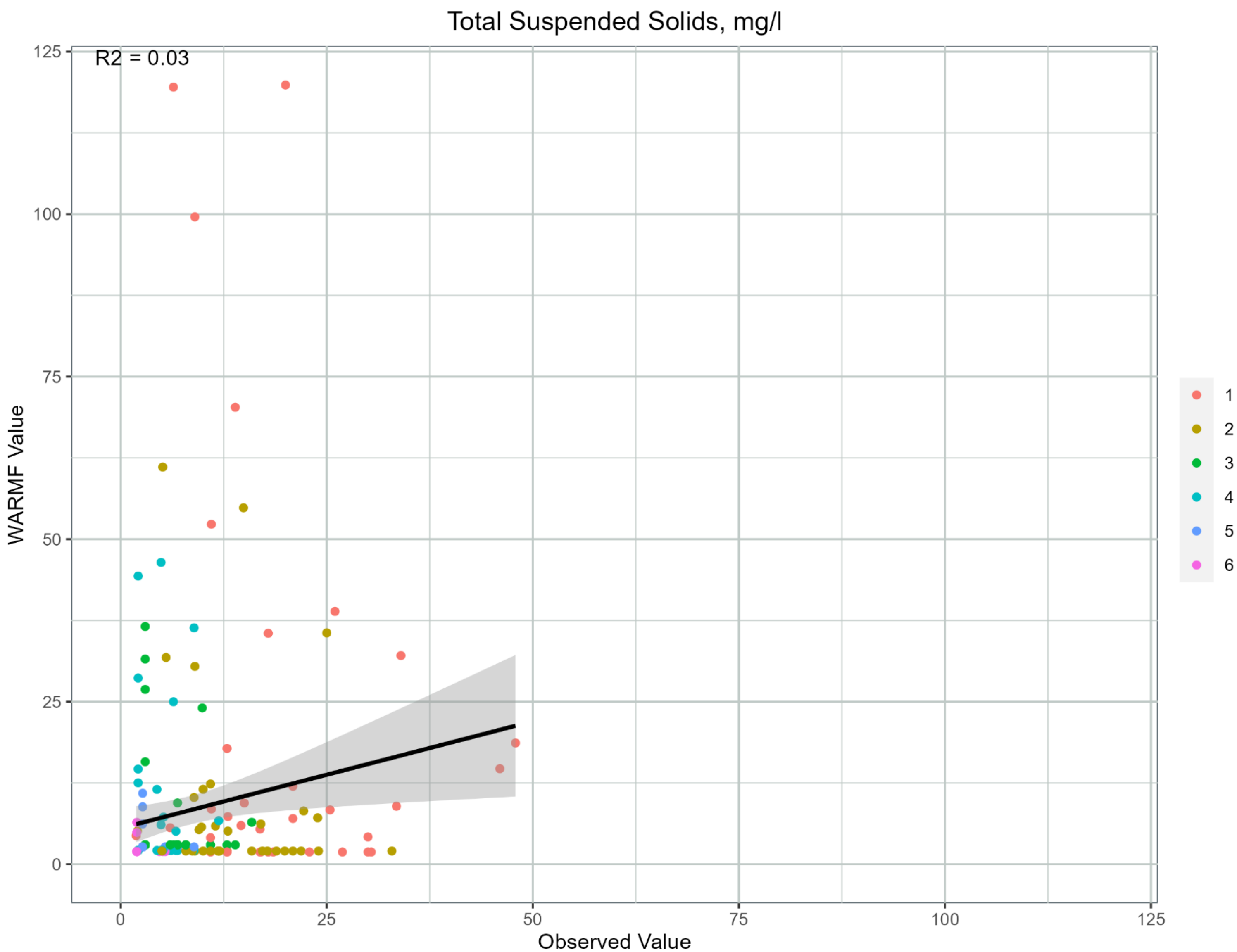

Figure B-68. Scatter Plot Comparing WARMF Lake Simulated TSS Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

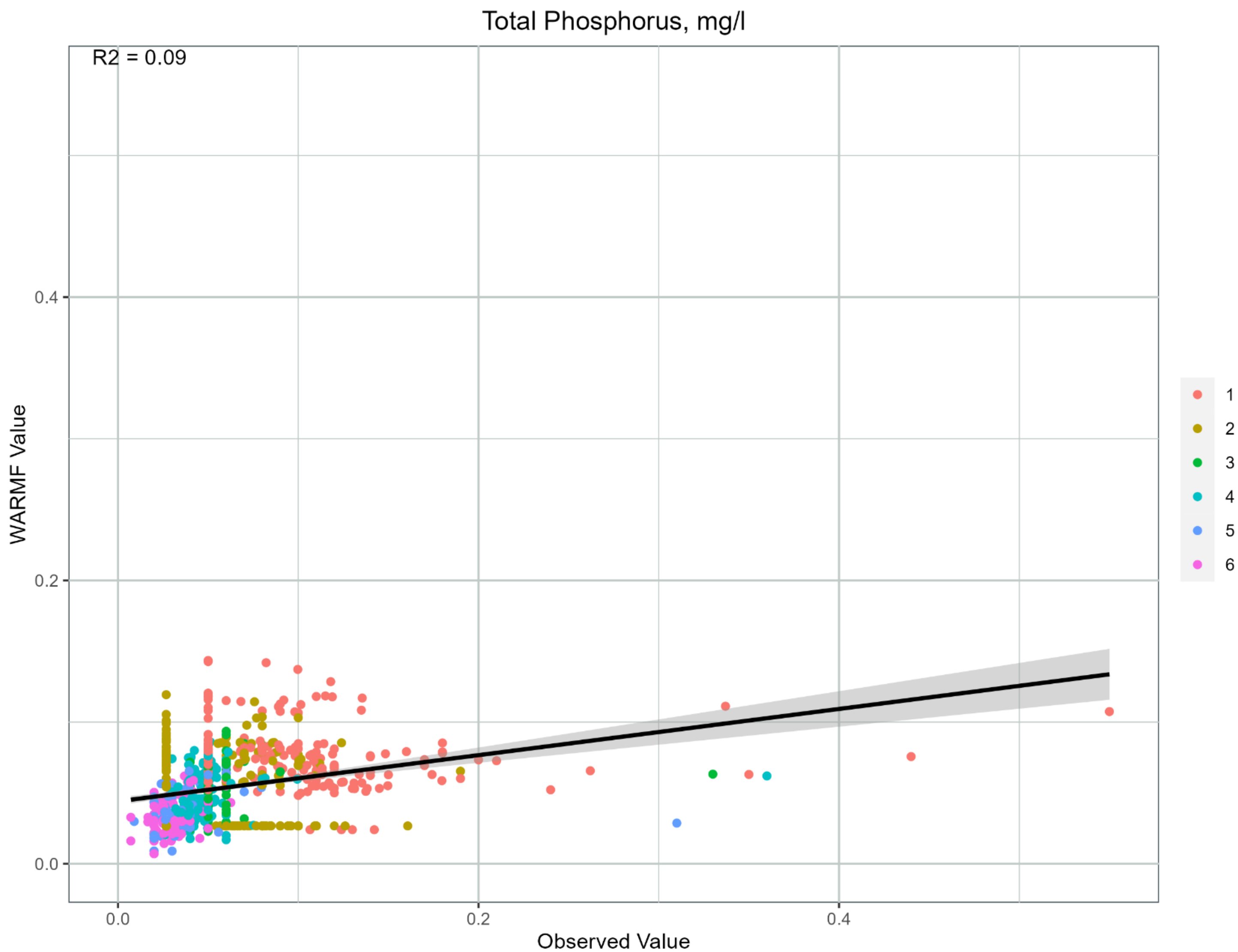

Figure B-69. Scatter Plot Comparing WARMF Lake Simulated TP Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

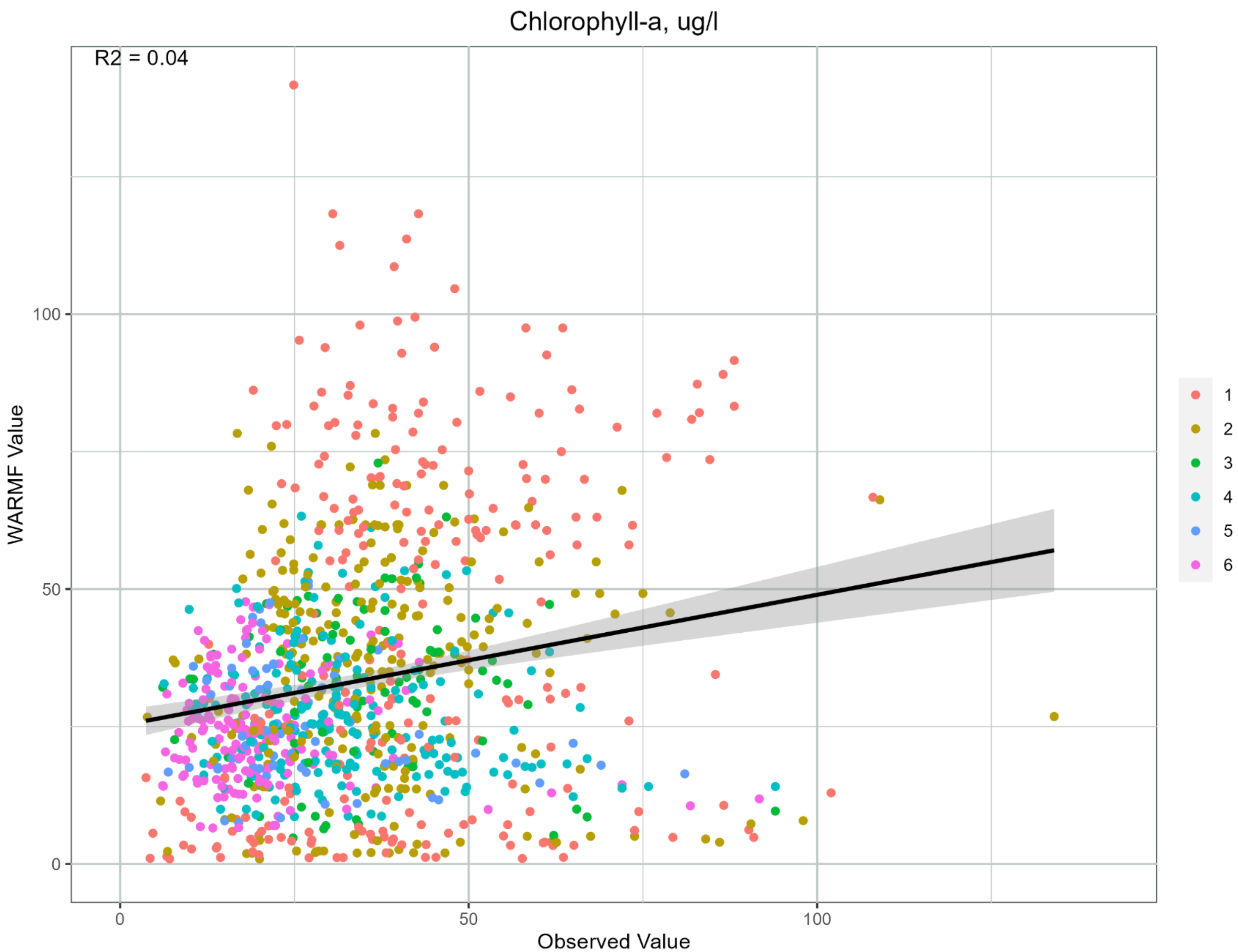

Figure B-70. Scatter Plot Comparing WARMF Lake Simulated Chlorophyll-a Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

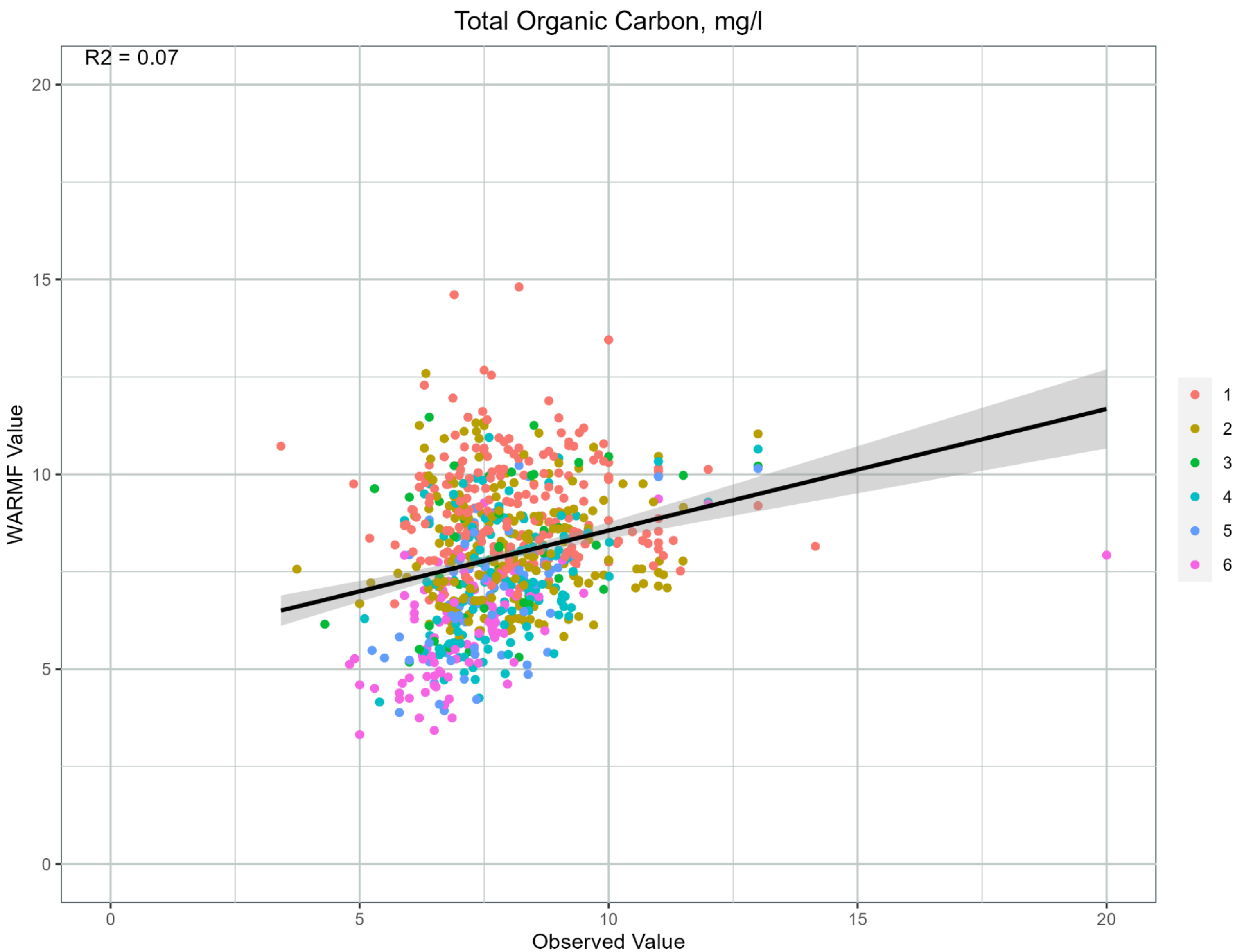

Figure B-71. Scatter Plot Comparing WARMF Lake Simulated TOC Concentrations to Observations Collected in Falls Lake for Six Mainstem Segments

Section 4: Sensitivity Analyses

Following calibration of WARMF Lake, sensitivity analyses were conducted on a subset of model coefficients to evaluate how changing model parameters would affect simulated water quality in Falls Lake. The purpose of the sensitivity analysis is to gain a better understanding of how changing a model input coefficient affects modeling results. The sensitivity analysis provides useful information regarding the relative importance of the physical, chemical and biological processes represented in the model and identifies the most influential coefficients for improving model accuracy. This information can also provide future insight to help identify research studies that would improve future modeling efforts under an adaptive management framework.

As the regulatory driver for the project is chlorophyll-a, this output parameter in Falls Lake is the focus of the sensitivity analyses. Nutrients and total organic carbon were also evaluated for change. Lake model coefficients addressing nutrient availability and algal kinetics were the focus of the sensitivity analyses. Sensitivity analyses on algal growth, sediment bed diffusion, nitrification, and organic material decay rates were conducted using the calibrated WARMF Lake model. The modeling team worked with the MRSW, "third-party" model reviewers, and DWR modelers to determine the coefficients and ranges for sensitivity analyses evaluation (Table B-10).

Table B-10. Model Coefficients Evaluated for Sensitivity for the WARMF Lake Model

Coefficient	Lower Value	Calibrated Value	Higher Value
Algal growth rate (1/d):			
Blue Green	0.8	0.9	1.0
Diatoms	1.7	1.8	1.9
Other Algae	0.8	0.9	1.0
Sediment bed diffusion rate (m^2/d)			
Upstream of Segment 4	8E-7	8E-6	8E-5
Downstream of Segment 3	3E-6	3E-5	3E-4
Water column and sediment bed nitrification rate (1/d)	0.01	0.015	0.02
Water column and sediment bed organic matter decay rate (1/d)	0.005	0.01	0.015

Figure B-72 through Figure B-103 show the results of the sensitivity analyses for three example lake segments for ammonia, nitrate plus nitrite, total nitrogen, total phosphorus, total organic carbon, total suspended sediment, and chlorophyll-a. These three segments represent the upper lake (Segment 1: upstream of Interstate 85), middle lake (Segment 4: between Rolling View marina and Highway 50), and lower lake (Segment 6: between Highway 98 and the dam).

Each of the sensitivity analysis figures shows the results of the calibrated model and the results of the higher or lower model coefficient value. For reference, the water quality observations used for model calibration are shown on each figure with bars representing plus or minus the allowable relative percent difference for laboratory duplicates. The comparison of the variation in the modeling results with the established laboratory variation in what is the "true" measurement of chlorophyll-a is extremely important. The assessment of compliance is applied to a fixed value of 40 ug/L. When a laboratory conducts its analysis on the same sample twice, there is an allowable difference in the measurement results. It is therefore reasonable to compare the allowable variation of a value measured in the laboratory to the simulated value. This issue was discussed extensively in the model review process. The subject matter experts and MRSW reached consensus that showing the allowable relative percent difference is a reasonable way to show the potential variation in the laboratory measurements for communicating modeling results.

Orange bars represent samples that were less than the reporting limit; the orange bars extend from zero to the reporting limit to show the potential range. Orange bars are different lengths in different segments depending on the organization performing the analysis and their respective reporting limits.

Ammonia, nitrate plus nitrite, TKN, and TOC were most sensitive to increases in bed diffusion rate. These constituents were also sensitive to organic matter decay rate. Ammonia and nitrate plus nitrite were also sensitive to the nitrification rate during parts of the simulation (conversion of ammonia to nitrite and then nitrate occurs through the nitrification process). Chlorophyll-a was sometimes sensitive to the bed diffusion rate, but generally concentrations were similar across the analyses. The algal growth rates sometimes shifted the timing of peak chlorophyll-a concentration but usually did not affect the magnitude of simulated values; an exception occurs in early to mid-2017 in Segment 1 when very high concentrations of chlorophyll-a (up to 400 µg/L) were simulated when growth rates were increased. Total phosphorus was generally not sensitive to these parameters with the exception of very high TP concentrations simulated with the high algal growth rate analysis. The high TP concentrations lagged the very high chlorophyll-a concentrations that were simulated in Segment 1 in early to mid-2017. The model assumes a constant amount of phosphorus is stored in algae cells. When the algae associated with the simulated bloom died and decayed, the assumed amount of phosphorus was released into the water column. The simulated and observed TP before and after this simulated bloom was approximately 0.1 mg/L. The simulated bloom and release of TP into the water column raised the TP concentration to over 0.8 mg/L. This very high TP concentration is an artifact of the sensitivity analyses and model assumptions and highly unlikely. This simulated bloom caused similar anomalous peaks in TKN, total nitrogen, and TOC.

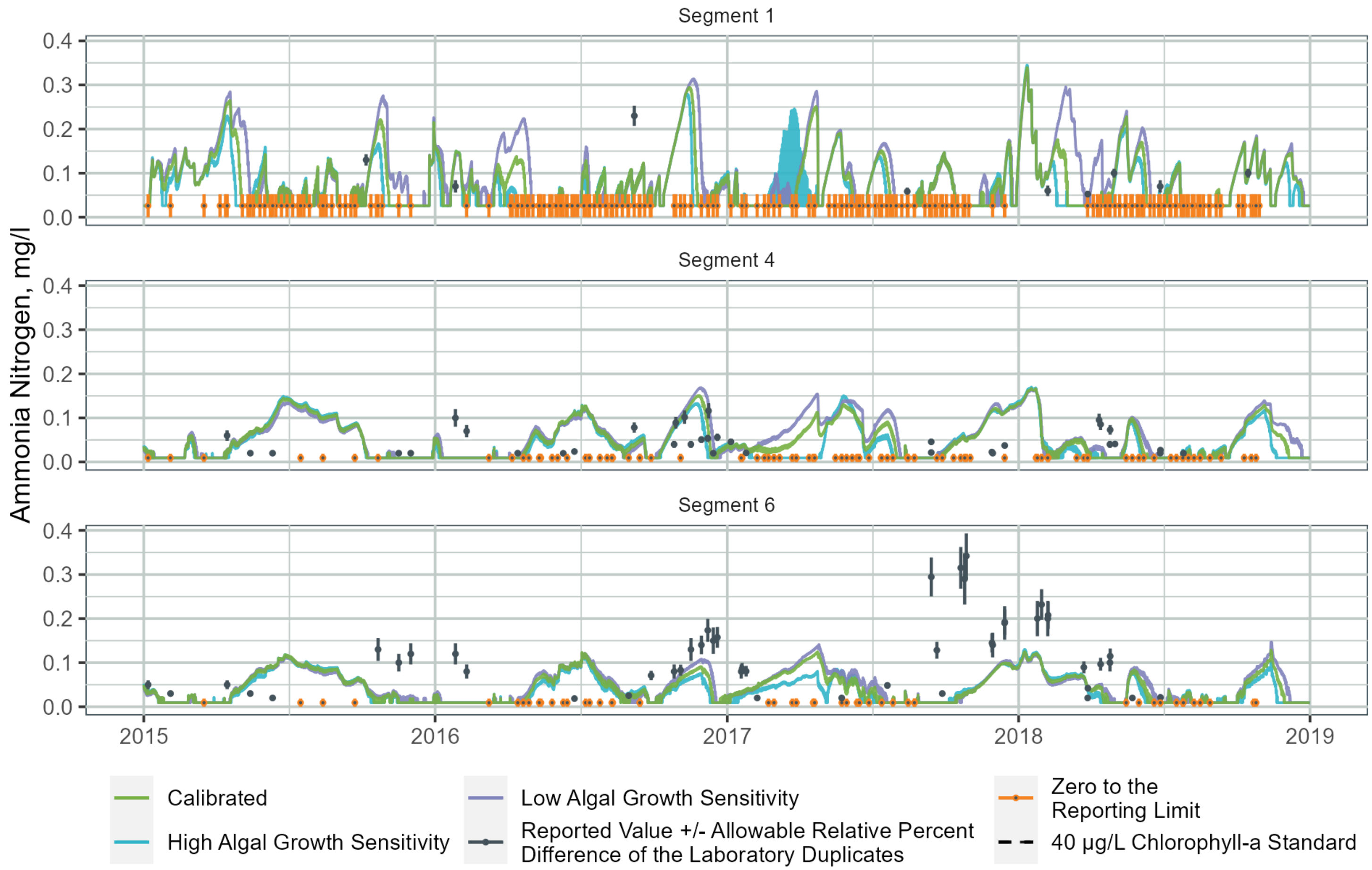

Figure B-72. Ammonia Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

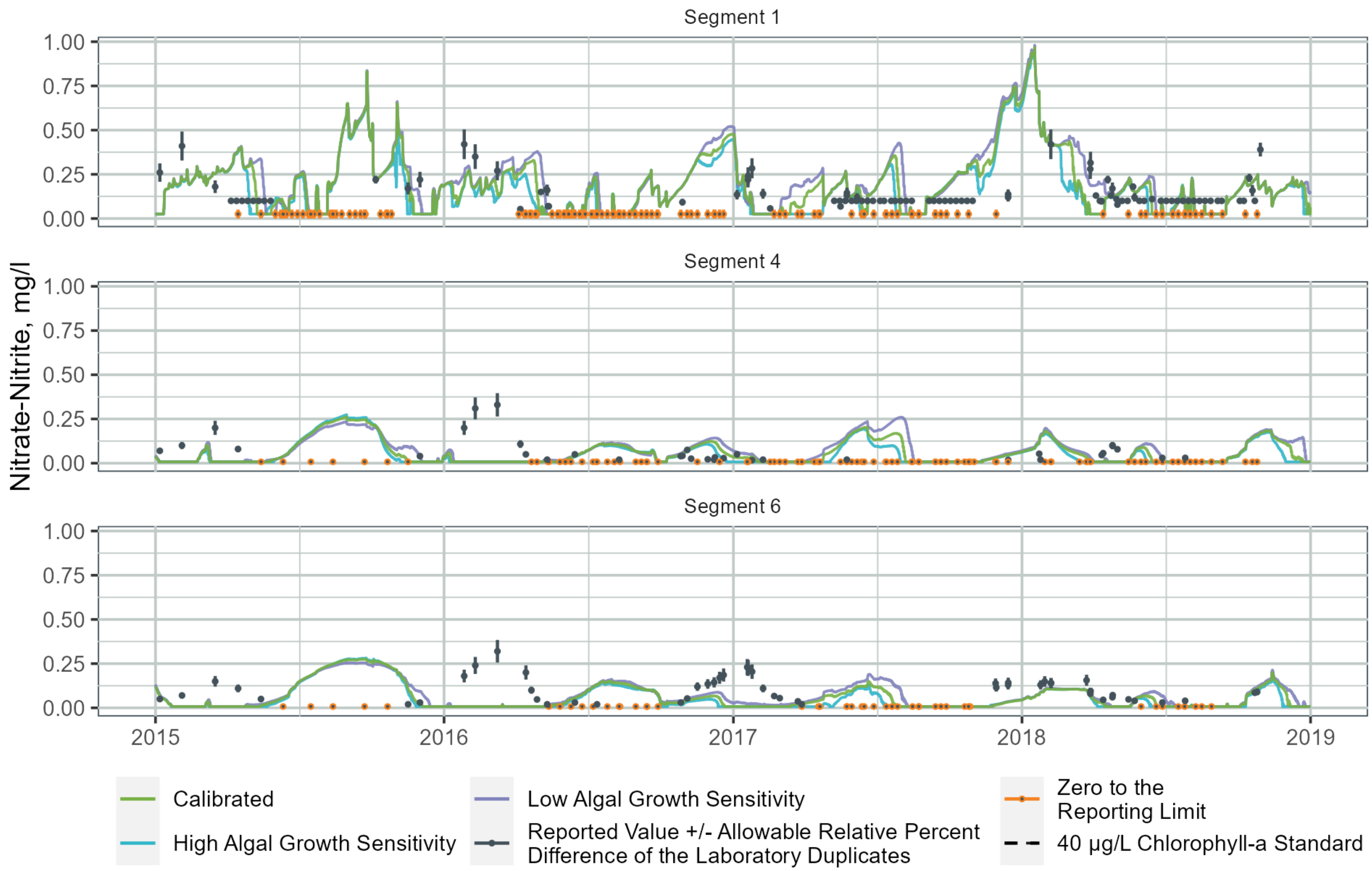

Figure B-73. Nitrate plus Nitrite Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

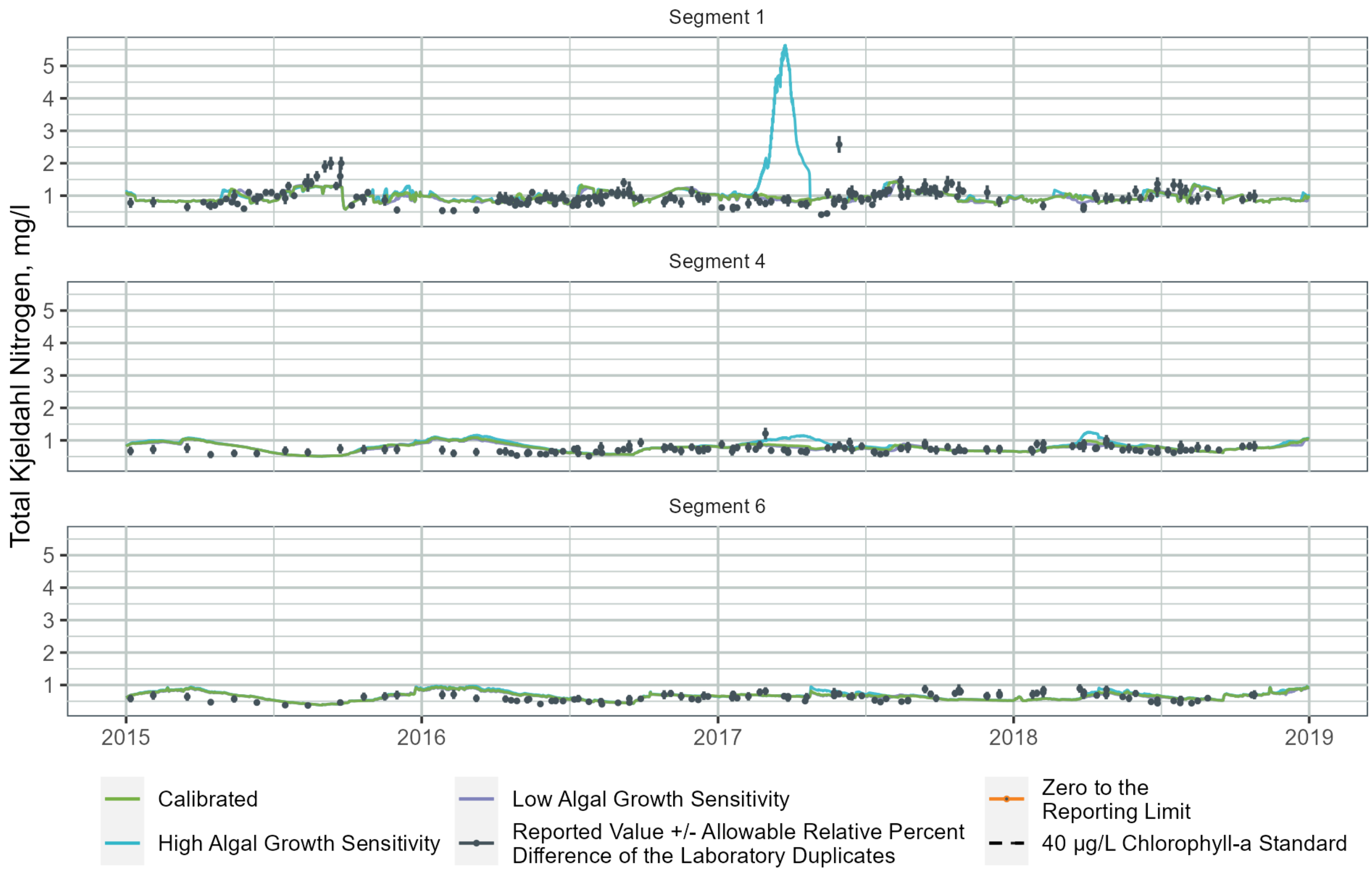

Figure B-74. TKN Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

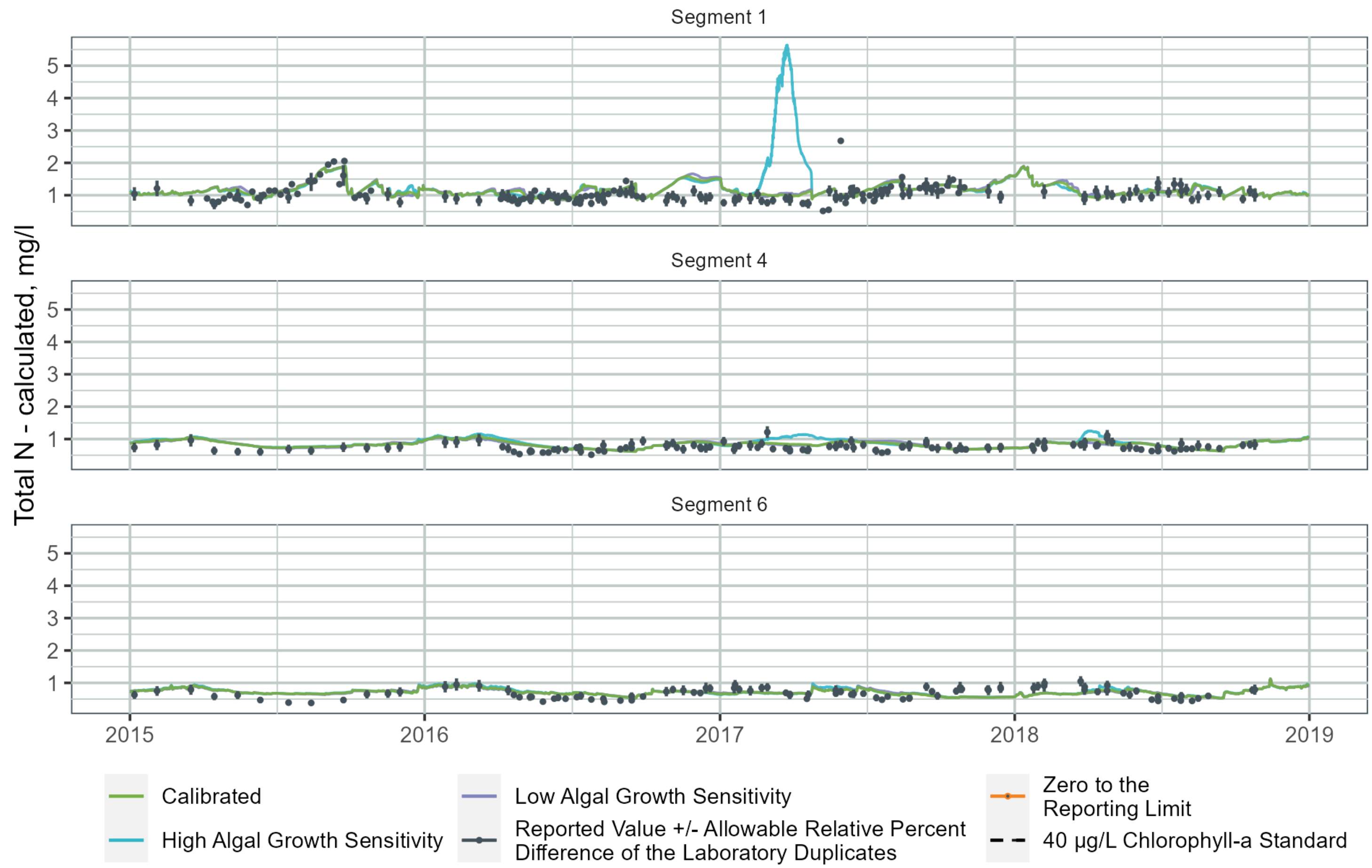

Figure B-75. TN Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

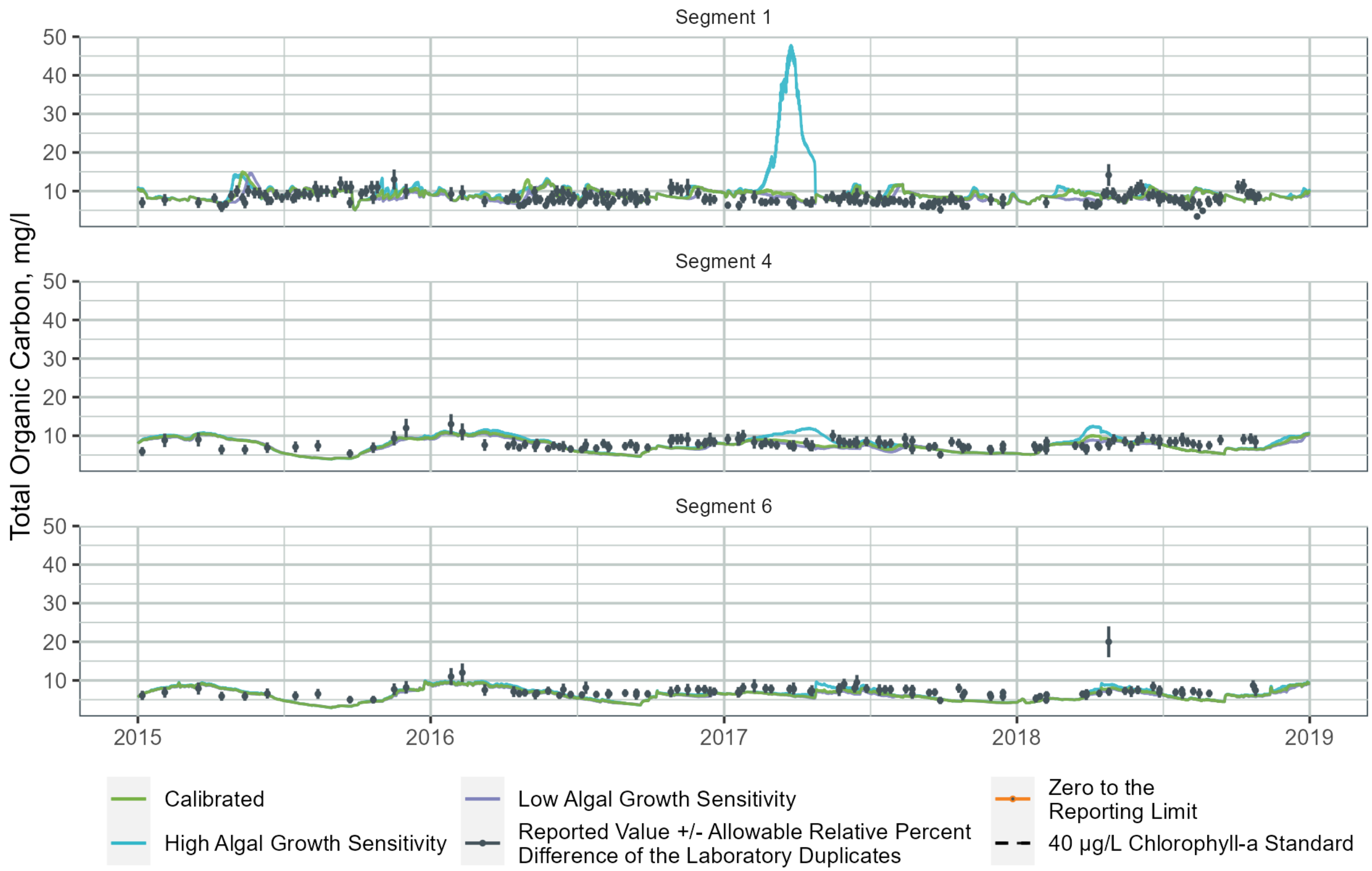

Figure B-76. TOC Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

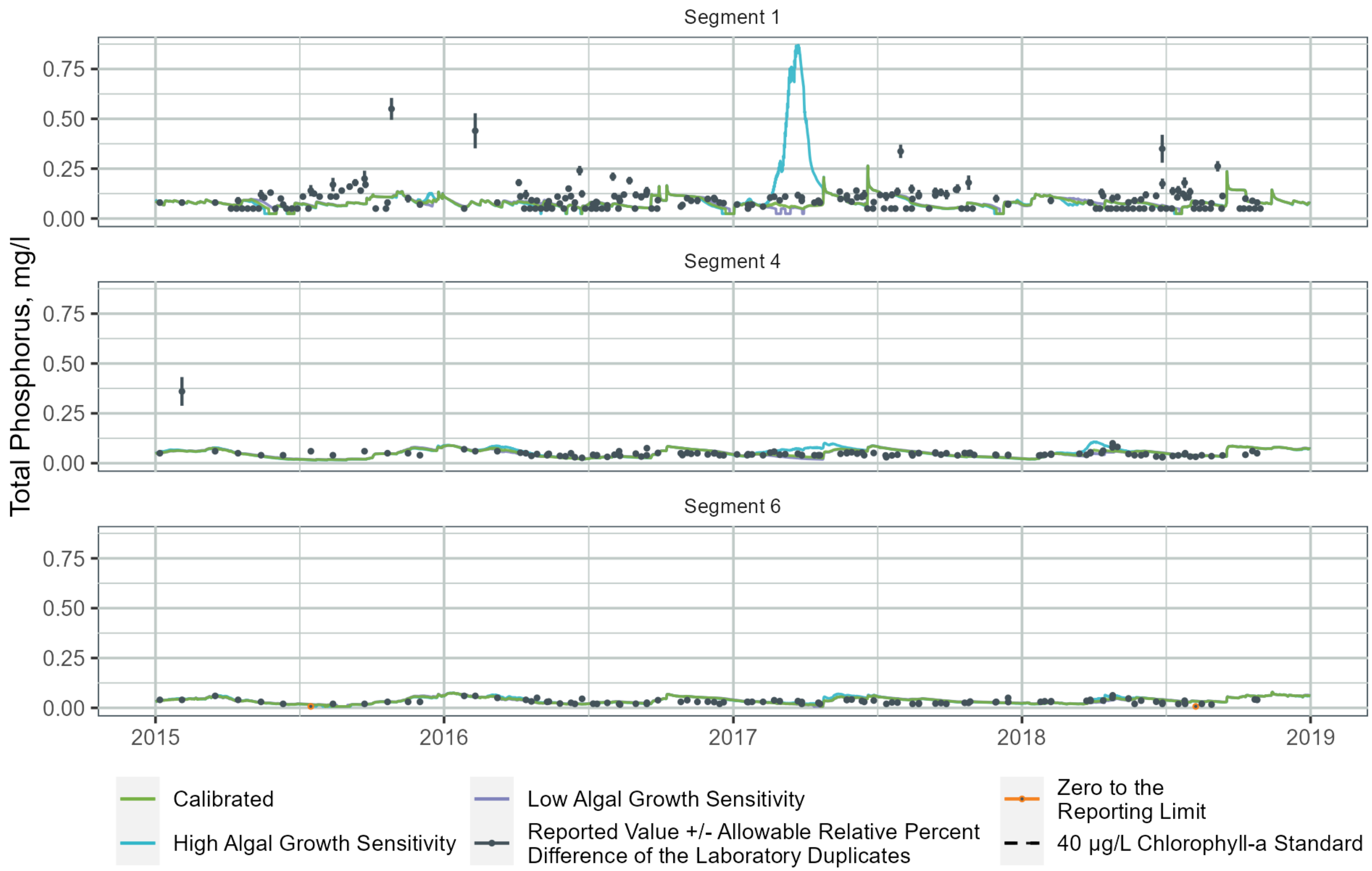

Figure B-77. TP Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

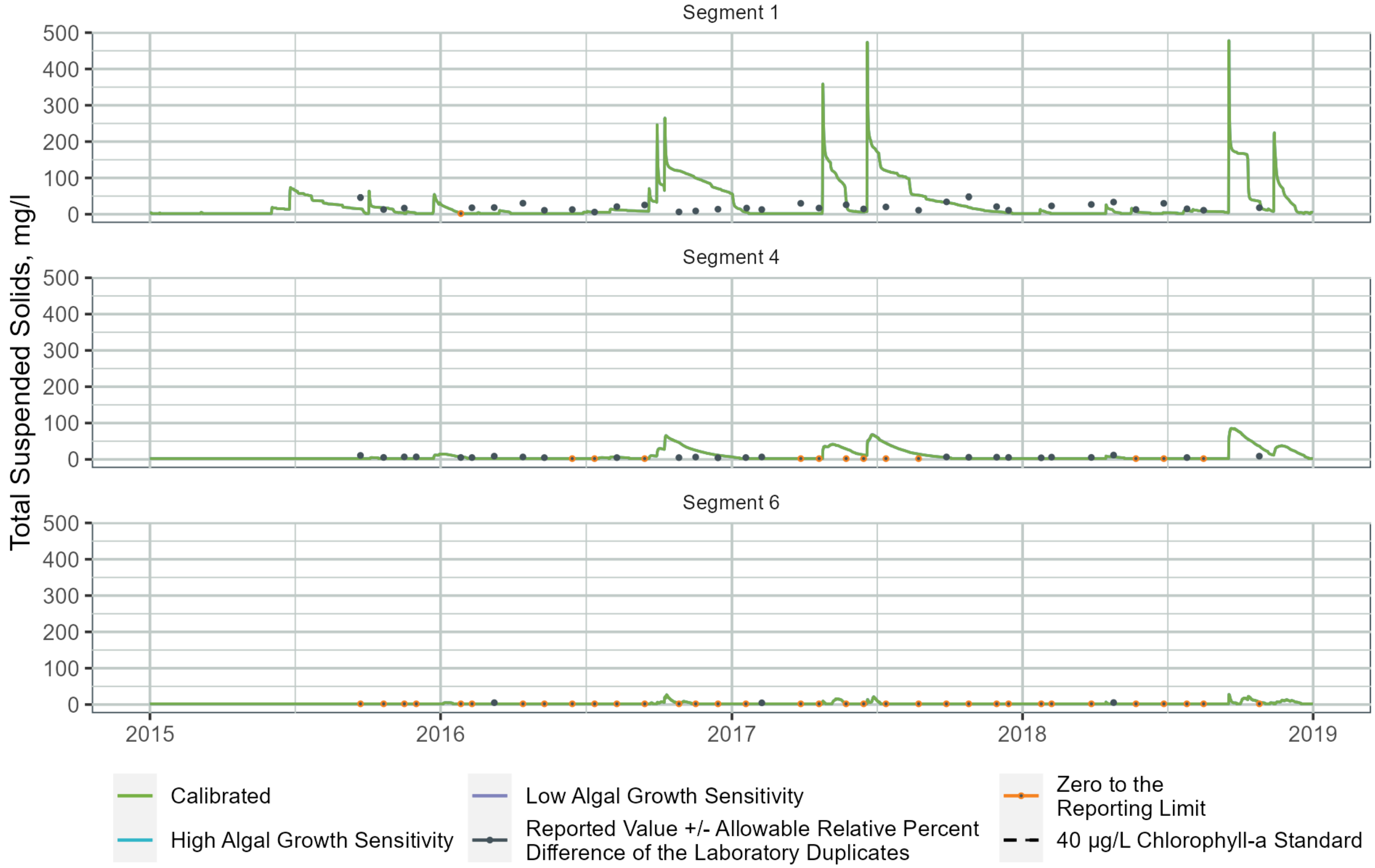

Figure B-78. TSS Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

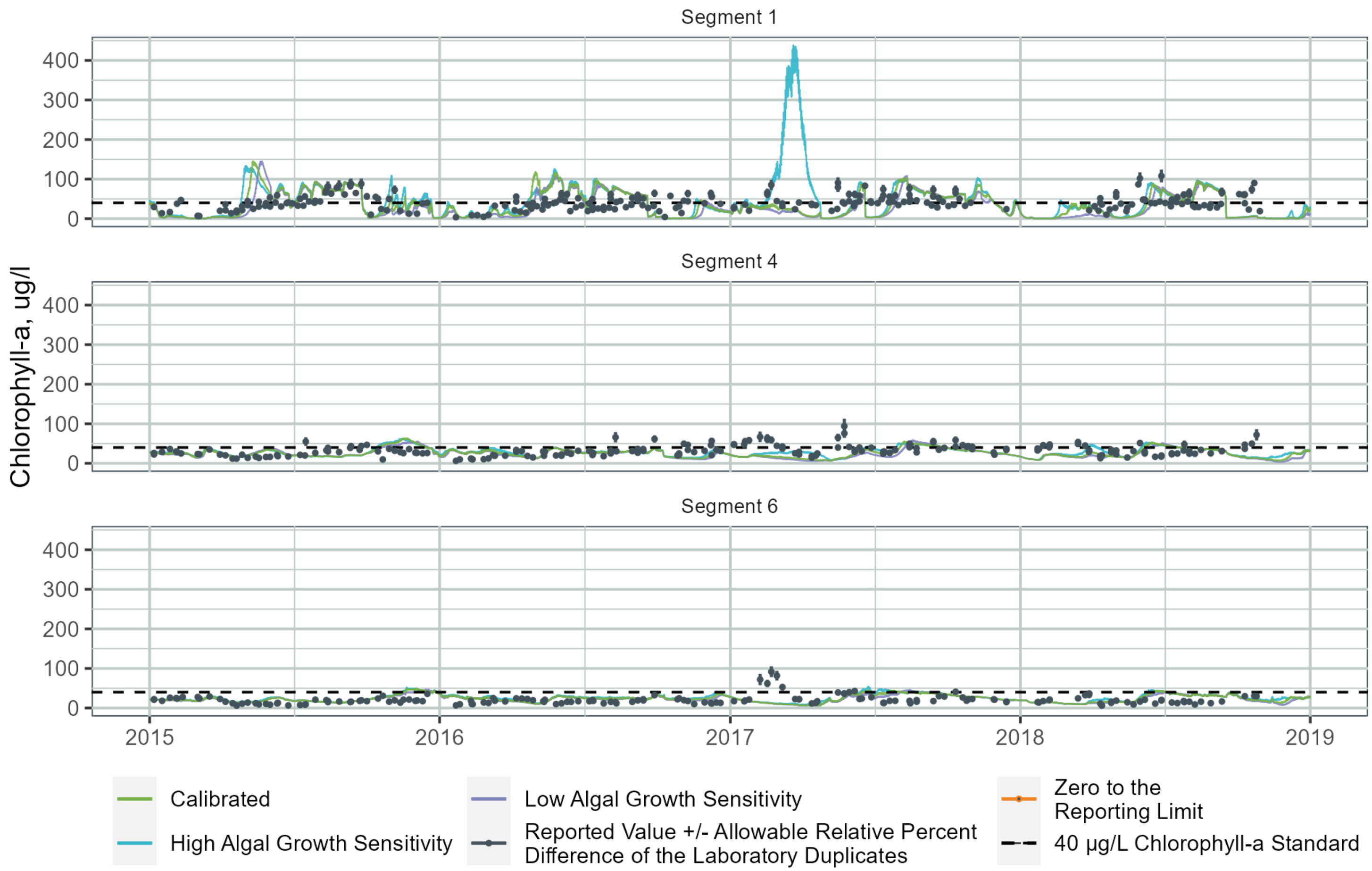

Figure B-79. Chlorophyll-a Sensitivity to Algal Growth Rate at Three WARMF Lake Segments

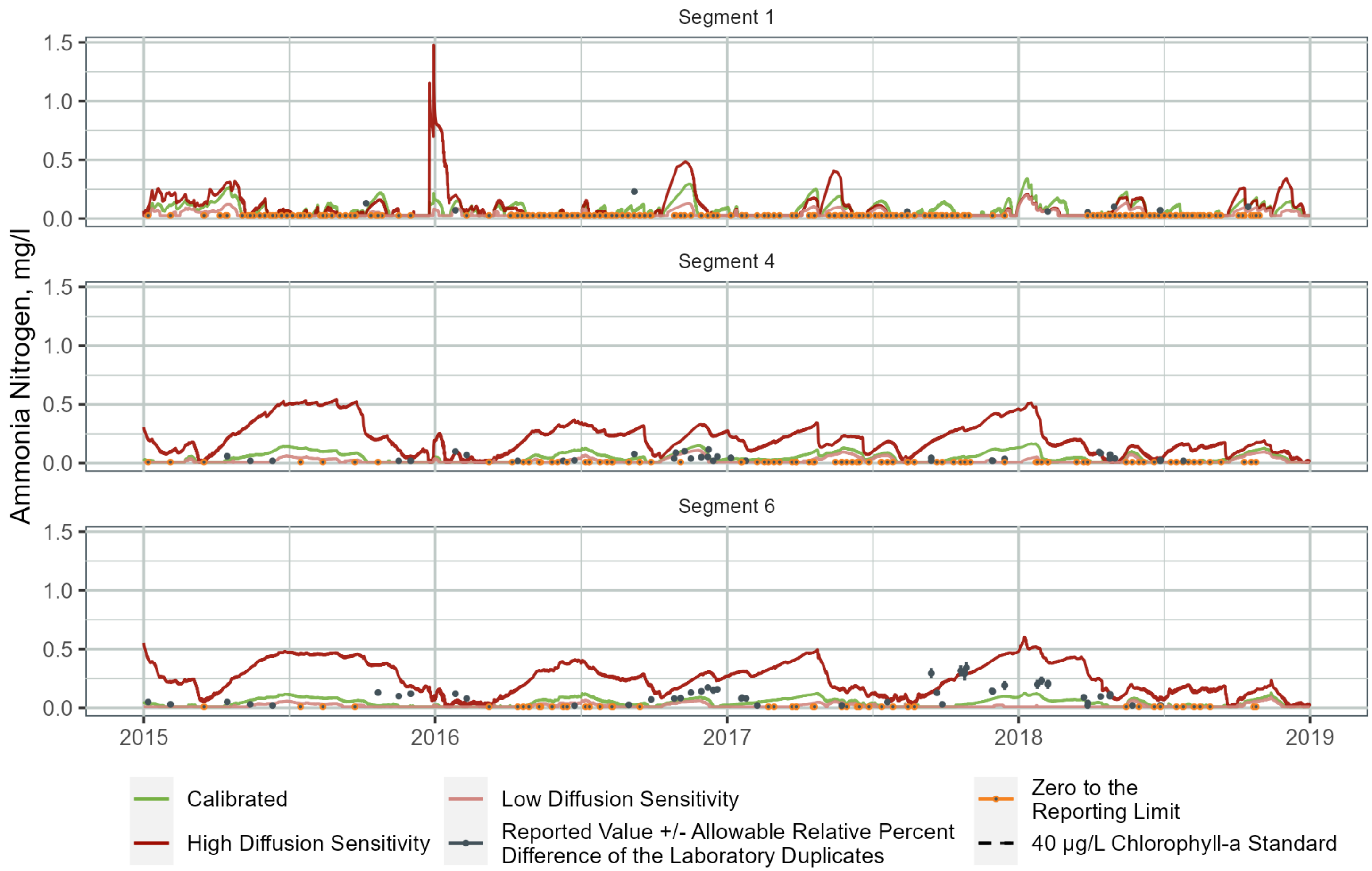

Figure B-80. Ammonia Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

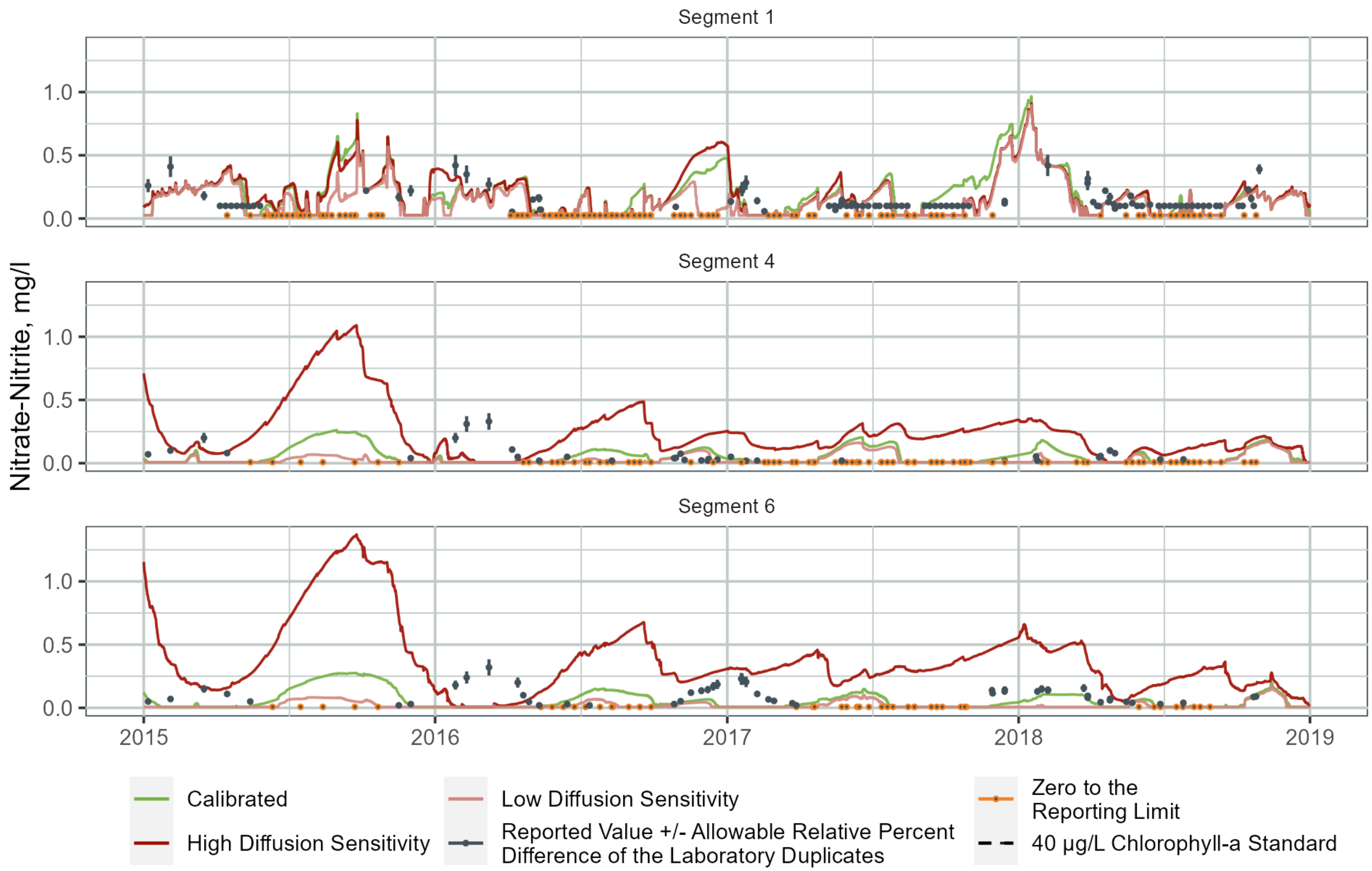

Figure B-81. Nitrate plus Nitrite Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

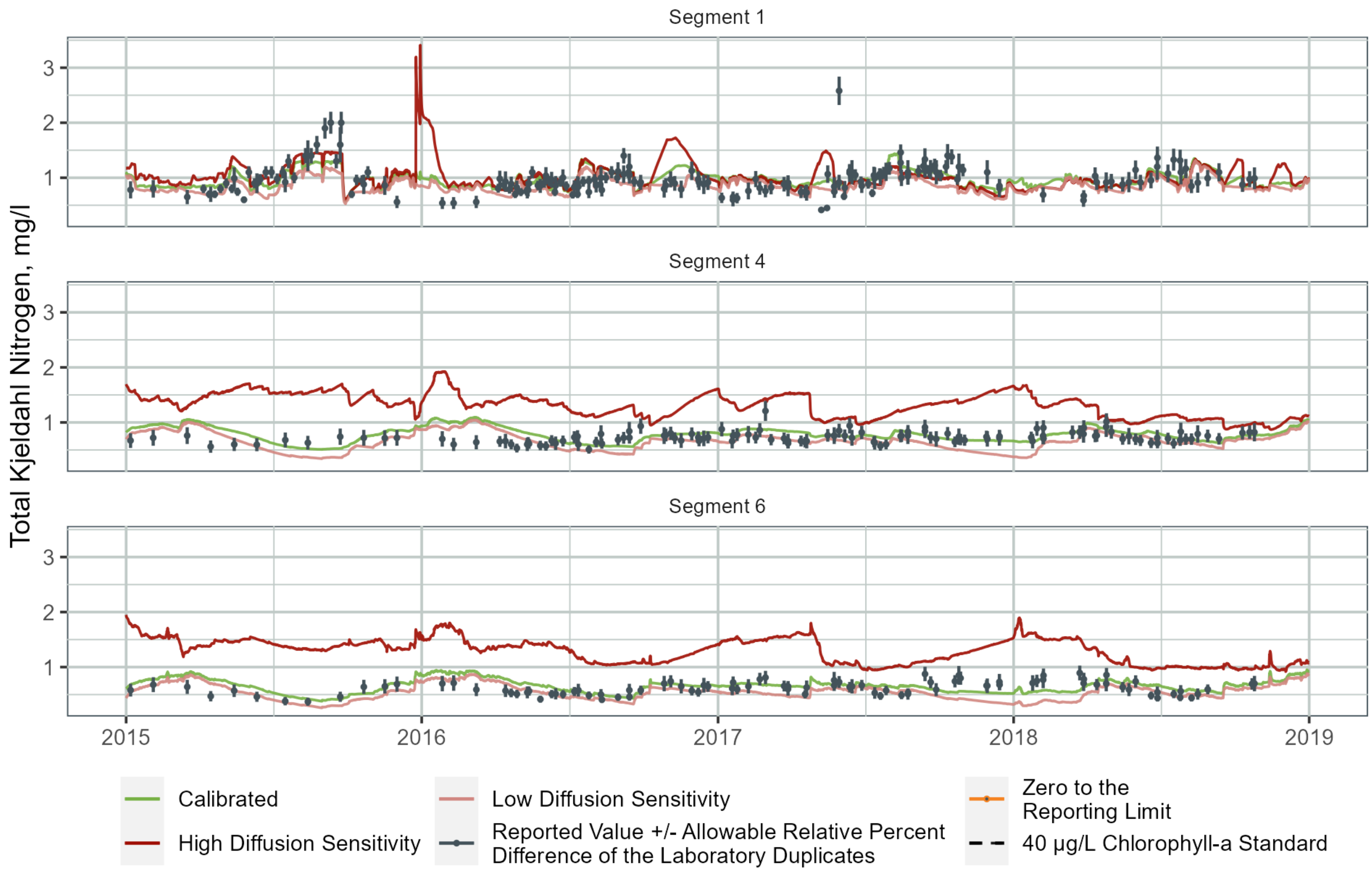

Figure B-82. TKN Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

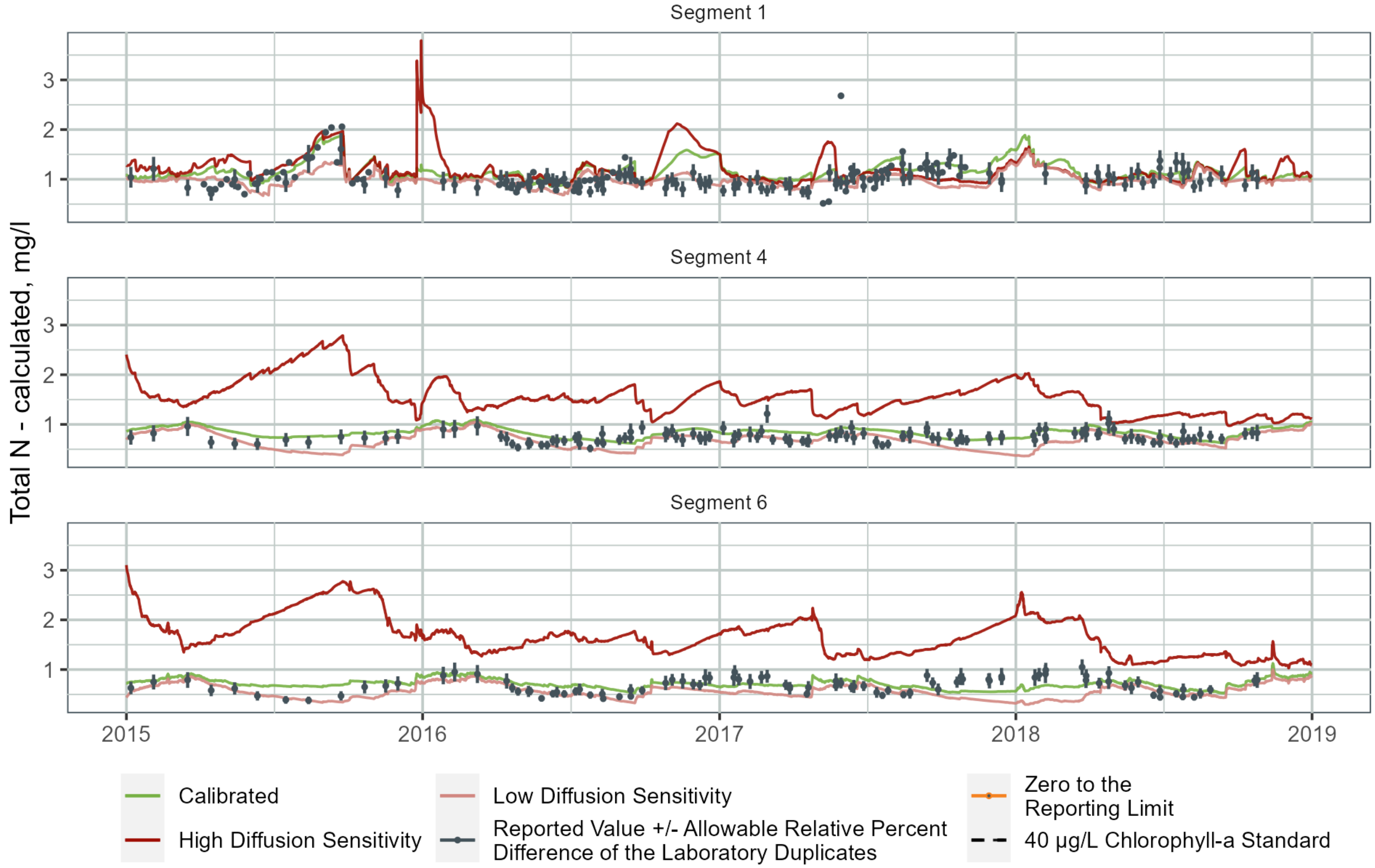

Figure B-83. TN Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

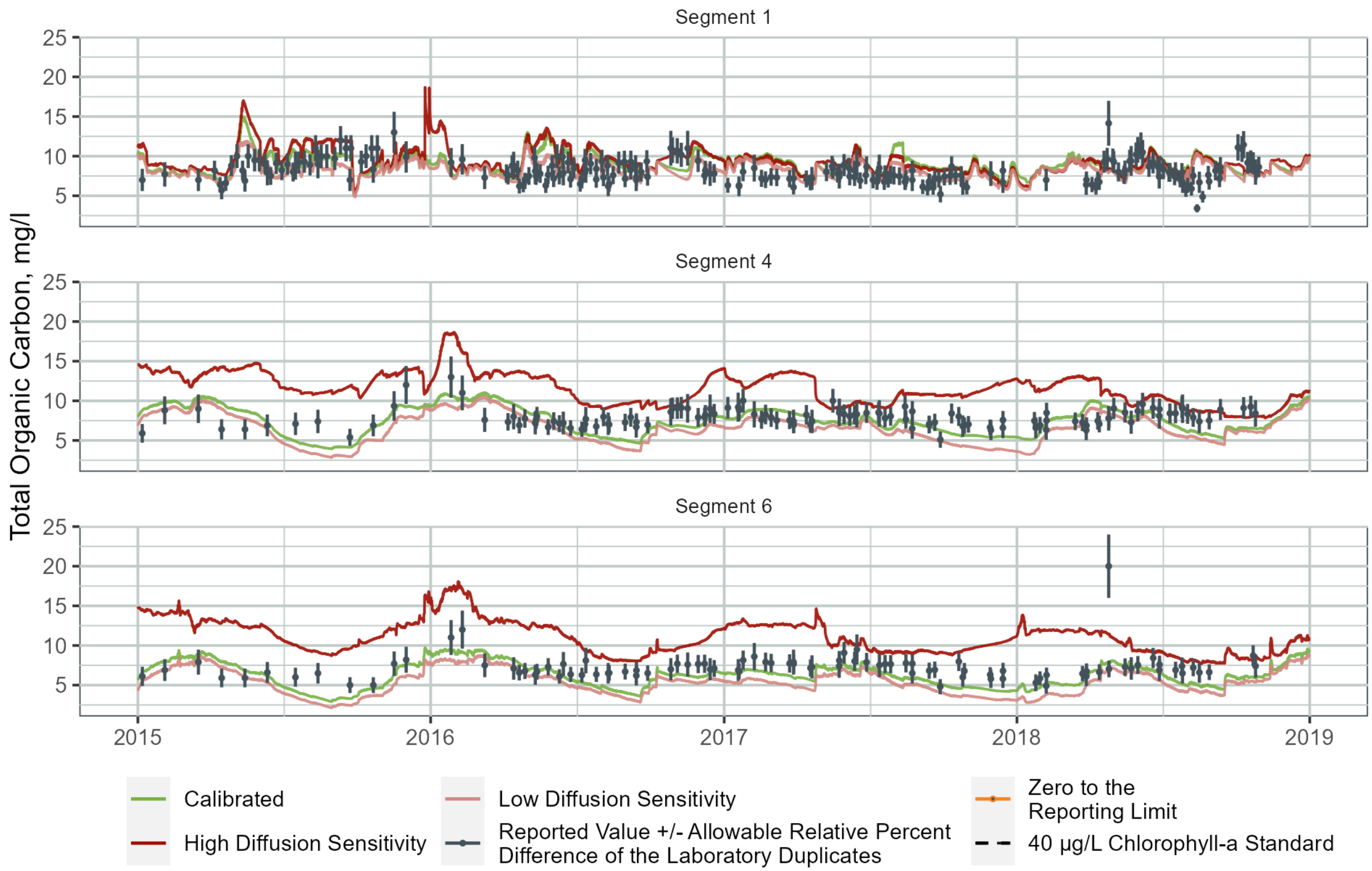

Figure B-84. TOC Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

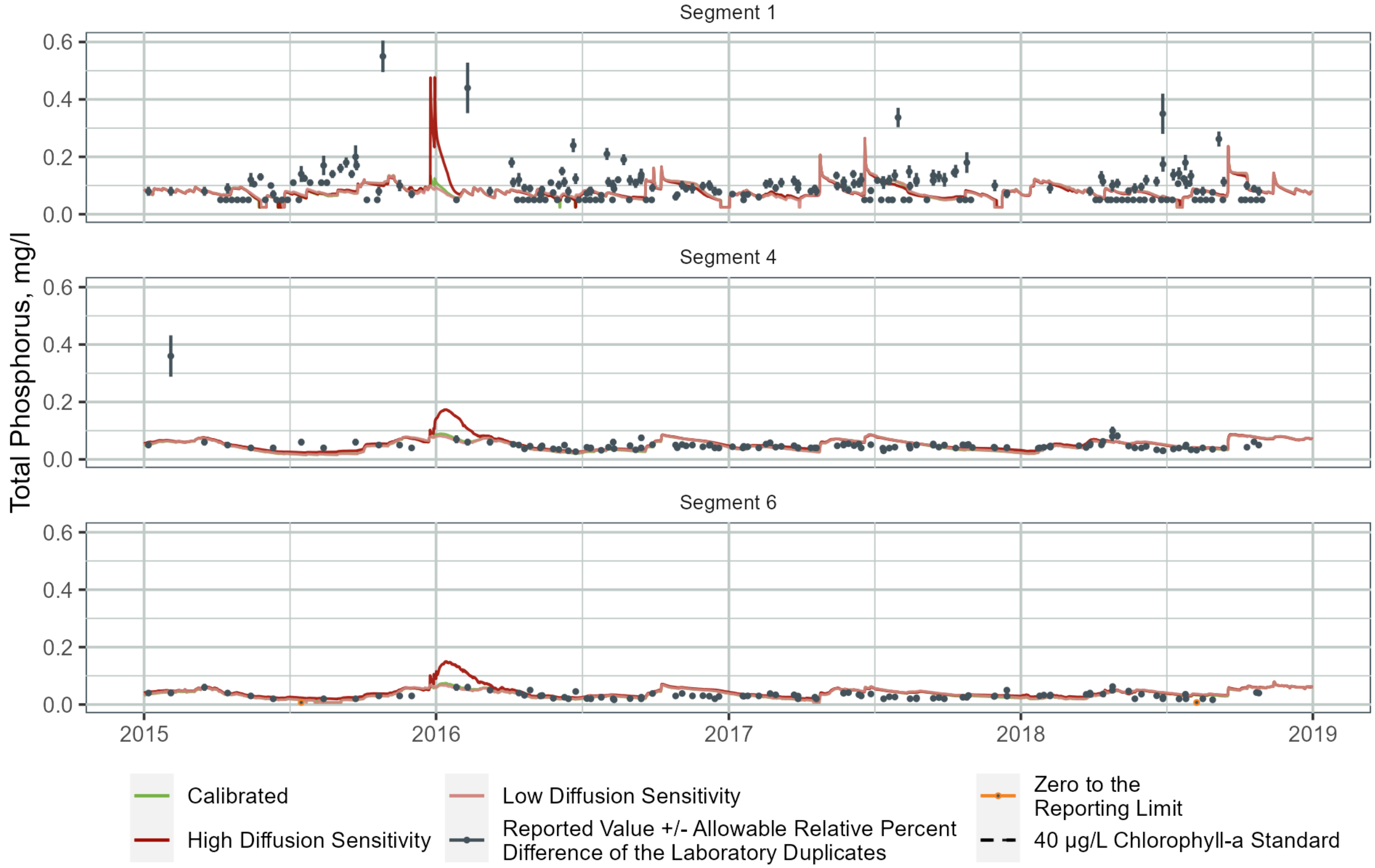

Figure B-85. TP Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

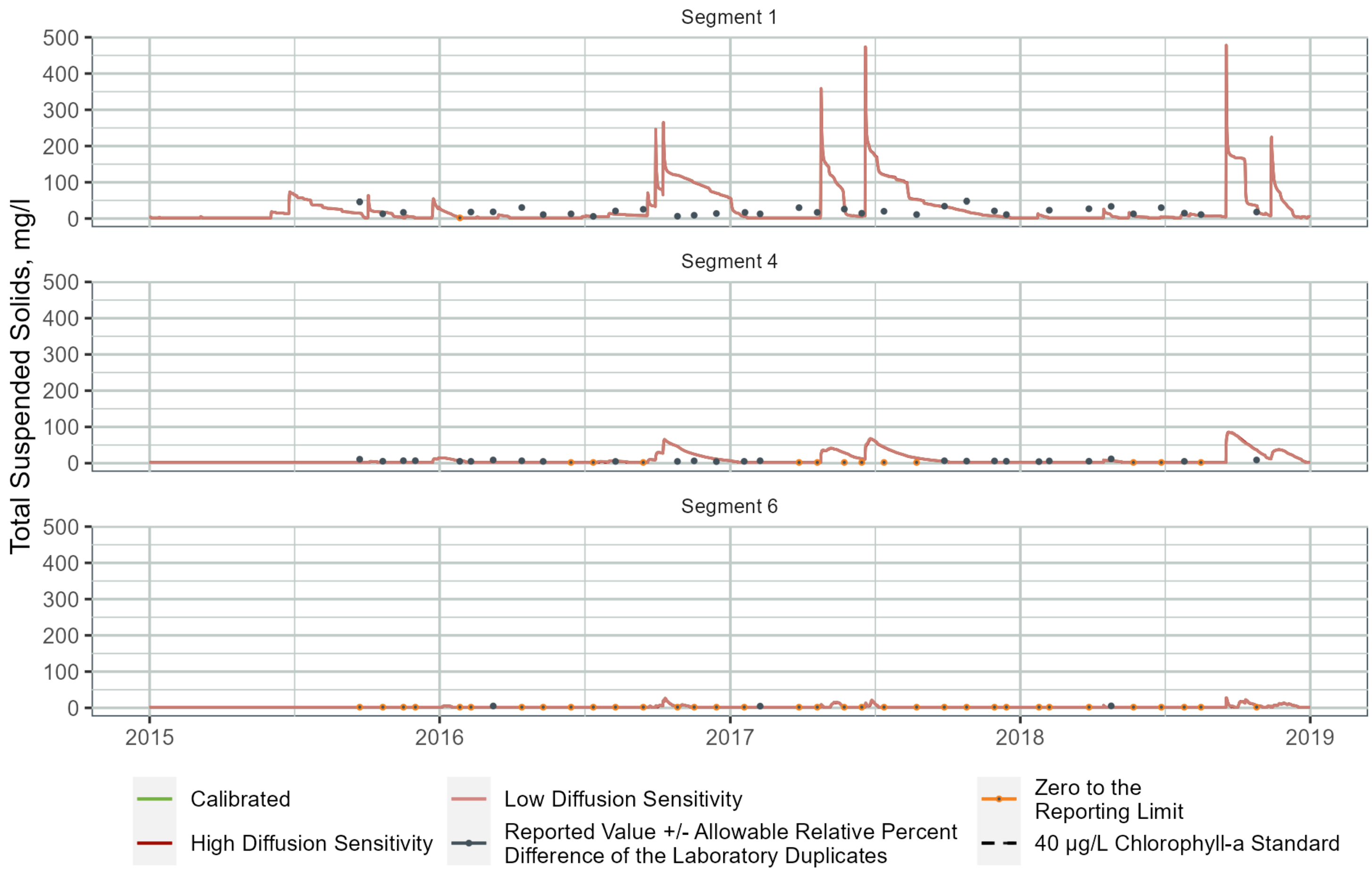

Figure B-86. TSS Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

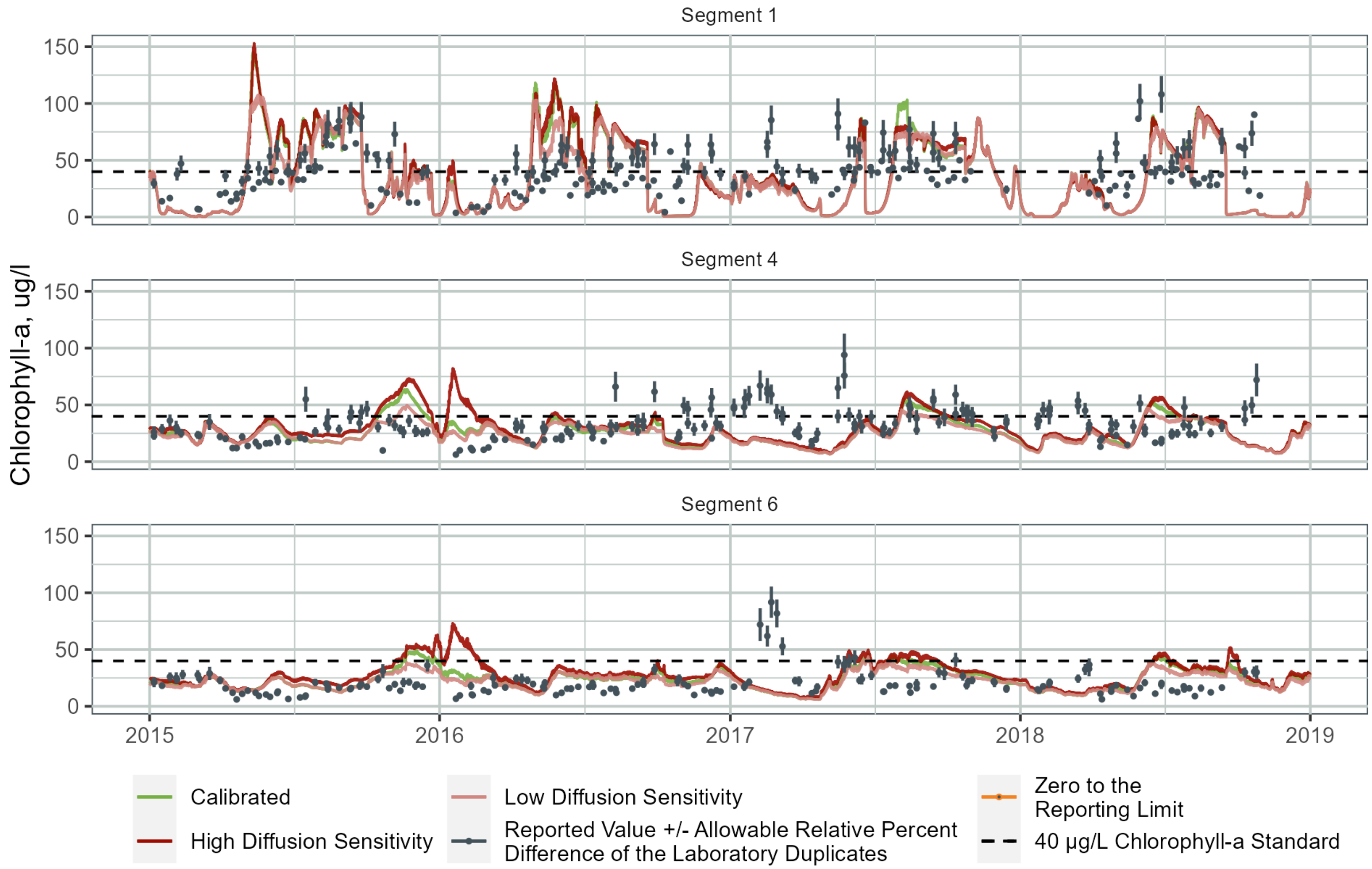

Figure B-87. Chlorophyll-a Sensitivity to Sediment Bed Diffusion Rate at Three WARMF Lake Segments

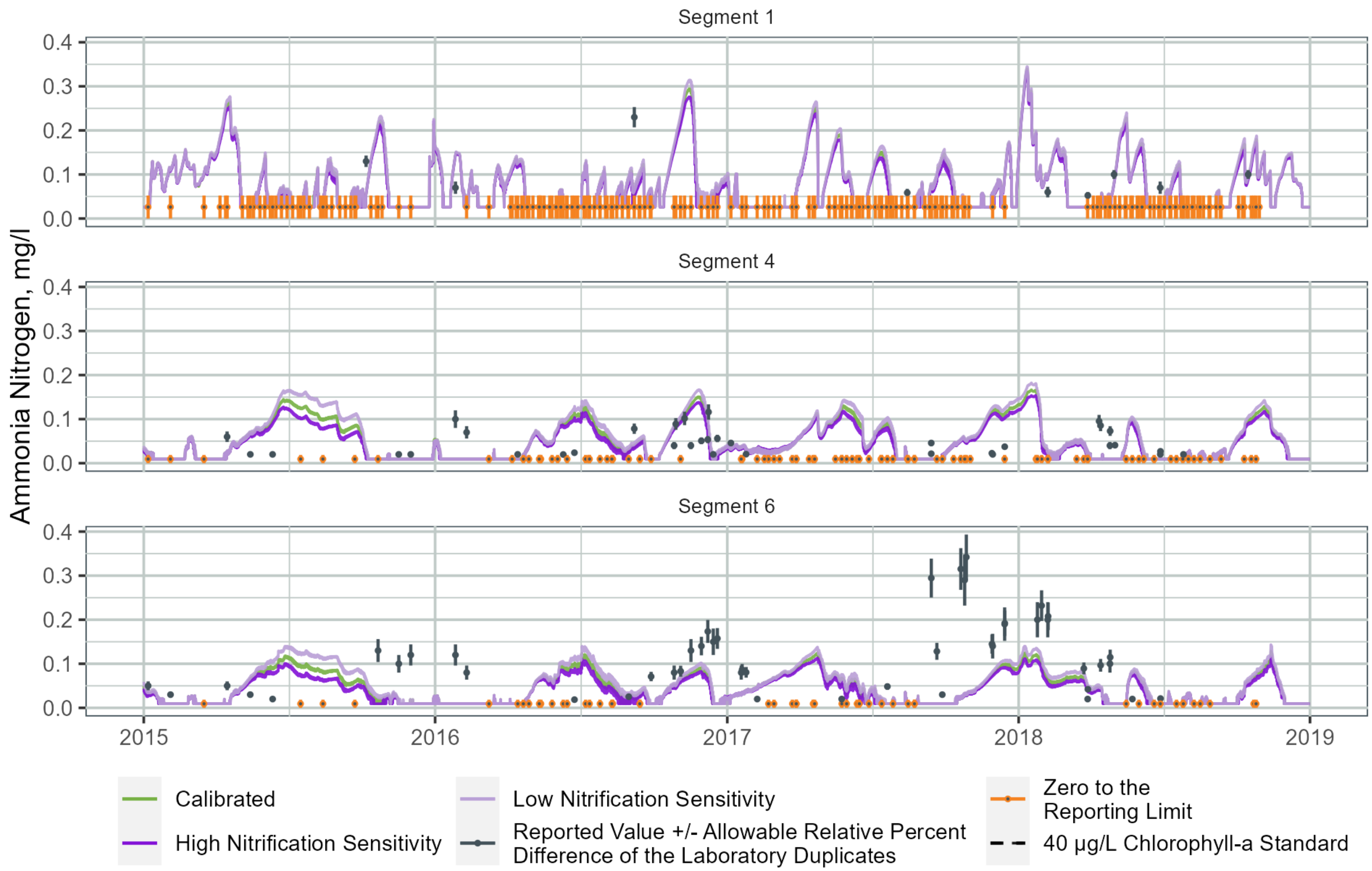

Figure B-88. Ammonia Sensitivity to Nitrification Rate at Three WARMF Lake Segments

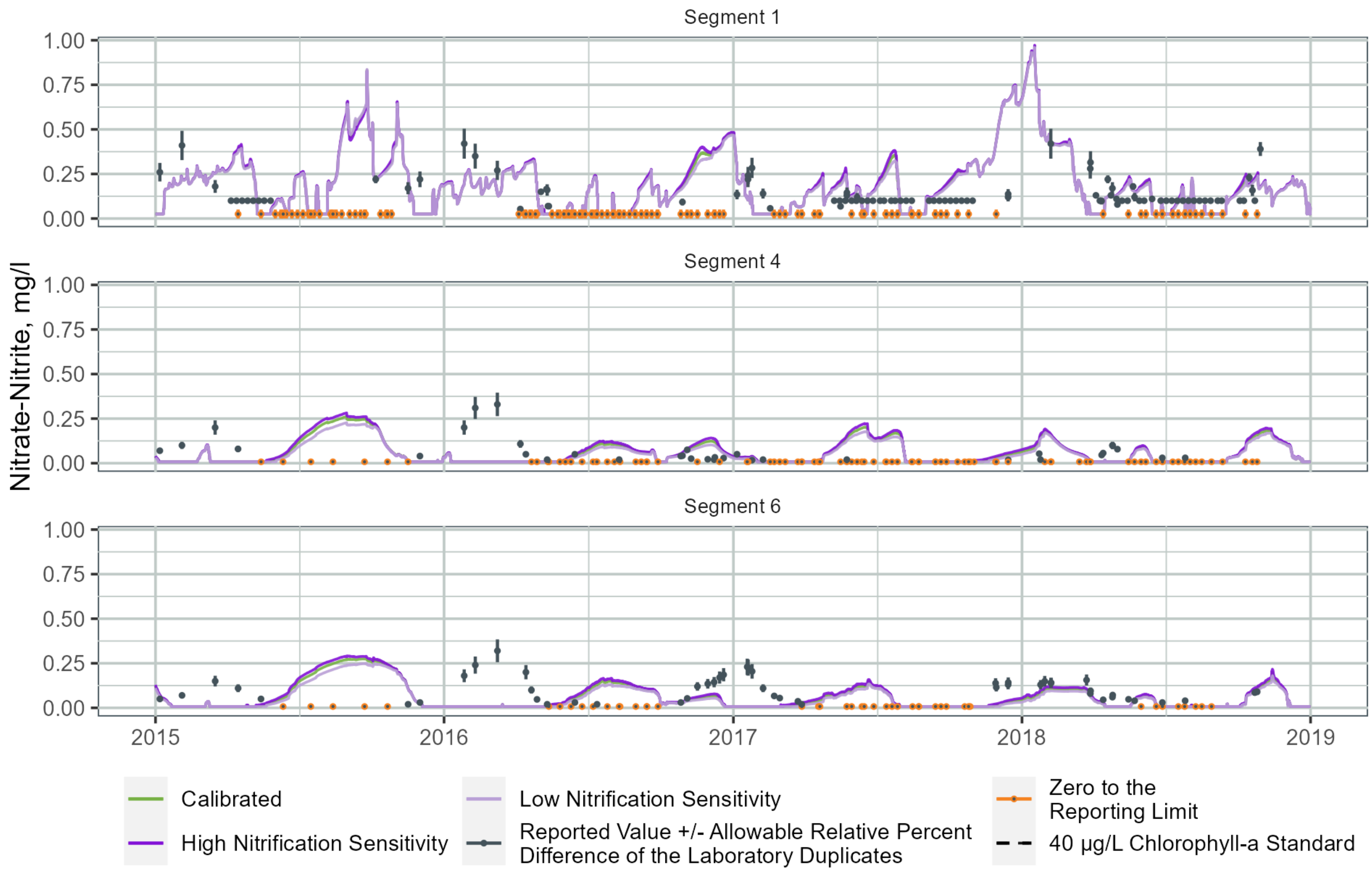

Figure B-89. Nitrate plus Nitrite Sensitivity to Nitrification Rate at Three WARMF Lake Segments

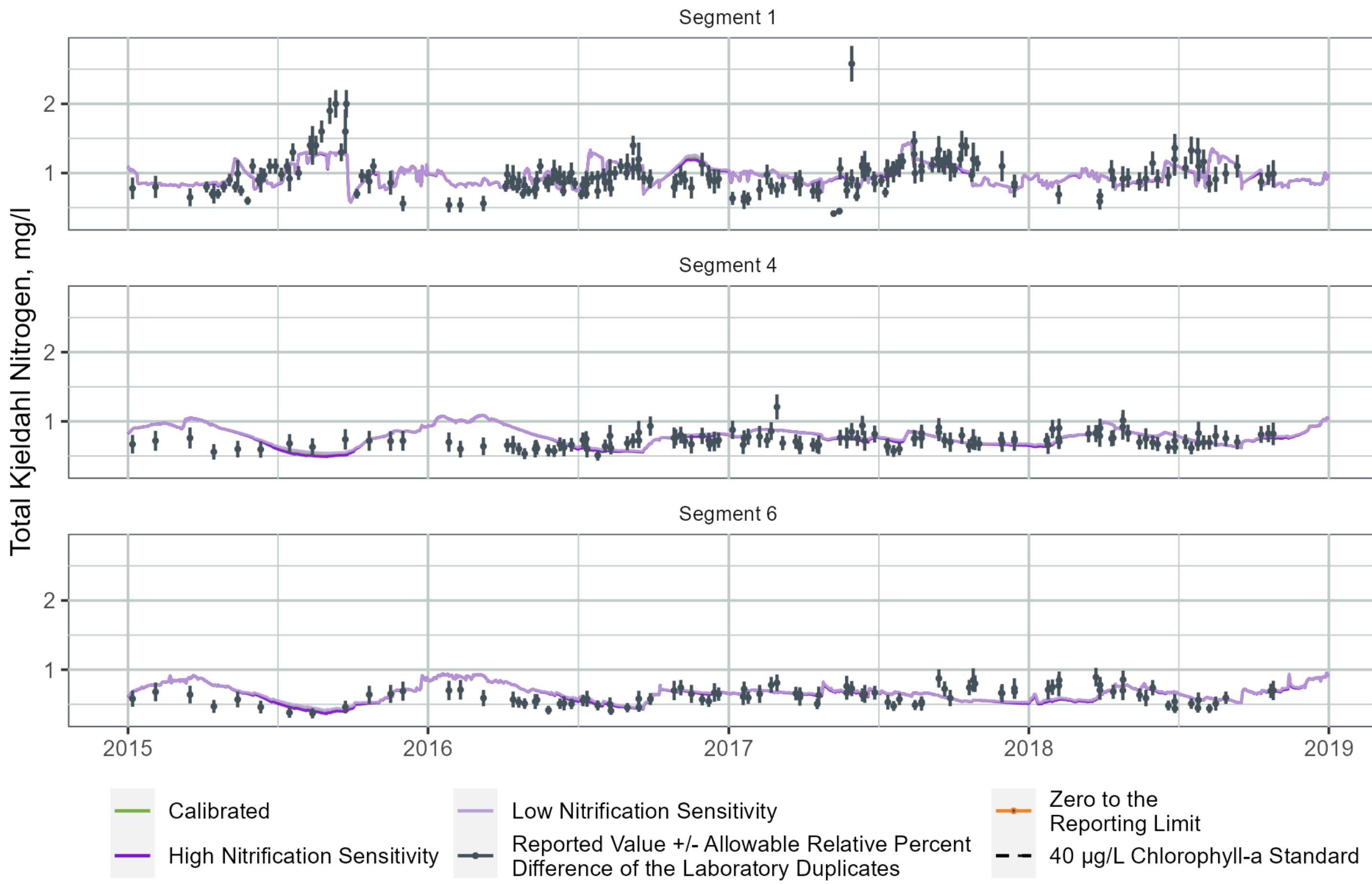

Figure B-90. TKN Sensitivity to Nitrification Rate at Three WARMF Lake Segments

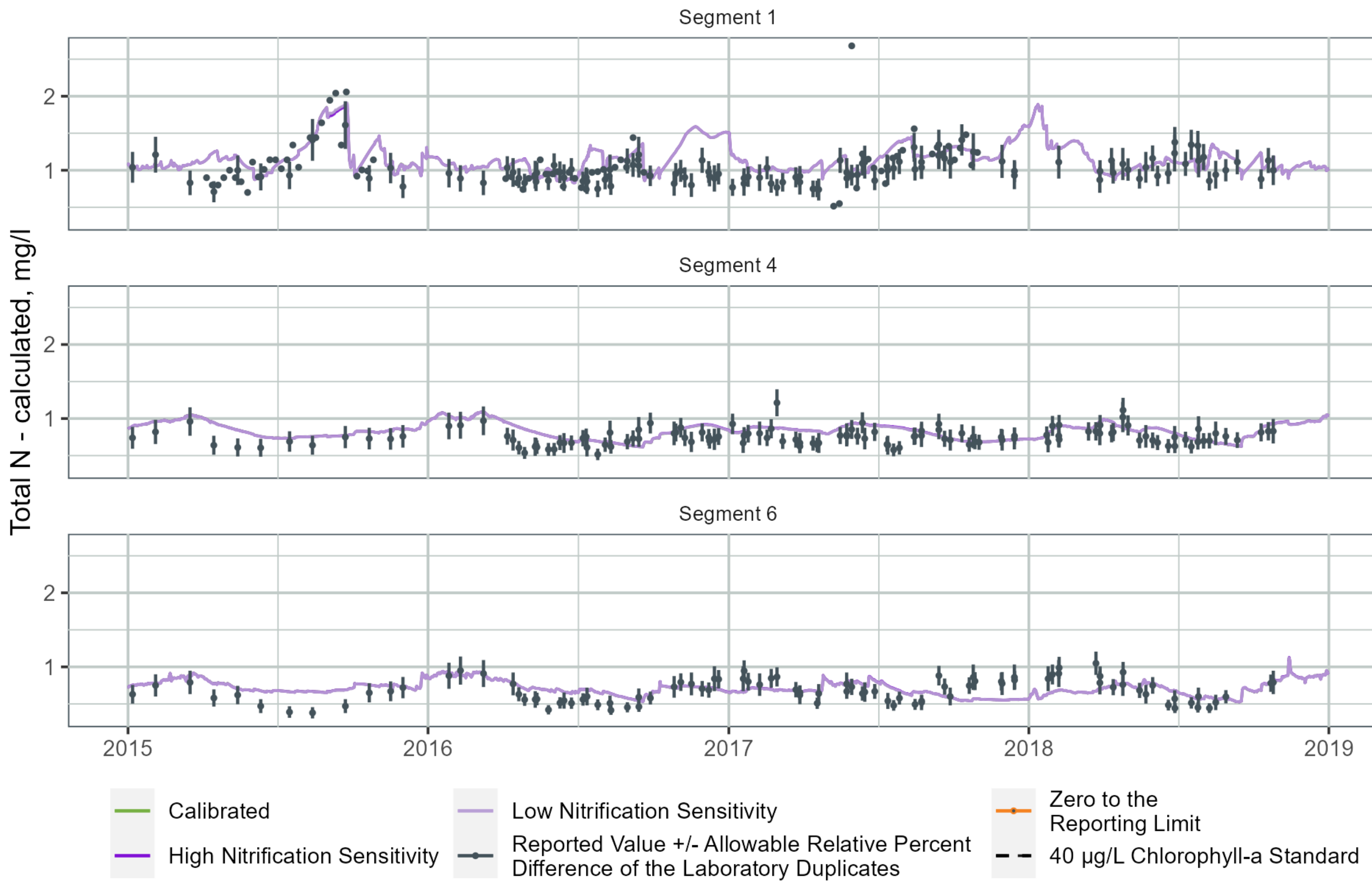

Figure B-91. TN Sensitivity to Nitrification Rate at Three WARMF Lake Segments

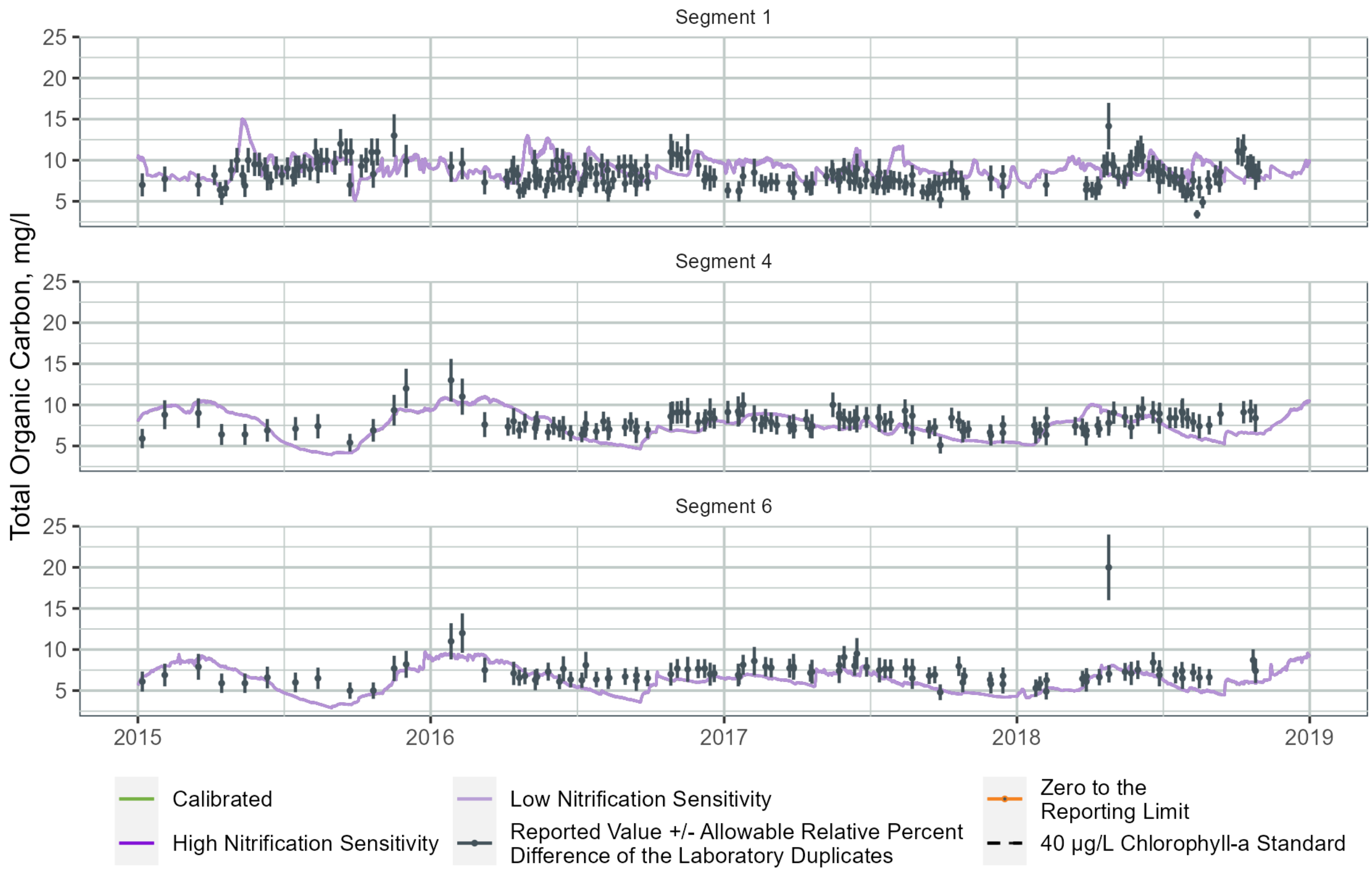

Figure B-92. TOC Sensitivity to Nitrification Rate at Three WARMF Lake Segments

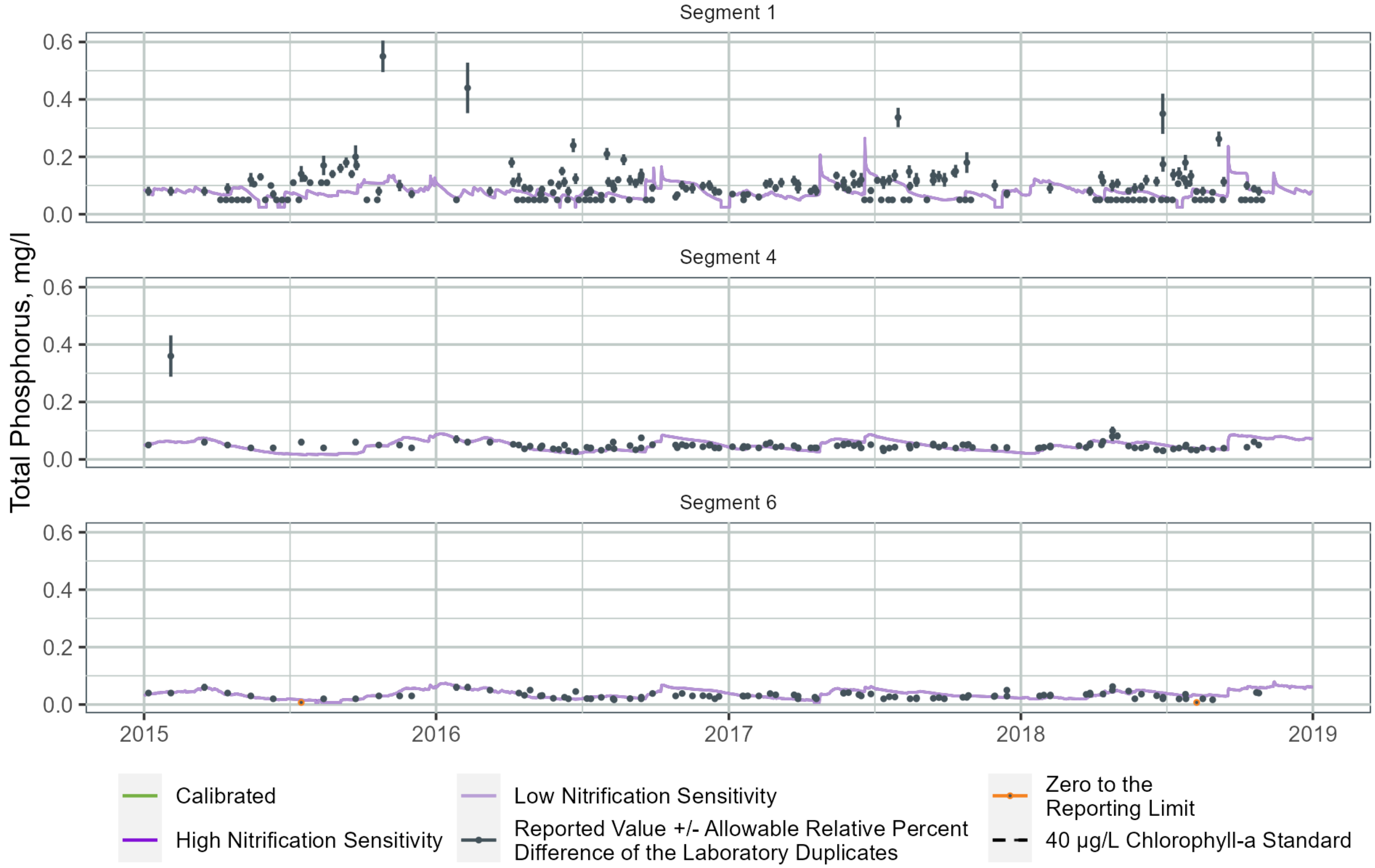

Figure B-93. TP Sensitivity to Nitrification Rate at Three WARMF Lake Segments

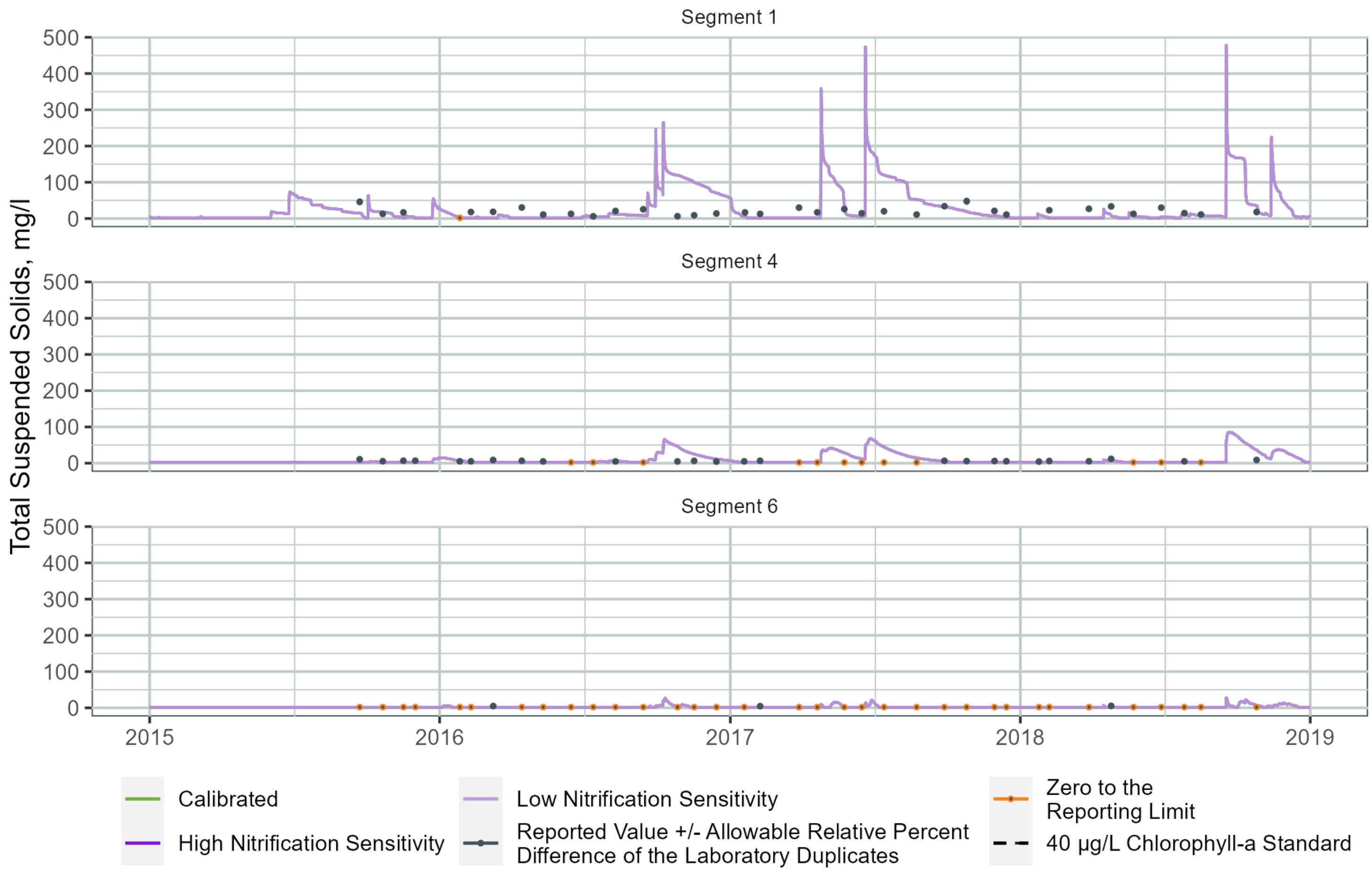

Figure B-94. TSS Sensitivity to Nitrification Rate at Three WARMF Lake Segments

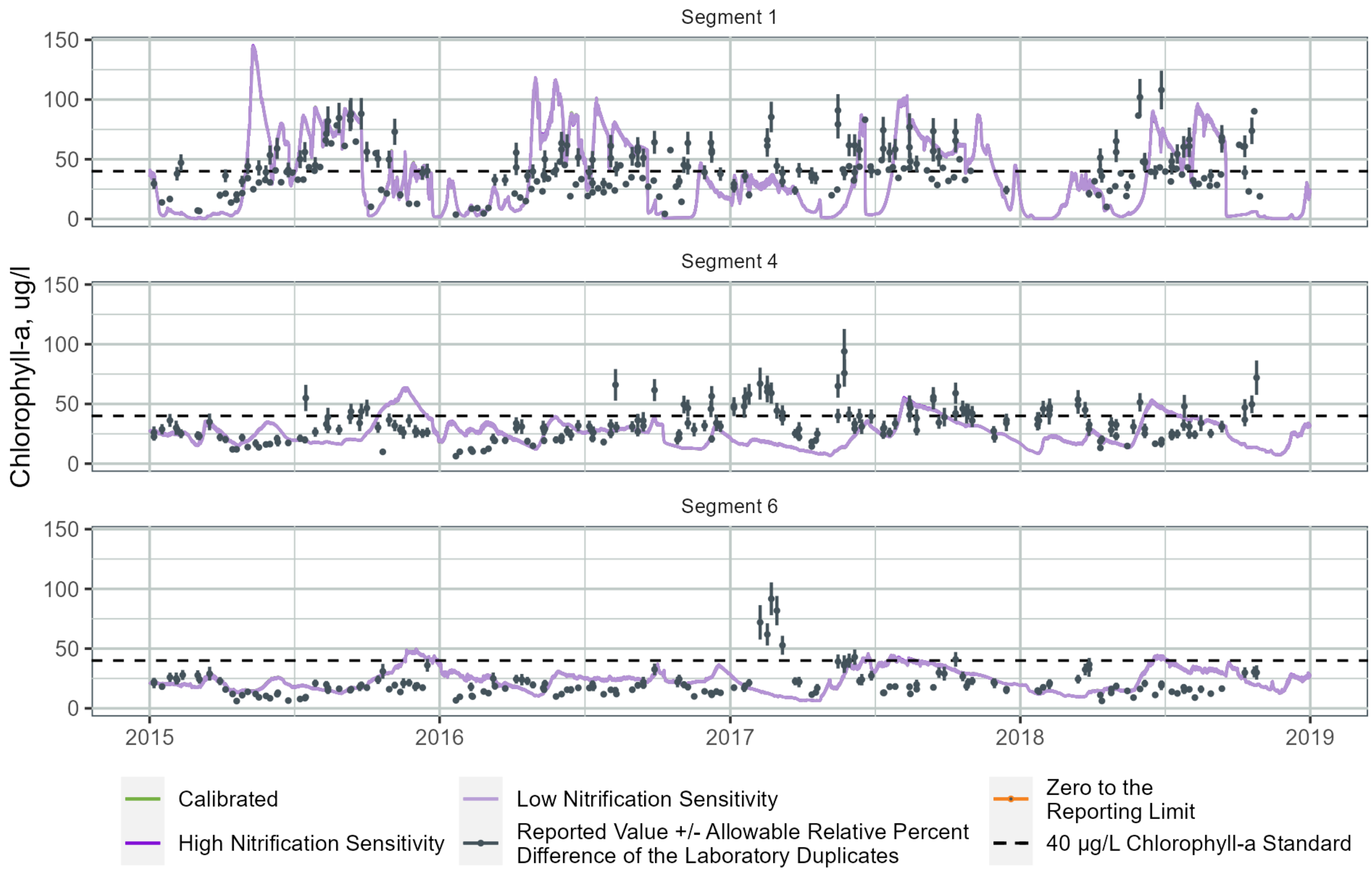

Figure B-95. Chlorophyll-a Sensitivity to Nitrification Rate at Three WARMF Lake Segments

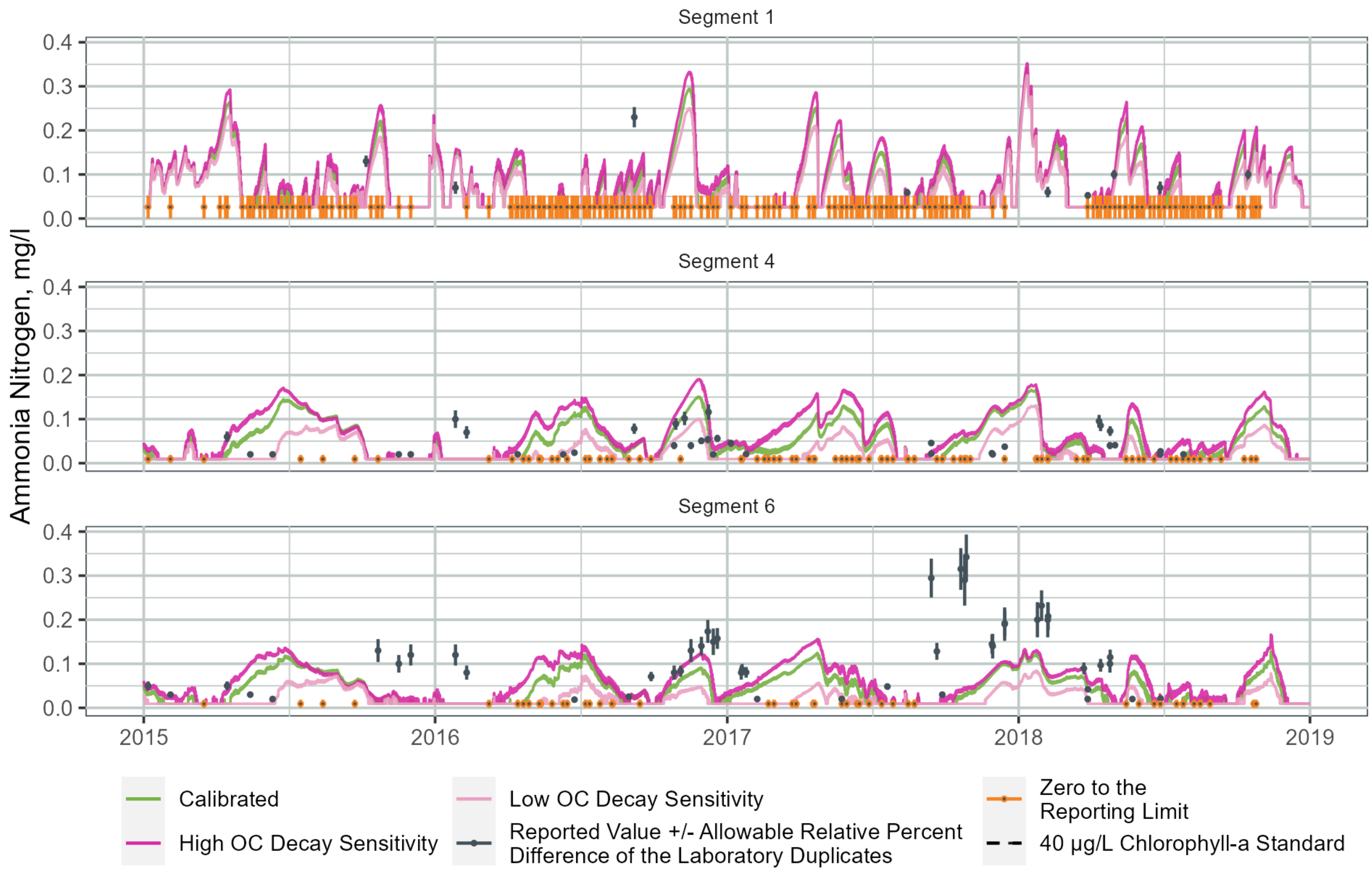

Figure B-96. Ammonia Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

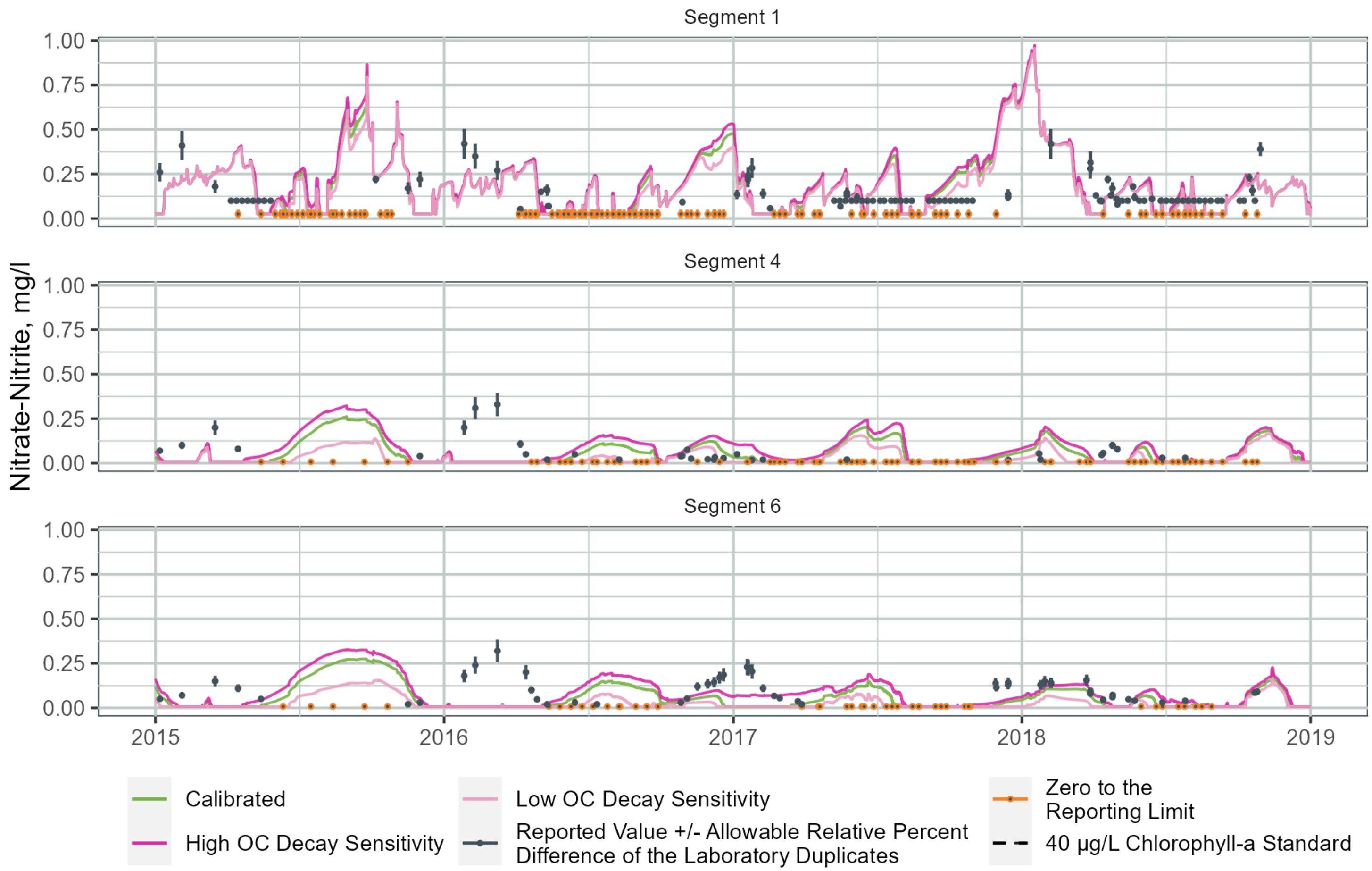

Figure B-97. Nitrate plus Nitrite Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

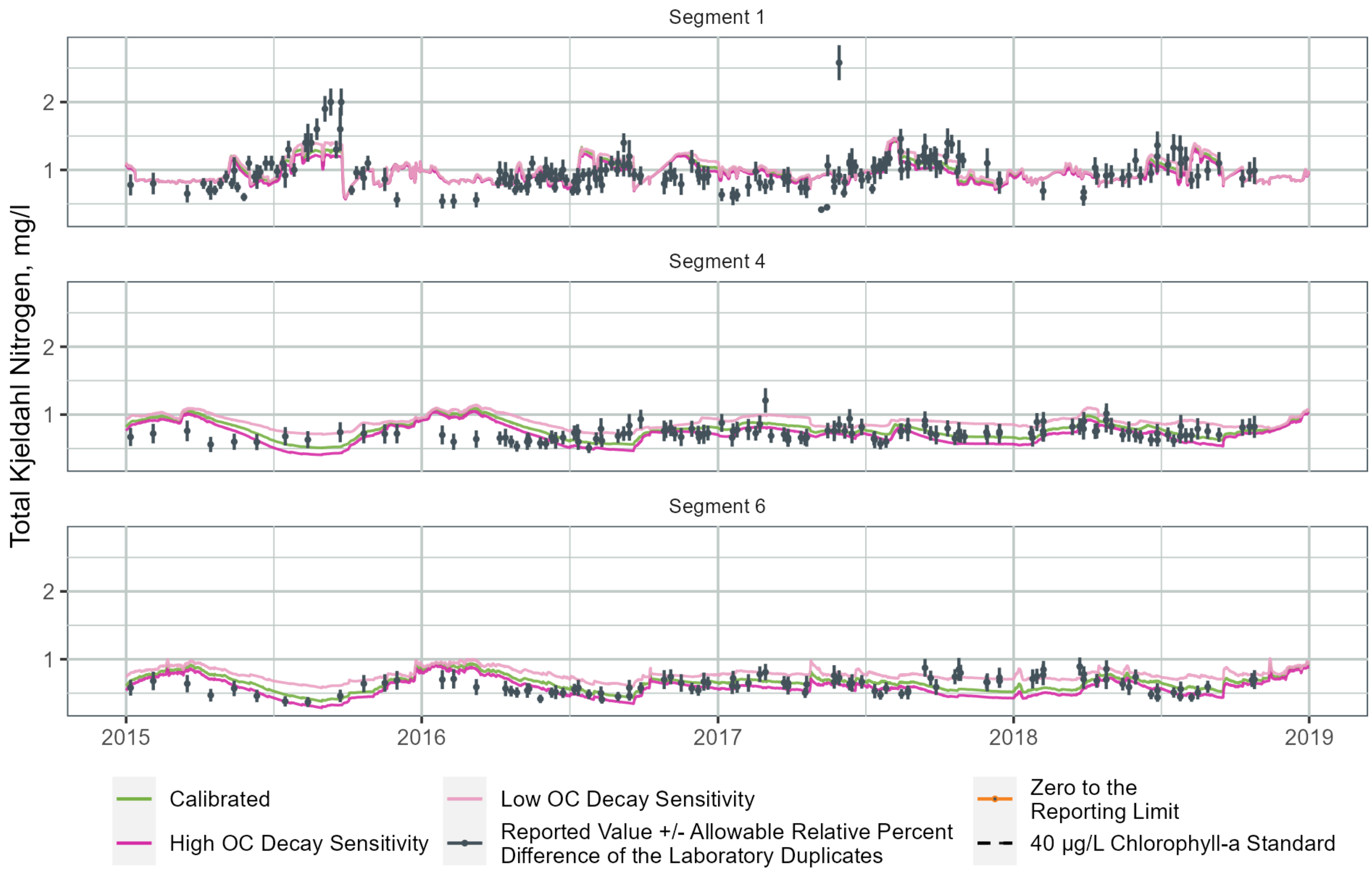

Figure B-98. TKN Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

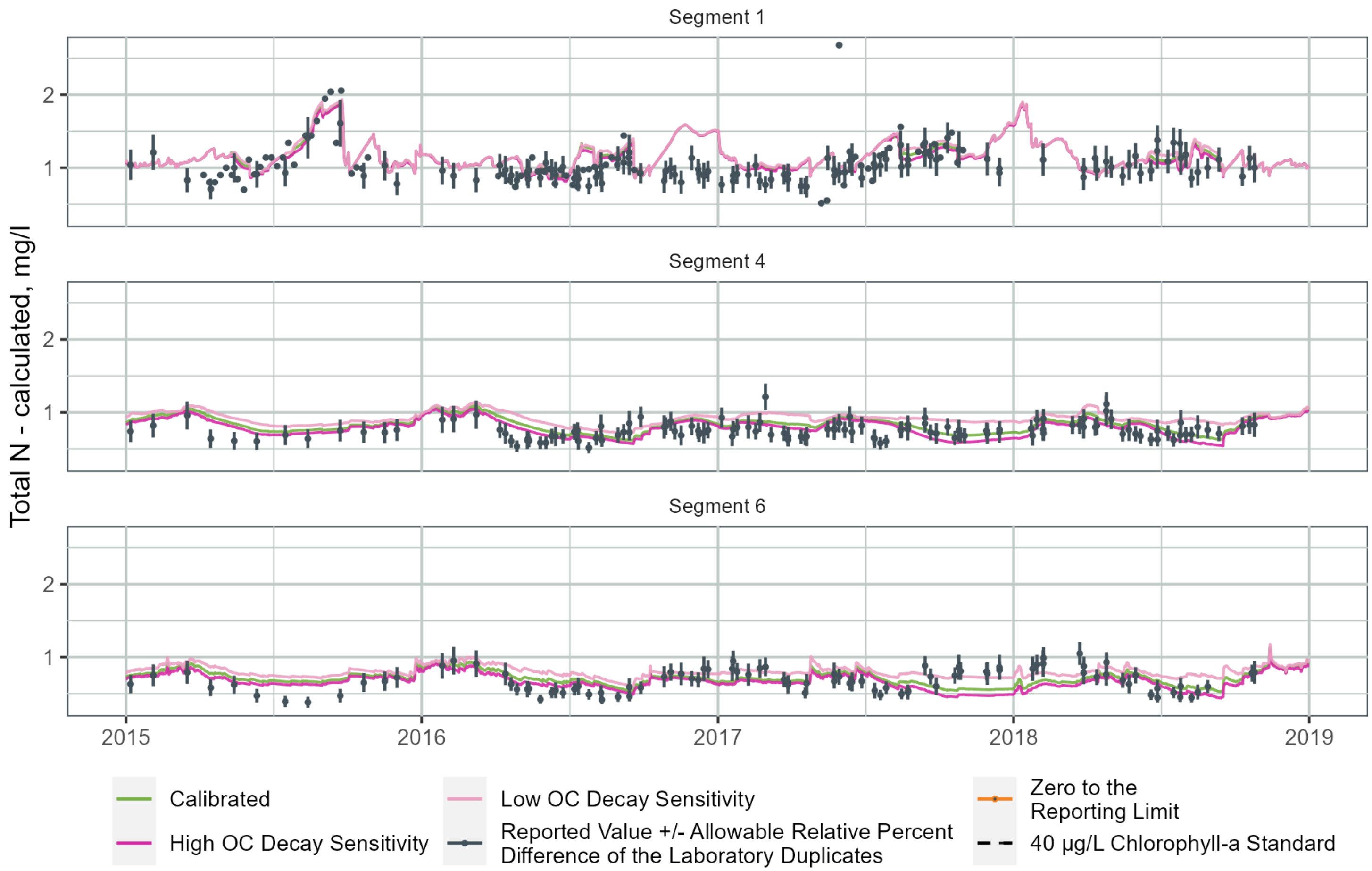

Figure B-99. TN Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

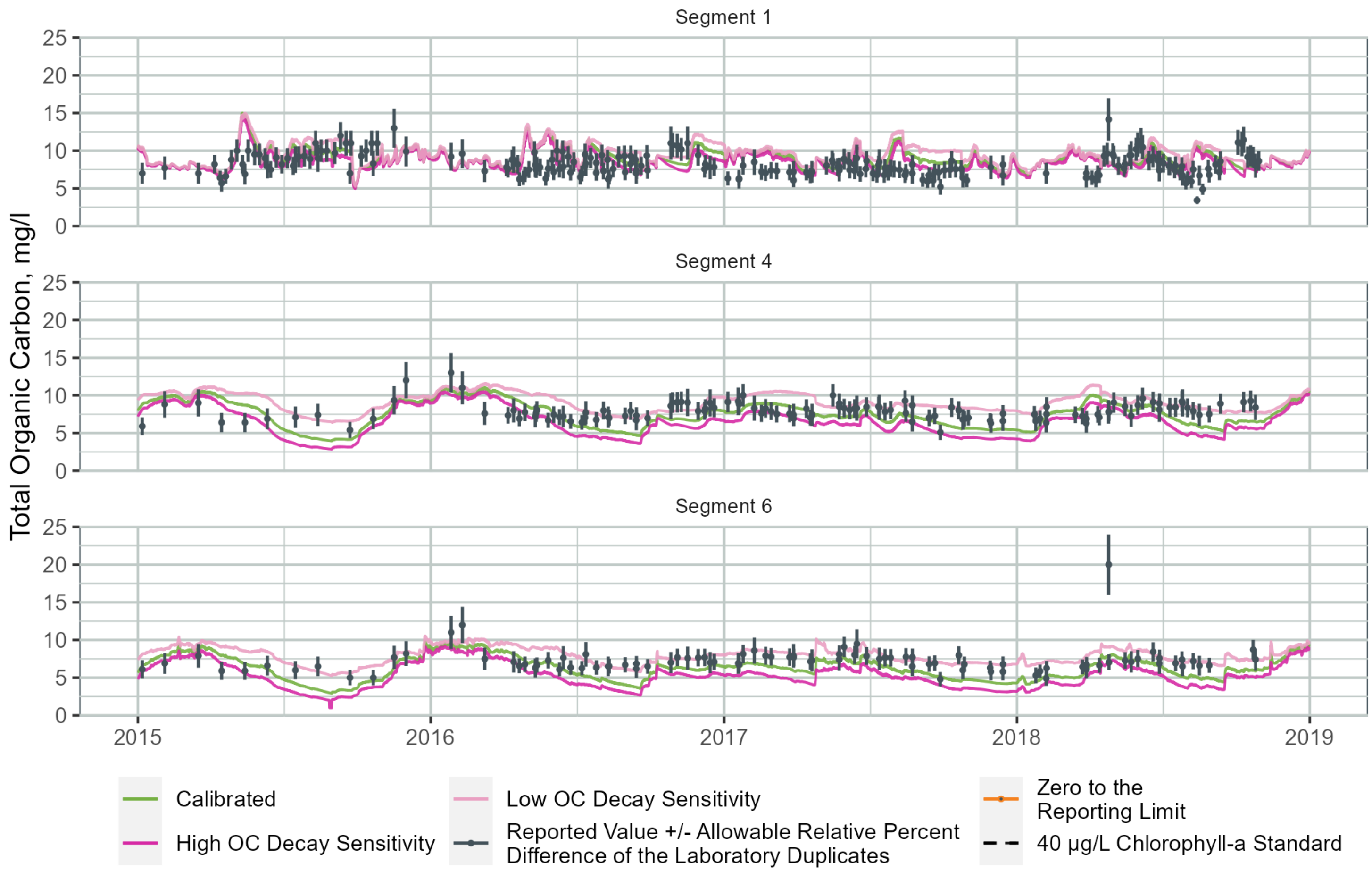

Figure B-100. TOC Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

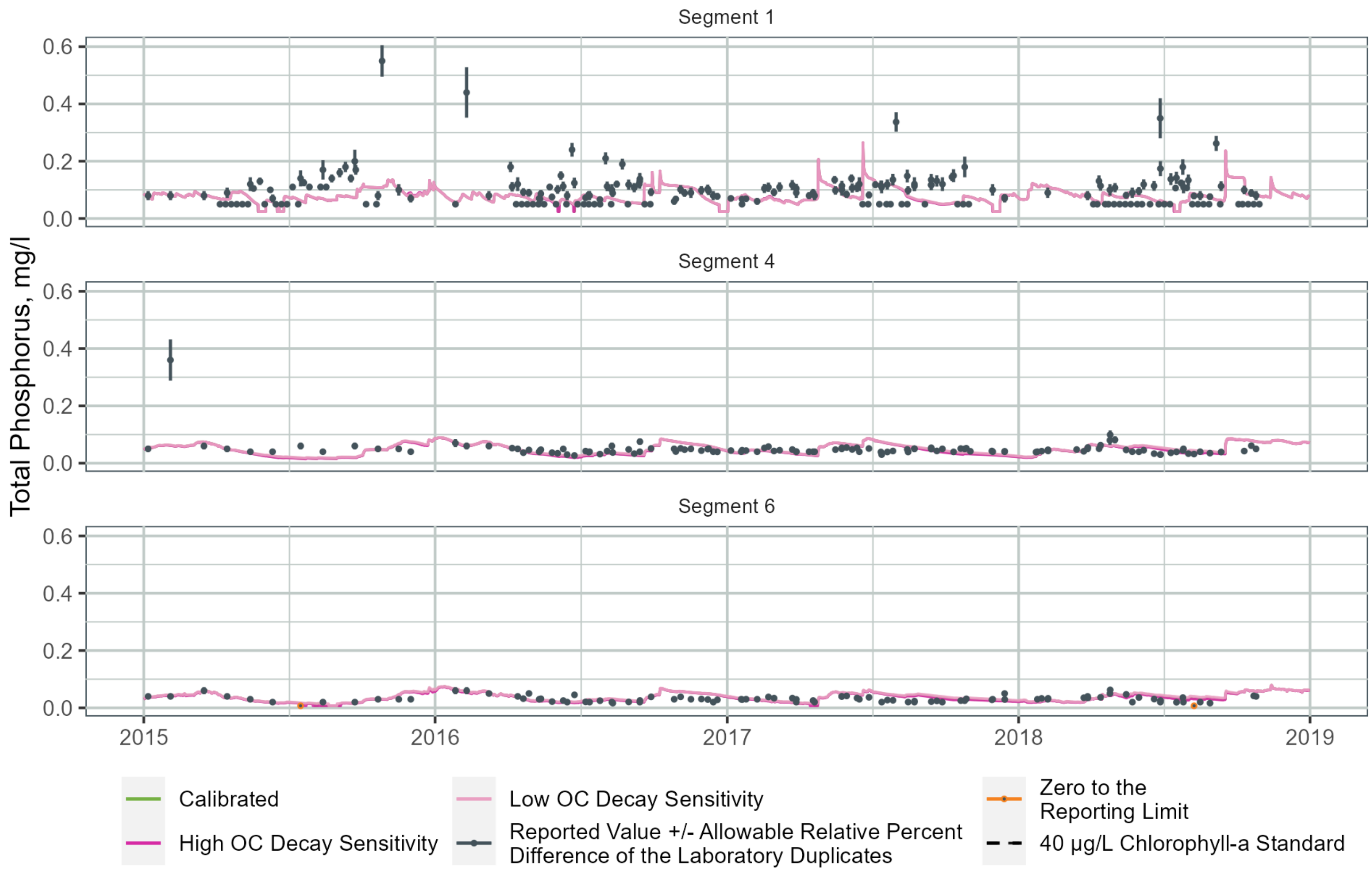

Figure B-101. TP Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

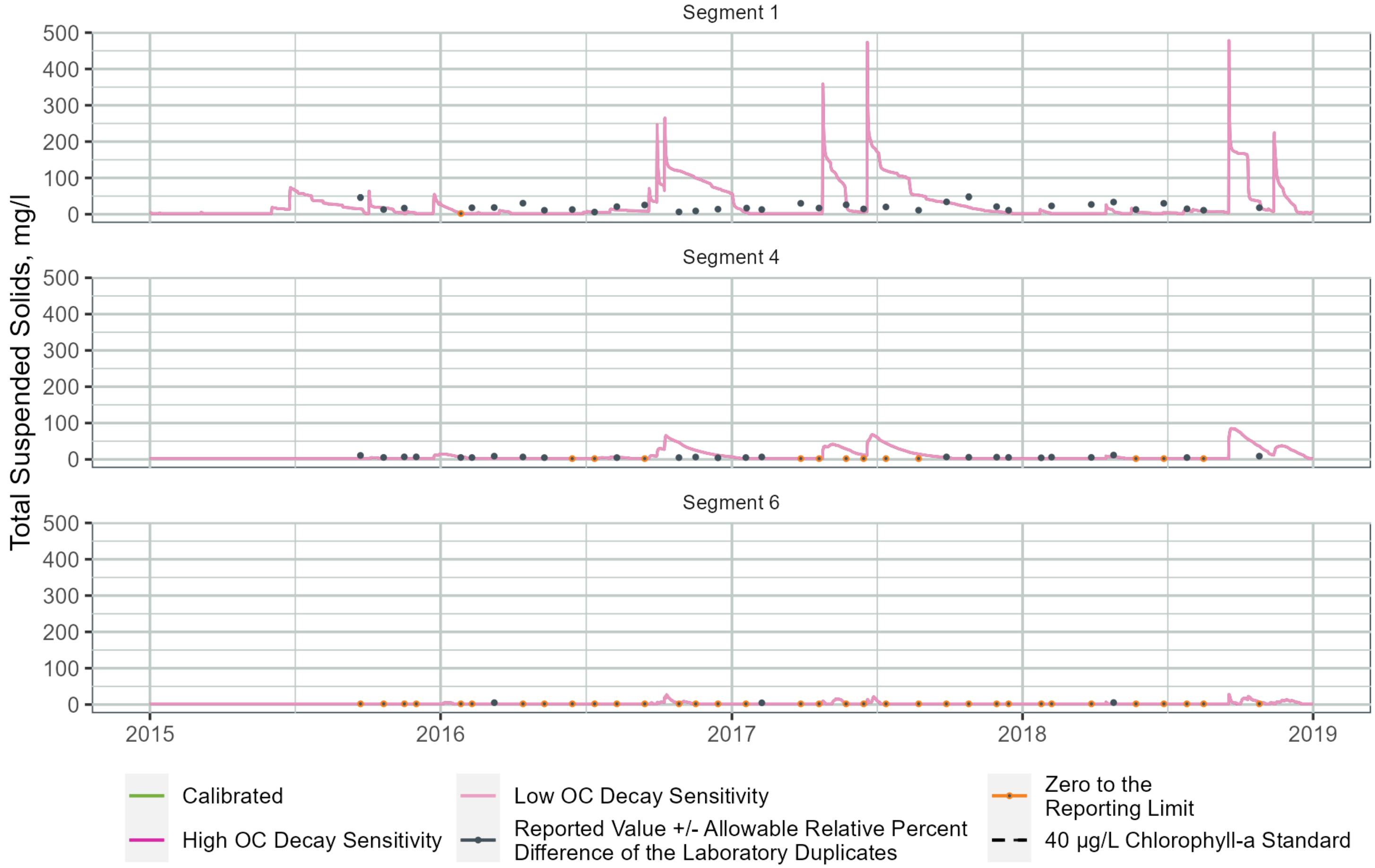

Figure B-102. TSS Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

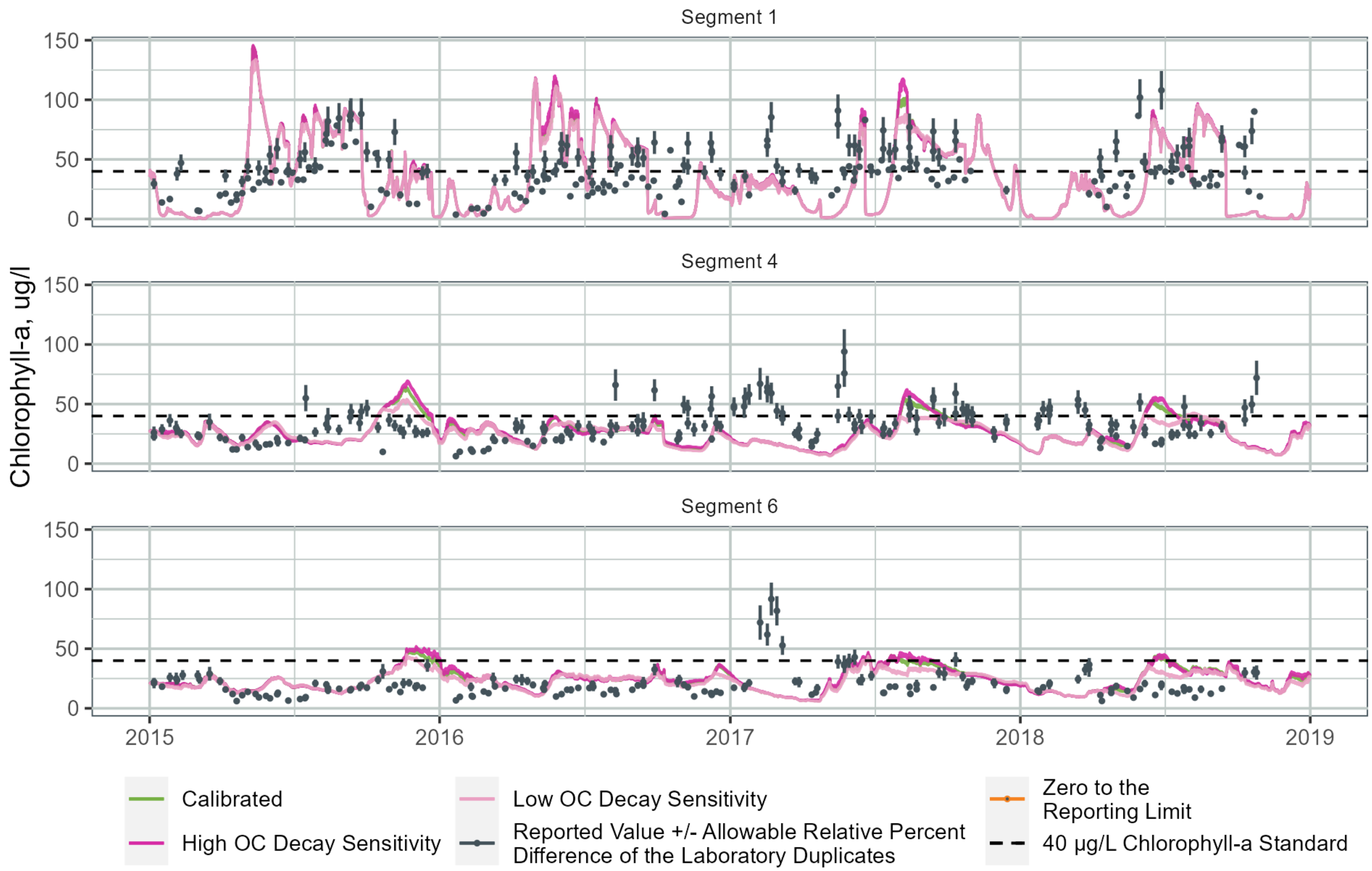

Figure B-103. Chlorophyll-a Sensitivity to Organic Matter Decay Rate at Three WARMF Lake Segments

Section 5: Scenario Analyses

The MRSW chose to apply the WARMF Lake model for scenarios dealing with changes in the watershed because the WARMF watershed and lake models are directly linked. All watershed-based scenarios evaluated with WARMF Lake were run for five iterations (25 years) as described in the UNRBA Watershed Modeling Report (BC and Systech Water Resources 2023). To reflect the correct starting conditions for the lake sediments during the study period, the Falls Lake sediments were set to initial conditions at the beginning of each model iteration. The initial conditions for the Falls Lake sediments are based on sediment quality data collected in 2016, so resetting them each time the model is run provides a better representation of conditions during the study period (2014 to 2018).

As with the calibration figures provided in Section 3.3.2, the scenario figures display three example WARMF Lake segments:

- Segment 1 upstream of Interstate 85
- Segment 4 between Rolling View marina and Highway 50
- Segment 6 between Highway 98 and the dam

5.1.1 WARMF Lake Simulation of Land Conversion to Forests and Removal of Nutrient Application and Wastewater-Related Discharges

The Scenario Screening Workgroup (SSG) of the MRSW selected this scenario to place a limit on what would be possible in Falls Lake with most human watershed inputs and impacts instantaneously removed. While there is no logistical way to reforest the watershed and remove humans and their impacts, this scenario simulates the "best case" condition for the watershed and the lake under a hypothetical condition given the size of the watershed, current soil characteristics, and current rates of atmospheric deposition. The human inputs and impacts removed from this scenario include point source discharges, nutrient application, impervious surfaces, and onsite wastewater treatment systems. All land uses except for wetlands and sub-impoundments were converted to mixed forest for this scenario. Rates of atmospheric deposition rates are assumed to remain at current levels.

This scenario establishes the lowest potential watershed-based land use loading to Falls Lake and the resulting lake water quality if conditions on the ground were to change instantaneously. This "all forest" scenario is further described in the UNRBA Watershed Modeling Report (BC and Systech Water Resources 2023). Figure B-104 through Figure B-107 show the simulated and observed total nitrogen, total phosphorus, chlorophyll-a, and total organic carbon concentrations, respectively for this scenario (light green line) and the calibrated WARMF Lake model (dark green line).

For both the "all forest" scenario and the calibrated model, the upper lake has higher and more variable nutrient and chlorophyll-a concentrations than the lower lake. In the upper lake, the "all forest" scenario has lower chlorophyll-a concentrations than the calibrated model, but this scenario still exceeds the 40 µg/L chlorophyll-a standard (dashed line) in the upper lake approximately 31 percent of the time. For the calibrated model (2015 to 2018 conditions), 37 percent of the simulated chlorophyll-a values exceed 40 µg/L at this location. Therefore, while the percent exceedance decreases, not even this hypothetical scenario can meet the chlorophyll-a standard everywhere, all the time in Falls Lake. In other words, it is not possible to achieve the chlorophyll-a standard in Falls Lake as currently applied.

The impacts of this scenario on simulated lake water quality are less pronounced in the middle and lower lake segments where the simulated nutrient and chlorophyll-a concentrations are similar for most of the simulation period for both scenarios. However, the "all forest" scenario reduces the frequency of chlorophyll-a exceedances from 11 percent to 8 percent in Segment 4 and from 6 percent to 0.6 percent in Segment 6. The "all forest" scenario could theoretically result in attainment of the standard near the dam, but it would not result in attainment at other lake stations. The "all forest" scenario is not intended to represent a feasible solution to meeting the chlorophyll-a standard, and removal of residents from the watershed is not being proposed. It is rather used to illustrate the infeasibility of meeting the 40 µg/L chlorophyll-a standard as it is currently applied in Falls Lake.

Not even this hypothetical "all forest" scenario can meet the chlorophyll-a standard everywhere, all the time in Falls Lake.

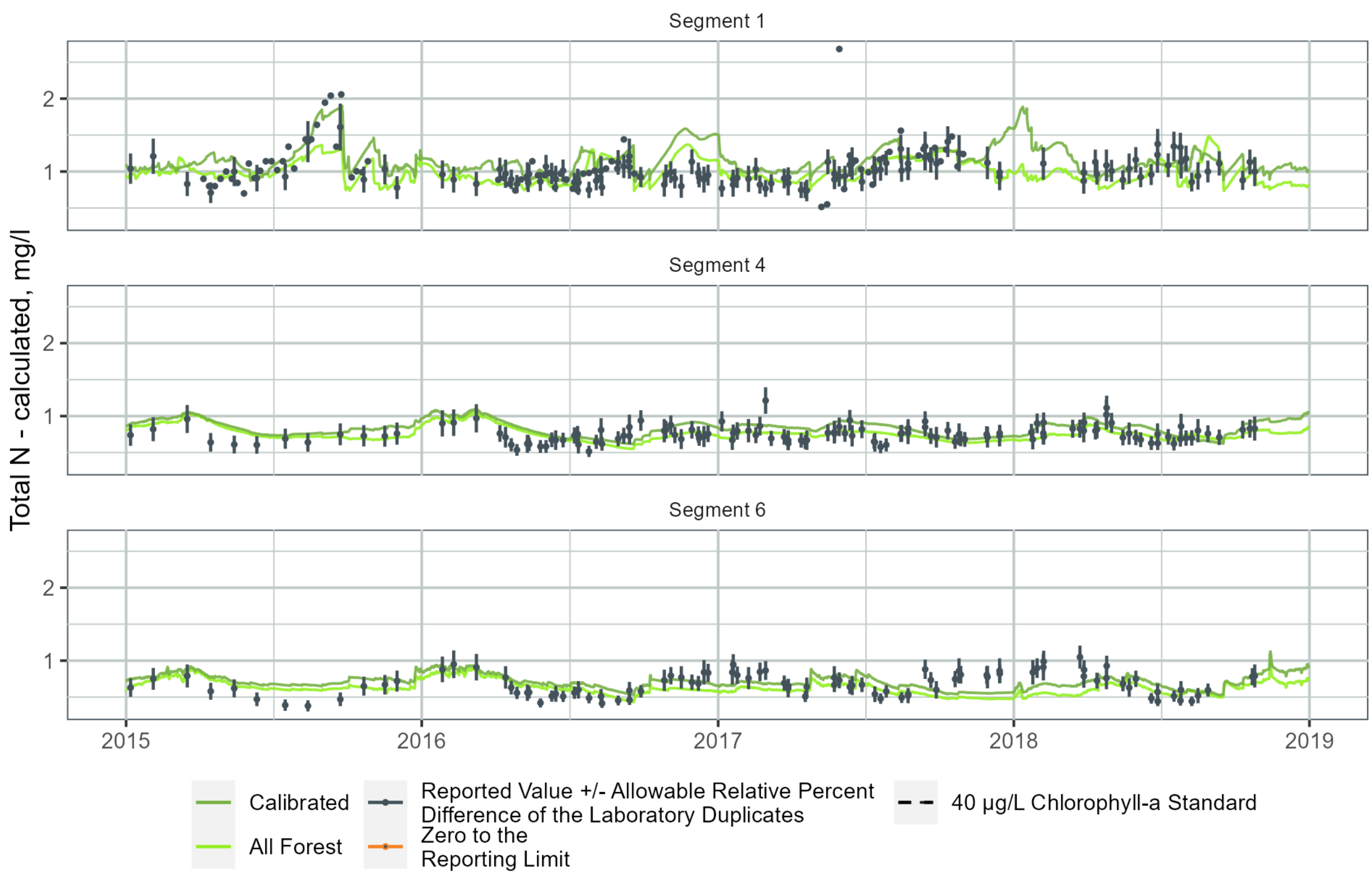

Figure B-104. WARMF Lake Simulated Total Nitrogen Concentrations for the Calibrated Model Compared to the Instantaneous Land Conversion to All Forest with Elimination of Onsite and Centralized Wastewater Treatment Discharges and Nutrient Application to Land Surfaces (Atmospheric Deposition is not Altered from the Calibrated Model) in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

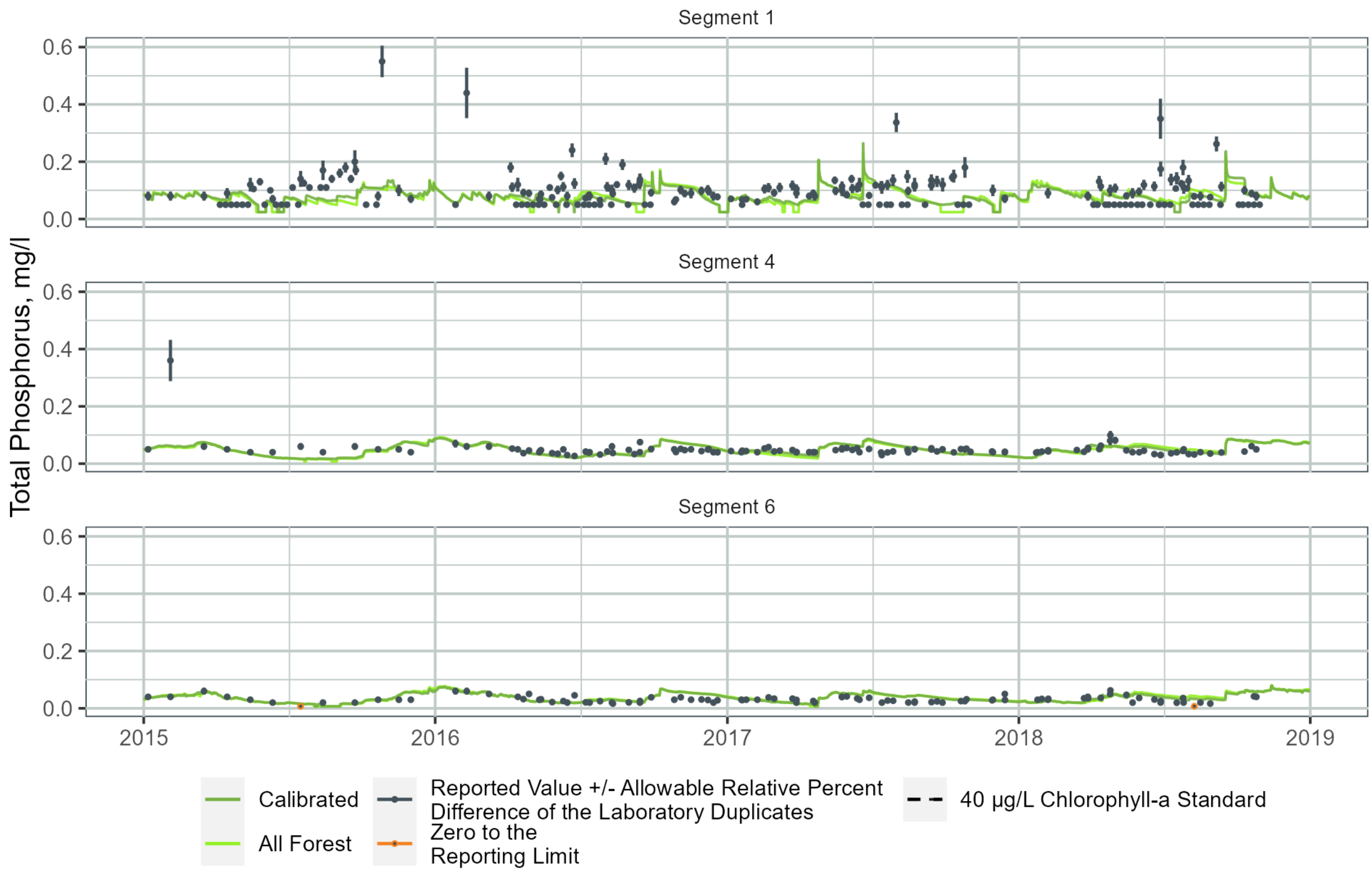

Figure B-105. WARMF Lake Simulated Total Phosphorus Concentrations for the Calibrated Model Compared to the Instantaneous Land Conversion to All Forest with Elimination of Onsite and Centralized Wastewater Treatment Discharges and Nutrient Application to Land Surfaces (Atmospheric Deposition is not Altered from the Calibrated Model) in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

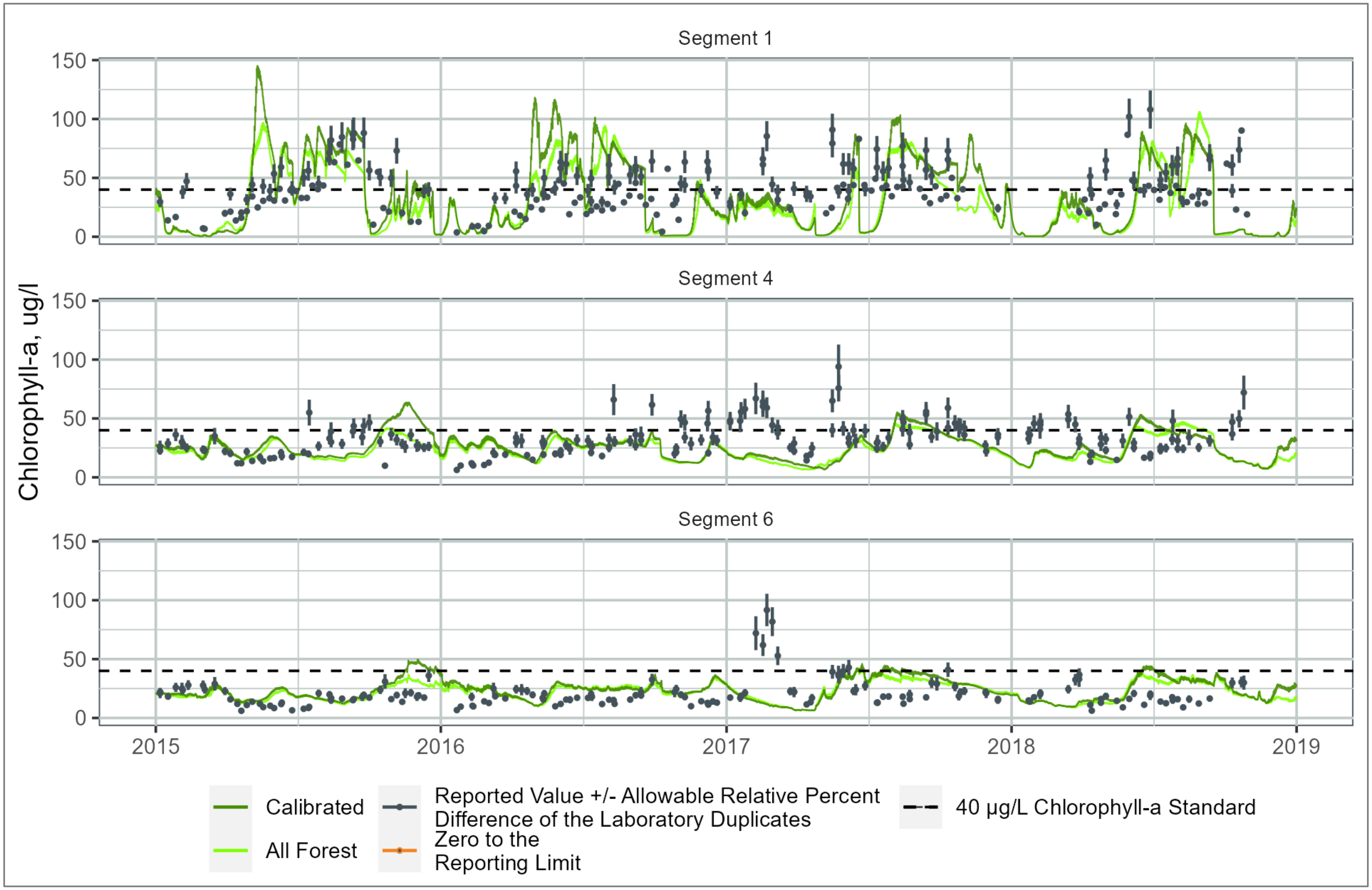

Figure B-106. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to the Instantaneous Land Conversion to All Forest with Elimination of Onsite and Centralized Wastewater Treatment Discharges and Nutrient Application to Land Surfaces (Atmospheric Deposition is not Altered from the Calibrated Model) in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

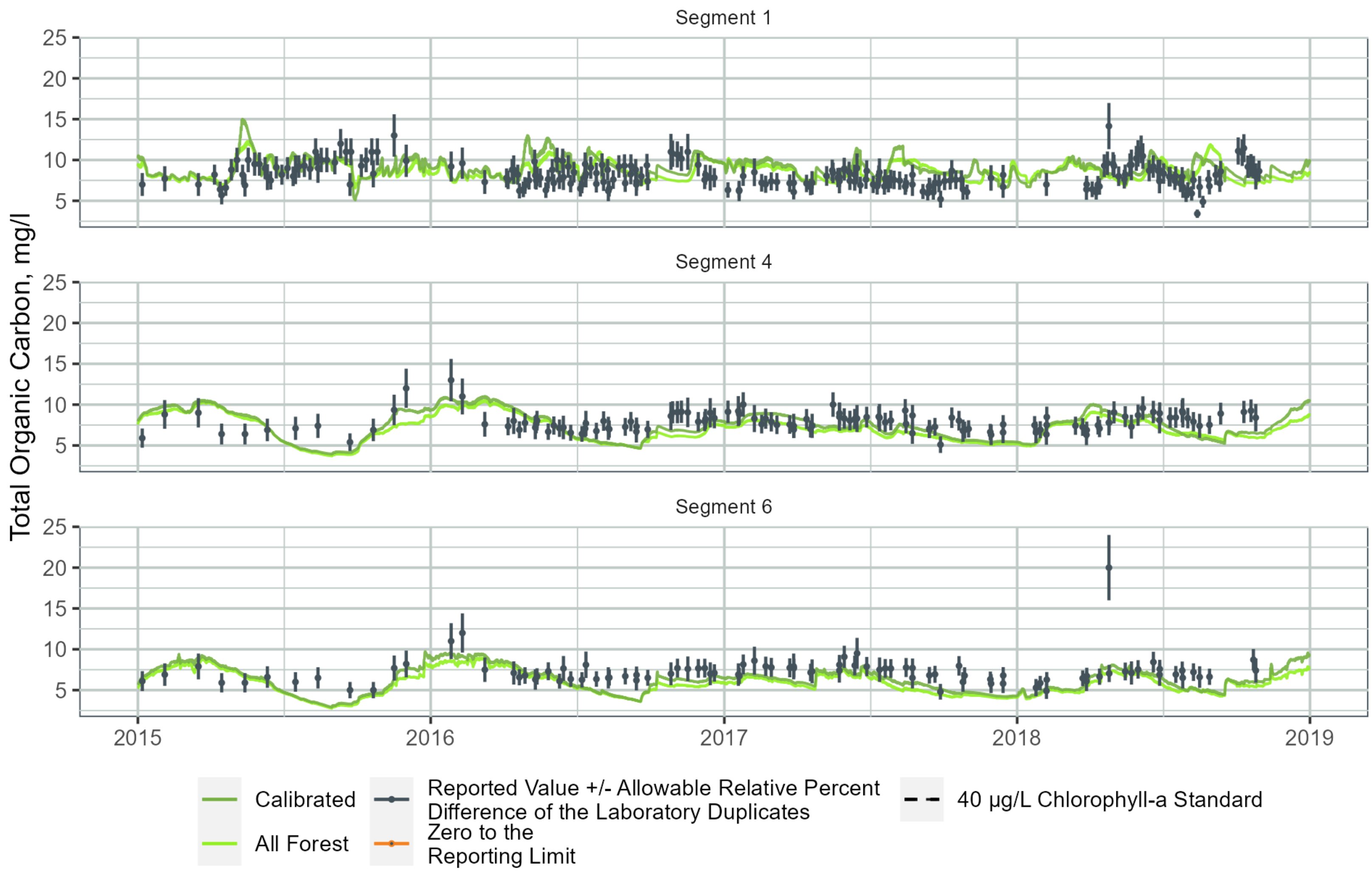

Figure B-107. WARMF Lake Simulated Total Organic Carbon Concentrations for the Calibrated Model Compared to the Instantaneous Land Conversion to All Forest with Elimination of Onsite and Centralized Wastewater Treatment Discharges and Nutrient Application to Land Surfaces (Atmospheric Deposition is not Altered from the Calibrated Model) in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

5.1.2 WARMF Lake Simulation with Changes to Rates of Atmospheric Deposition

Another scenario that was previously evaluated with the UNRBA WARMF watershed model (BC and Systech Water Resources 2023) either increased or decreased rates of atmospheric deposition by 25 percent for total nitrogen, total phosphorus, and total organic carbon. This amount is similar to the reduction in total nitrogen deposition that has occurred since 2006 in the watershed. To simulate these changes, the study period deposition rates were multiplied by 0.75 to represent 25 percent less atmospheric deposition or by 1.25 to represent 25 percent more atmospheric deposition.

Figure B-108 through Figure B-111 show the simulated and observed total nitrogen, total phosphorus, chlorophyll-a, and total organic carbon concentrations, respectively for 25 percent less deposition (light orange line), 25 percent more deposition (dark orange line), and the calibrated model (green line). There is little discernable difference among these three scenarios for water quality concentrations of nutrients, chlorophyll-a, and total organic carbon. In terms of percent exceedance of the chlorophyll-a standard, 25 percent less atmospheric deposition results in an exceedance of 36.1 percent in Segment 1 while 25 percent more atmospheric deposition results in an exceedance of 36.9 percent. In Segment 4, these two scenarios result in percent exceedances of 10.5 percent and 11.2 percent, respectively. In Segment 6, these two scenarios result in percent exceedances of 3.4 percent and 8.0 percent, respectively.

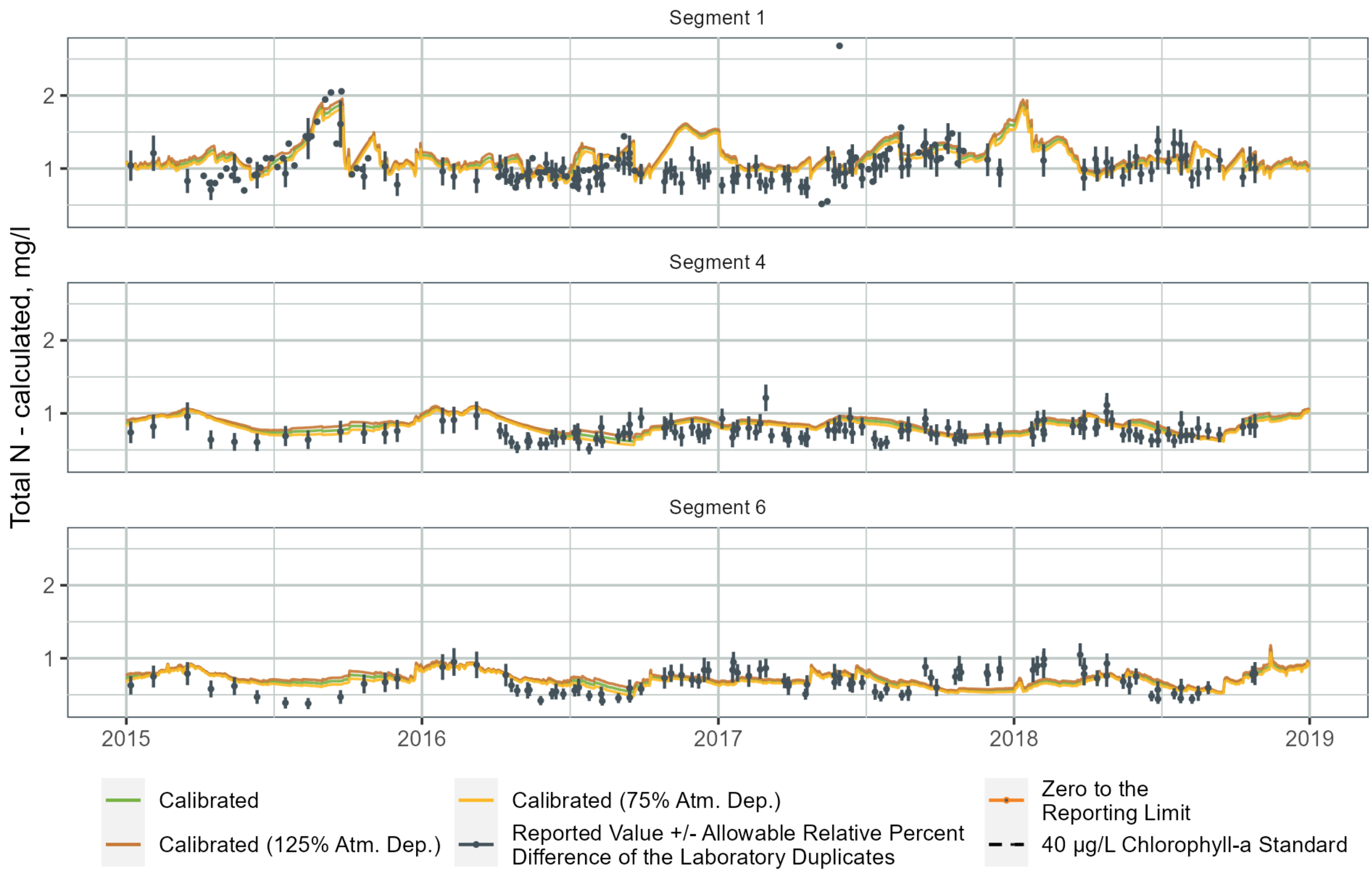

Figure B-108. WARMF Lake Simulated Total Nitrogen Concentrations for the Calibrated Model Compared to 25 Percent Increase or Decrease in Atmospheric Deposition of Total Nitrogen, Total Phosphorus, and Total Organic Carbon in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

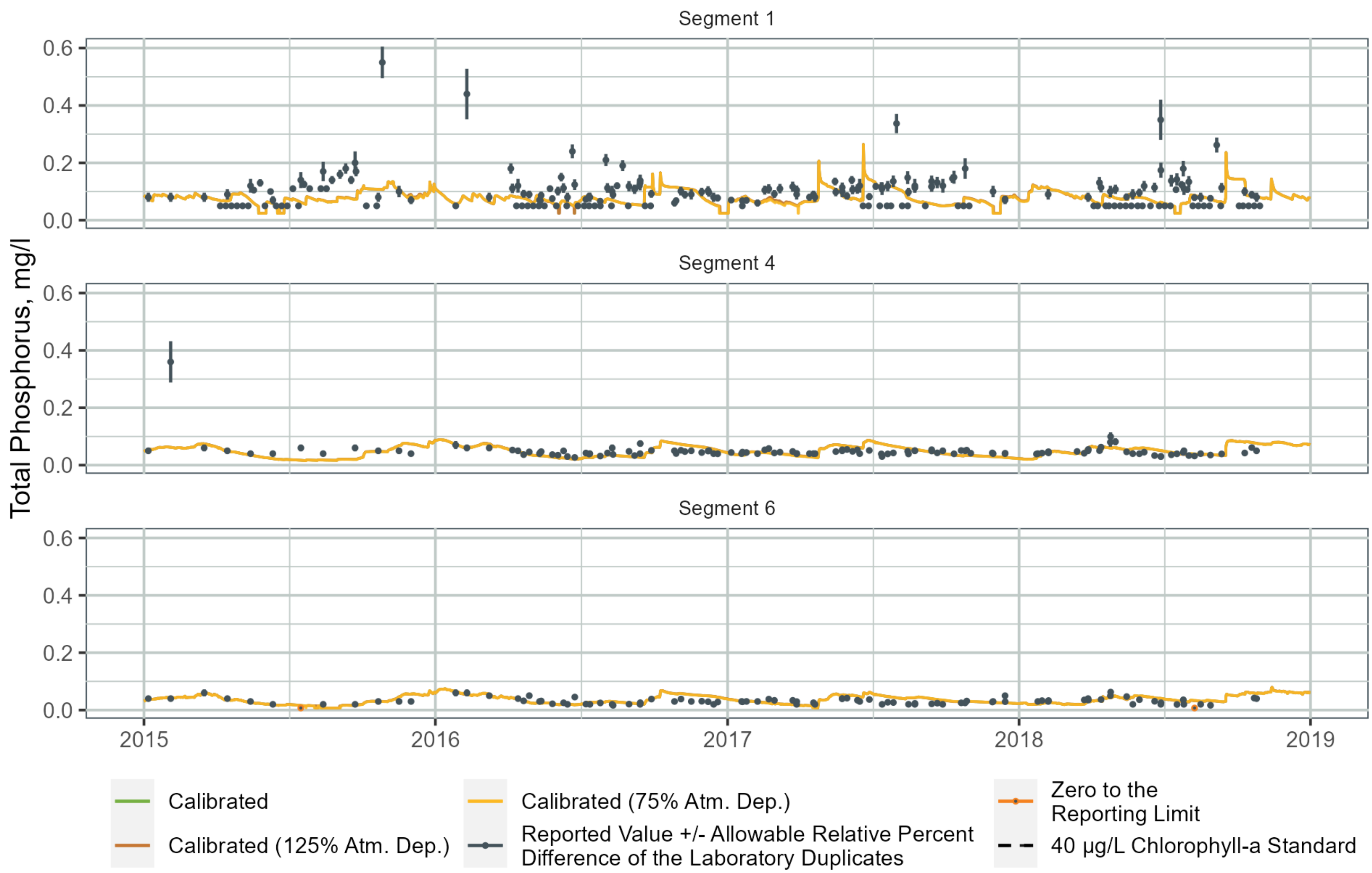

Figure B-109. WARMF Lake Simulated Total Phosphorus Concentrations for the Calibrated Model Compared to 25 Percent Increase or Decrease in Atmospheric Deposition of Total Nitrogen, Total Phosphorus, and Total Organic Carbon in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

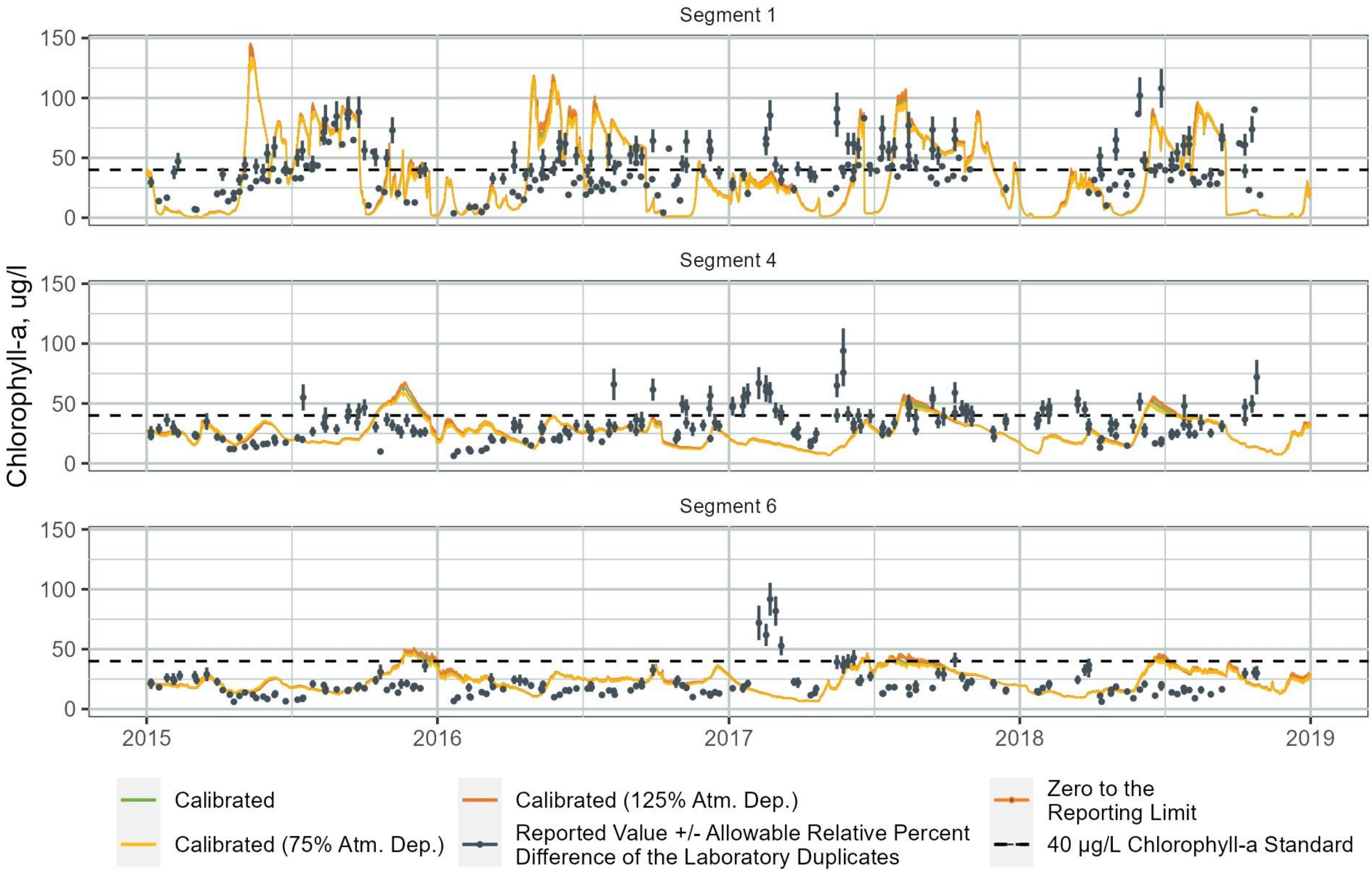

Figure B-110. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to 25 Percent Increase or Decrease in Atmospheric Deposition of Total Nitrogen, Total Phosphorus, and Total Organic Carbon in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

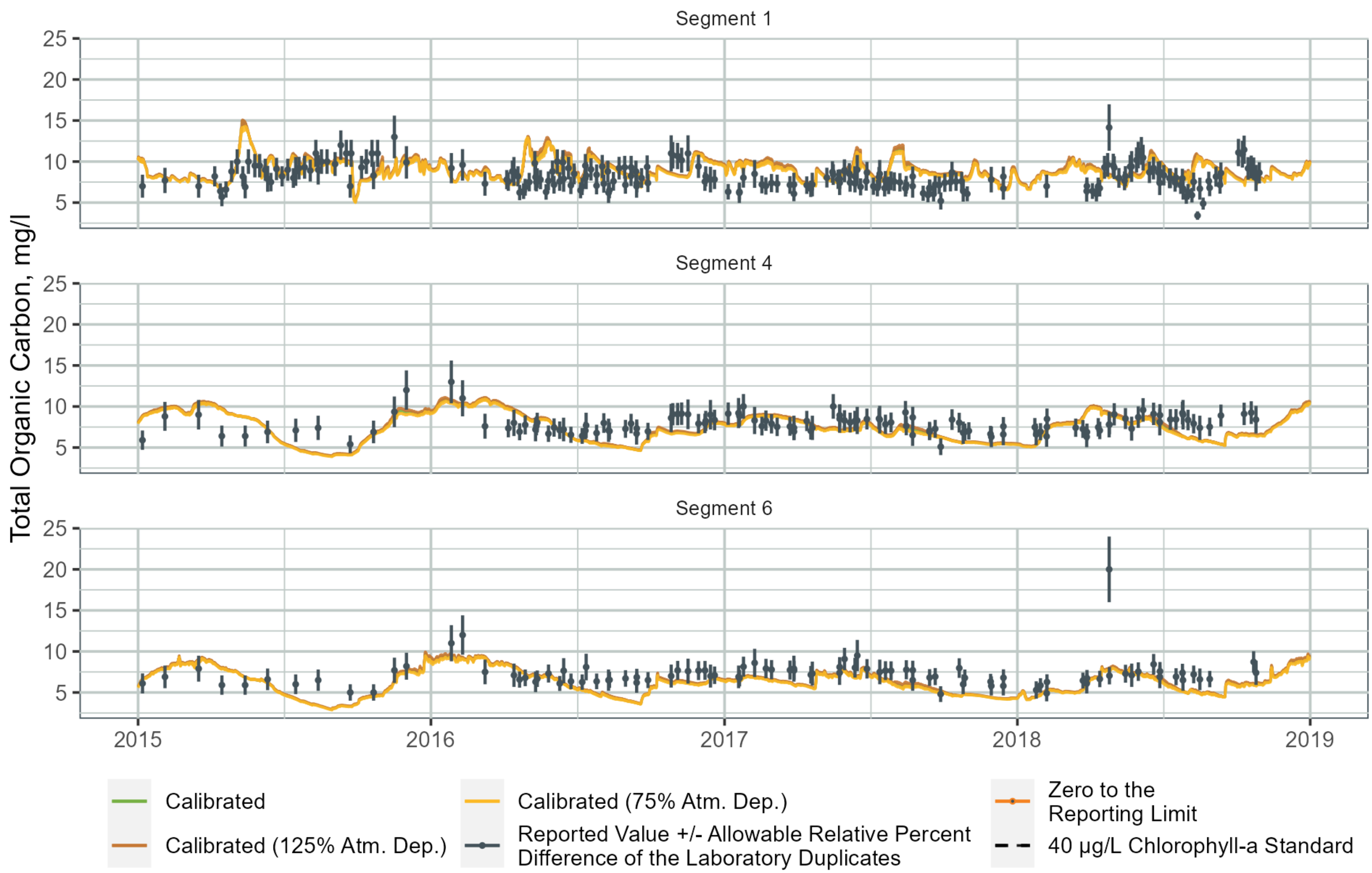

Figure B-111. WARMF Lake Simulated Total Organic Carbon Concentrations for the Calibrated Model Compared to 25 Percent Increase or Decrease in Atmospheric Deposition of Total Nitrogen, Total Phosphorus, and Total Organic Carbon in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

5.1.3 WARMF Lake Simulation with Changes to Precipitation Amounts

Our modeling shows that precipitation amount is the primary factor determining the amount of nutrient loading delivered to Falls Lake (BC and Systech Water Resources 2023). The average annual rainfall for the area is approximately 45 inches per year. The UNRBA study period represents an average to wet hydrologic condition with annual precipitation at the Raleigh Durham International Airport (RDU) ranging from 45.6 inches in 2017 up to 60.3 inches in 2018. The average rainfall over the UNRBA study period was 53.9 inches.

Two precipitation scenarios were developed for the WARMF watershed and Falls Lake model. One decreased precipitation amounts by 20 percent to represent rainfall amounts that occurred during the baseline modeling period for the Falls Lake rules and the monitoring studies conducted by the US Forest Service in the Falls Lake watershed. This scenario was developed by multiplying each precipitation input by a factor of 0.8 (every 6-hour precipitation value for the 78 precipitation stations represented in the watershed model). This factor reduced simulated annual precipitation at RDU airport to a range of 36.5 to 48.2 inches per year with an average of 43.1 inches. Conversely, a separate scenario was created in which each precipitation value in the watershed model was multiplied by 1.2 to represent a 20 percent increase in rainfall amount. This scenario was conducted to evaluate larger, more frequent storm events to represent a "climate change" scenario as requested by UNRBA stakeholders at technical workshops as well as PFC and Board members.

Figure B-112 through Figure B-115 show the simulated and observed total nitrogen, total phosphorus, chlorophyll-a, and total organic carbon concentrations, respectively, for 20 percent less precipitation (light blue line), 20 percent more precipitation (dark blue line), and the calibrated model (green line). For most of the simulation period, the three scenarios track relatively closely in terms of water quality. The most dramatic differences occur in Segment 1 where the 20 percent less precipitation scenario results in much higher simulated maximum chlorophyll-a concentrations that do not occur under the calibrated model or the 20 percent more precipitation scenario, particularly in the first half of 2017. This increase in simulated chlorophyll-a concentration is likely because less rainfall results in stagnation of the lake water allowing more time for algae to grow. This bloom and subsequent die off and release of nutrients and organic carbon also cause increases in simulated total nitrogen, total phosphorus, and total organic carbon concentrations.

These precipitation scenarios illustrate that delivered nutrient loading is not the only determinant of algal growth and chlorophyll-a concentrations in Falls Lake.

Based on the UNRBA watershed model, 20 percent less rainfall results in 35 percent less total nitrogen and 42 percent less total phosphorus delivered to Falls Lake respectively. With less simulated precipitation, the model predicts concentrations in Segment 1 that are higher than any observed in the lake. Algal growth rates in the model had to be set high to capture the magnitude of chlorophyll-a observations from 2014 to 2018. Some of the observations were as high as 100 µg/L, but the lower rainfall scenario predicts concentrations up to 400 µg/L. The combination of less precipitation and slower water movement in this shallow segment likely results in these very high simulated values. Because some of the simulated values are higher than any ever observed in Falls Lake, they are likely an artifact of the modeling and not a realistic representation of potential outcomes. As shown in Figure B-112 through Figure B-115, simulation of values in Segments 3 and 6 are within observed ranges and appear reasonable.

On the other hand, a 20 percent increase in rainfall increases delivered total nitrogen and total phosphorus loads by 36 percent and 60 percent, respectively, but these load increases do not translate to increases in simulated chlorophyll-a concentrations. When nutrient loading to Falls Lake is high, stream flows are also high and the residence time in the lake is shortened. These conditions do not allow sufficient time for algae to grow. These precipitation scenarios illustrate that delivered nutrient loading is not the only determinant of algal growth and chlorophyll-a concentrations in Falls Lake.

Simulated percent exceedance of the chlorophyll-a standard in Segment 1 is 52 percent under the 20 percent less rainfall scenario and 29 percent under the 20 percent more rainfall scenario. In Segment 4, 20 percent less rainfall results in a percent exceedance of 12 percent, and 20 percent more rainfall results in a percent exceedance of 15 percent (opposite trend compared to Segment 1). In Segment 6, both scenarios result in approximately 5 percent exceedance of the chlorophyll-a standard, further demonstrating the stability of chlorophyll-a concentrations in this part of the lake.

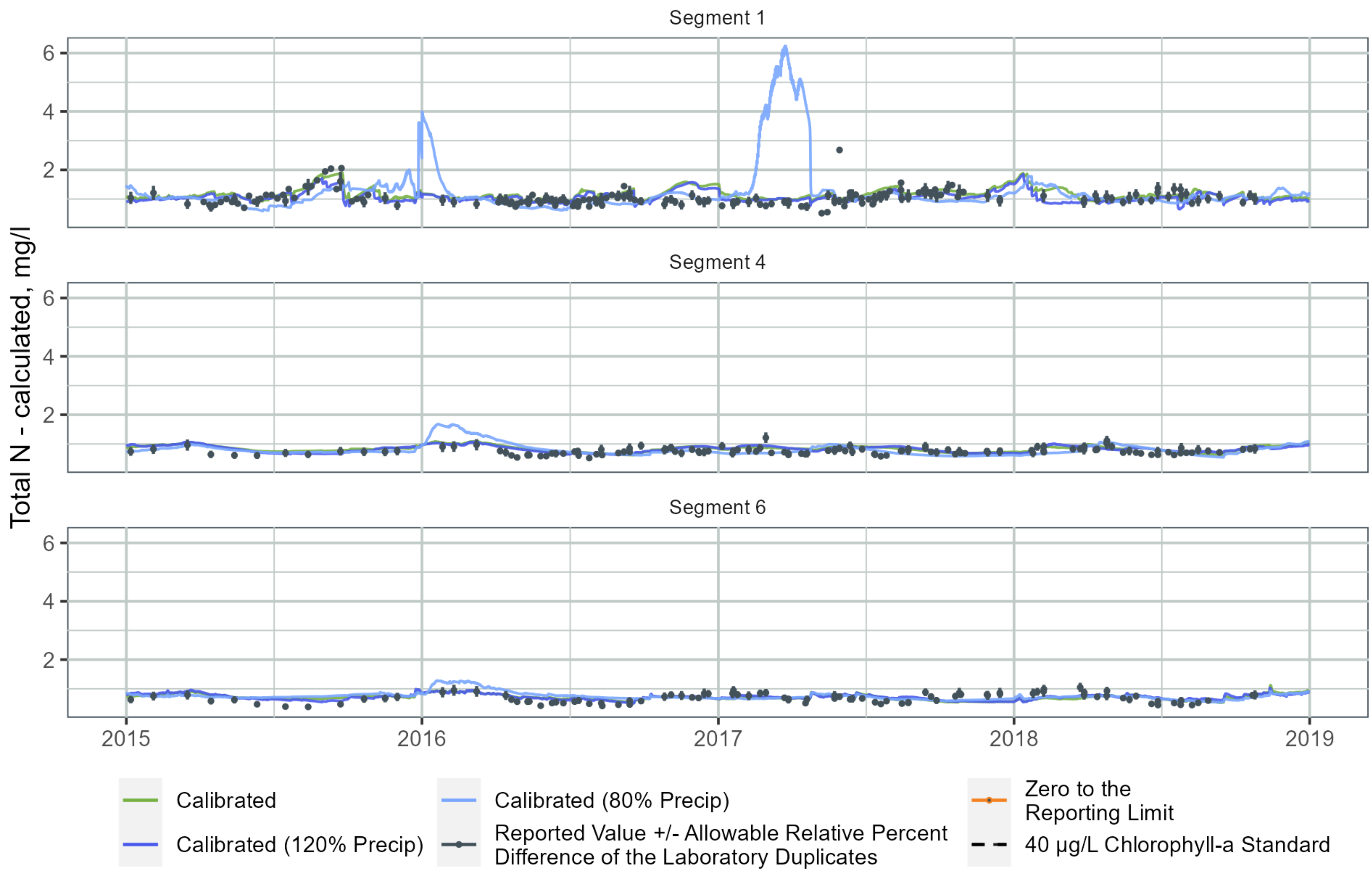

Figure B-112. WARMF Lake Simulated Total Nitrogen Concentrations for the Calibrated Model Compared to 20 Percent Increase or Decrease in Rainfall Amount in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

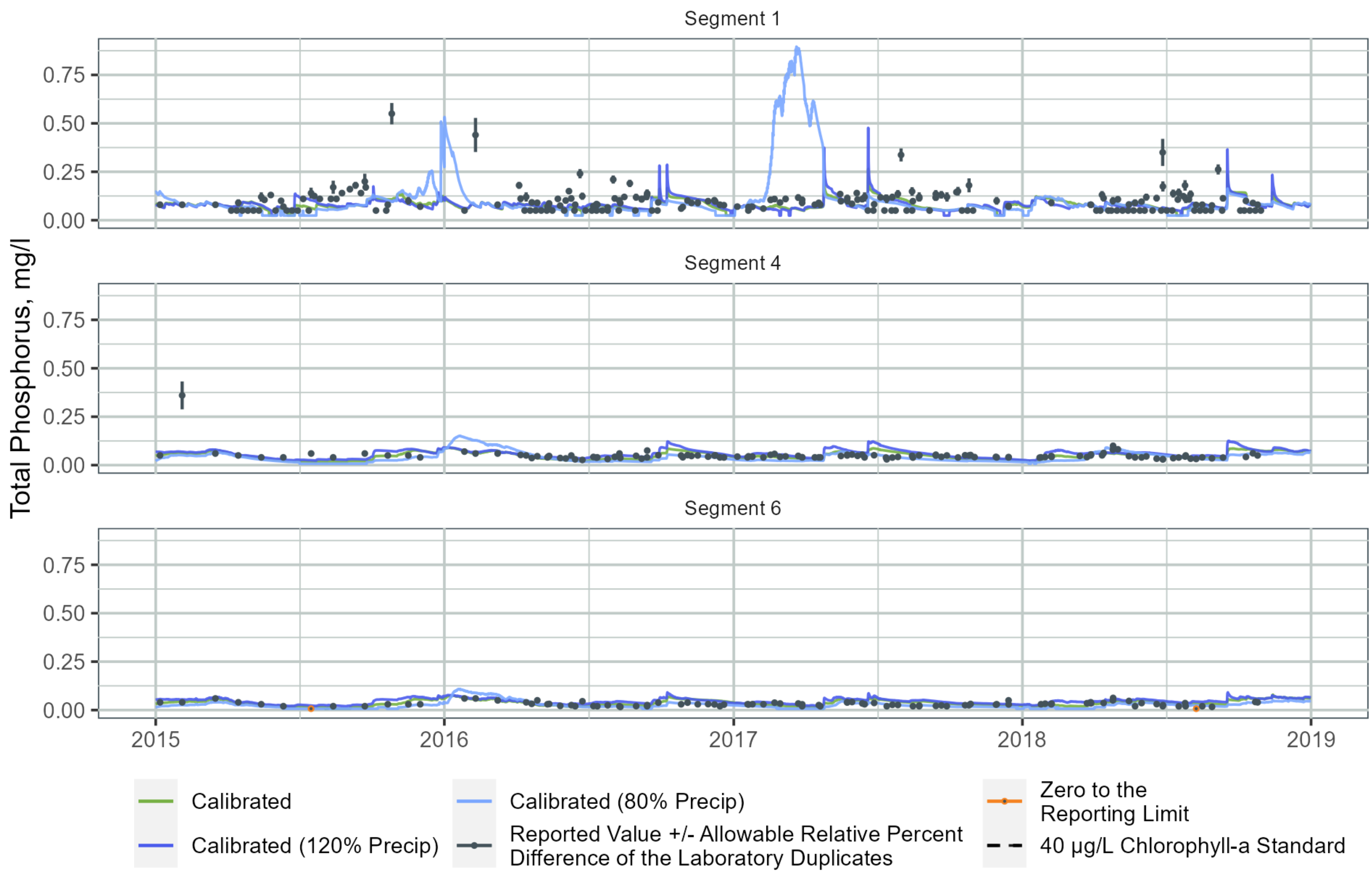

Figure B-113. WARMF Lake Simulated Total Phosphorus Concentrations for the Calibrated Model Compared to 20 Percent Increase or Decrease in Rainfall Amount in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

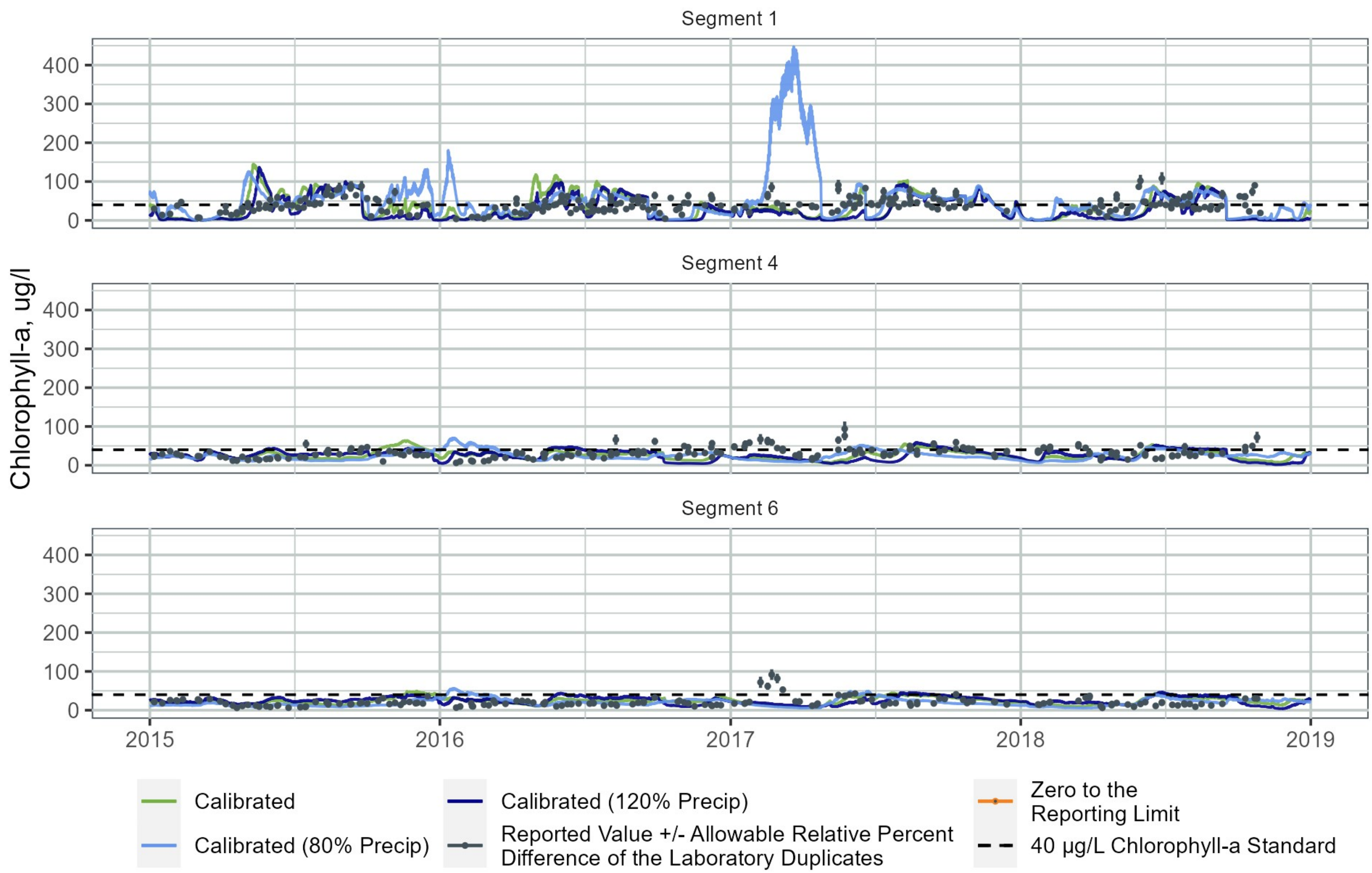

Figure B-114. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to 20 Percent Increase or Decrease in Rainfall Amount in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

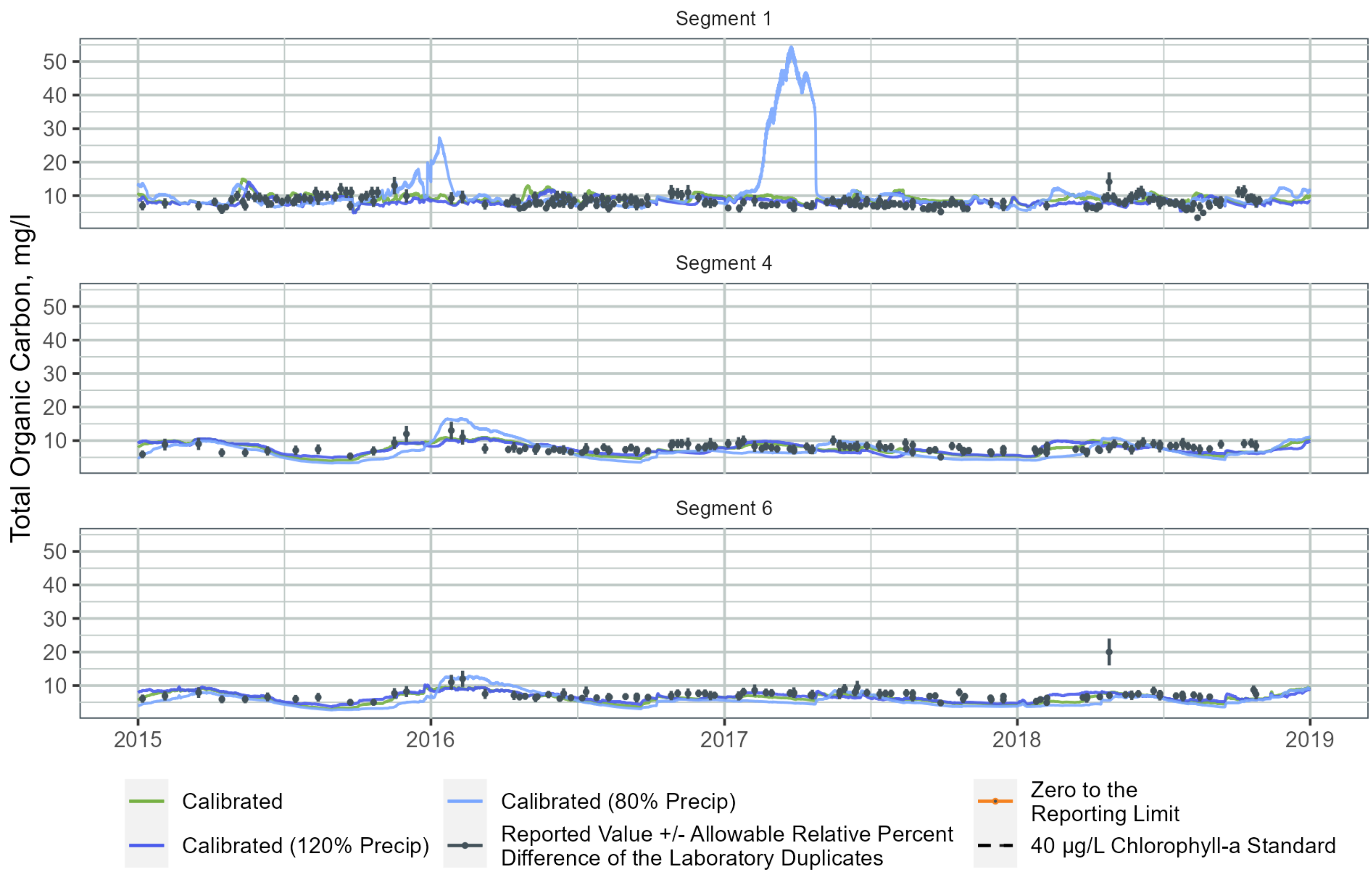

Figure B-115. WARMF Lake Simulated Total Organic Carbon Concentrations for the Calibrated Model Compared to 20 Percent Increase or Decrease in Rainfall Amount in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

5.1.4 WARMF Lake Simulation with Changes to Lake Operations

A WARMF Lake model scenario was designed to address a question frequently asked by stakeholders regarding the impact of USACE lake operations on nutrient cycling, algal growth, and chlorophyll-a concentrations in Falls Lake. A scenario was evaluated that simulates an outflow structure at the normal pool elevation (251.5 feet above mean sea level), so water is not retained for flood control purposes. Under current operations, following a large rain event, the USACE stores water in the lake to minimize downstream flooding. The USACE closes the flow release gates to store the water, and the lake water level rises. Once the risk of downstream flooding has passed, the USACE releases water from Falls Lake. These releases continue until the target elevation is met. If a large event has not occurred, the USACE balances releases with inflows to maintain normal pool. Because large rain events are relatively infrequent, the USACE is usually able to maintain normal pool except during drought periods. Therefore, most of the time, the water level is 251.5 feet.

Because the USACE already targets normal pool elevation in their operation of Falls Lake, this scenario did not significantly affect simulated water quality in Falls Lake. Figure B-116 through Figure B-119 show the simulated and observed total nitrogen, total phosphorus, chlorophyll-a, and total organic carbon concentrations, respectively for this scenario (dark purple line) and the calibrated WARMF Lake model (dark green line).

Maximum values of chlorophyll-a increased, decreased, or shifted in time depending on when and where the simulation is compared to the calibrated model. However, the percent of simulated chlorophyll-a concentrations for Segment 1 near Interstate 85 exceeding the standard was similar under both conditions (35 percent for the lake operation scenario and 37 percent for the calibrated model. In Segment 4, the percent exceedance is 11 percent for both scenarios. In Segment 6, the percent exceedance is 5.9 percent of the calibrated model and 5.5 percent for the lake operation scenario. This indicates that while lake operation by the USACE to reduce downstream flooding may impact the timing of peak chlorophyll-a concentrations in Falls Lake, it does not dictate whether or not Falls Lake would be compliant with the chlorophyll-a standard.

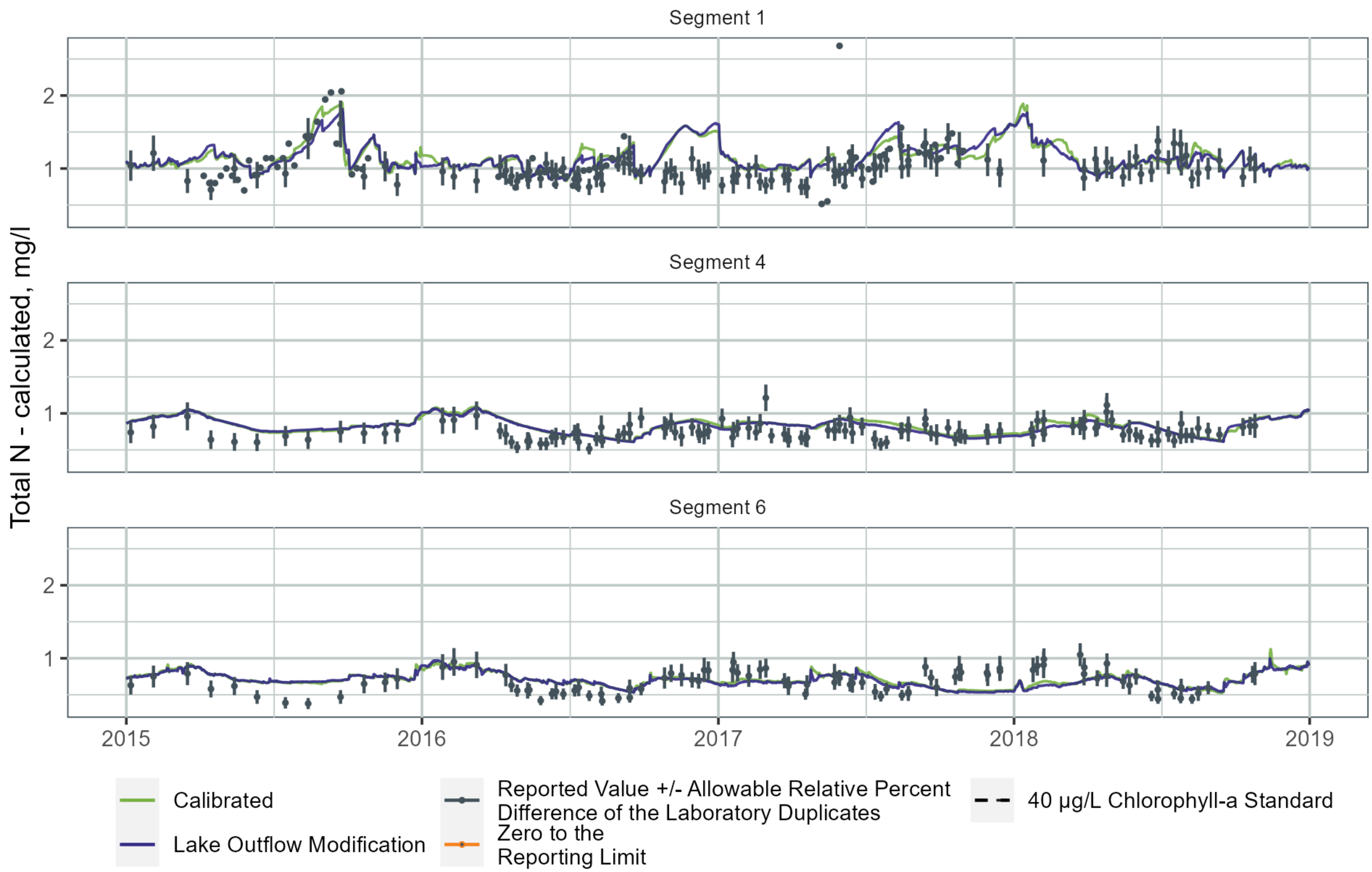

Figure B-116. WARMF Lake Simulated Total Nitrogen Concentrations for the Calibrated Model Compared to the Dam Release Scenario with the Spillway Elevation Set to Normal Pool in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

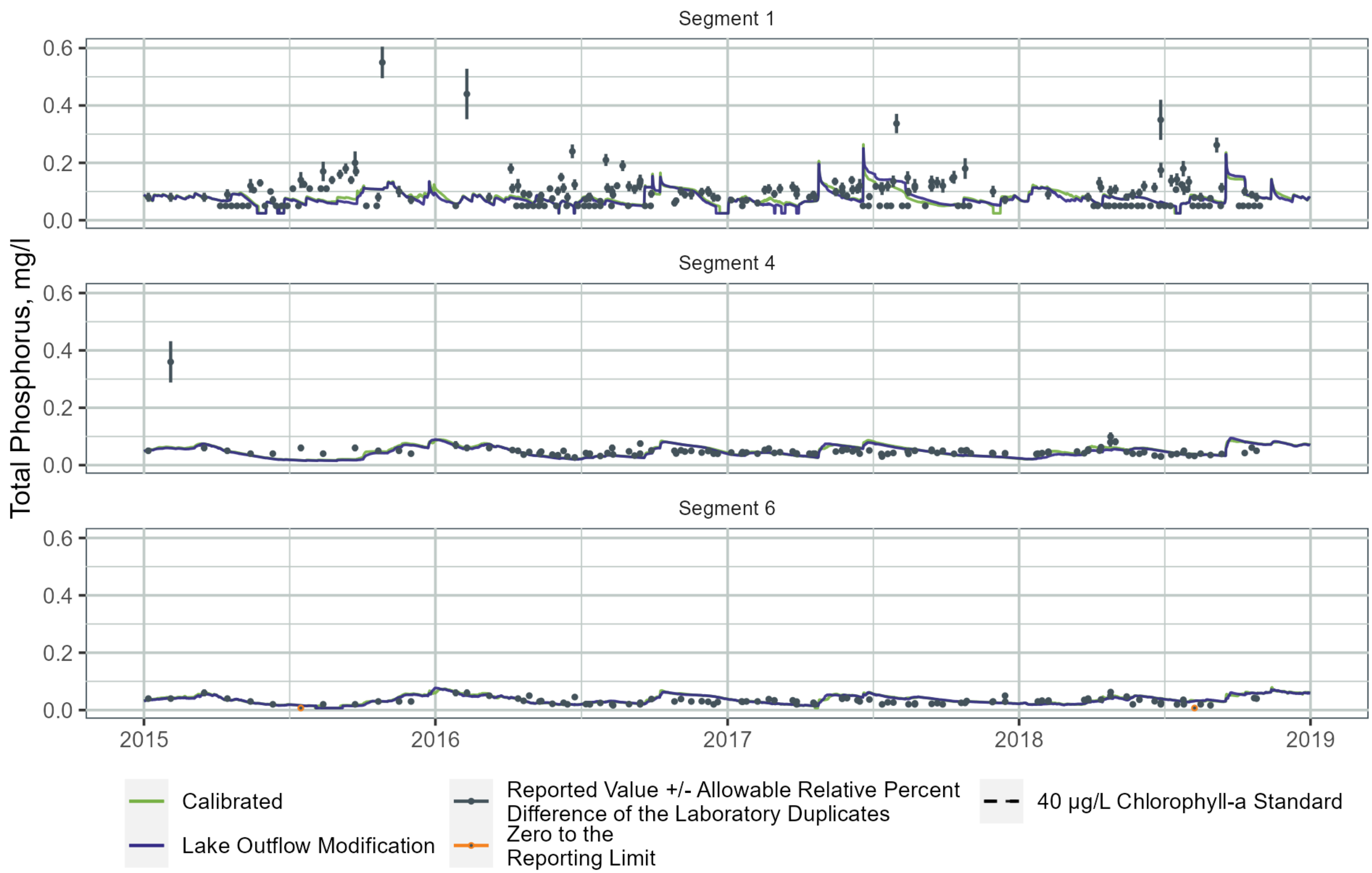

Figure B-117. WARMF Lake Simulated Total Phosphorus Concentrations for the Calibrated Model Compared to the Dam Release Scenario with the Spillway Elevation Set to Normal Pool in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

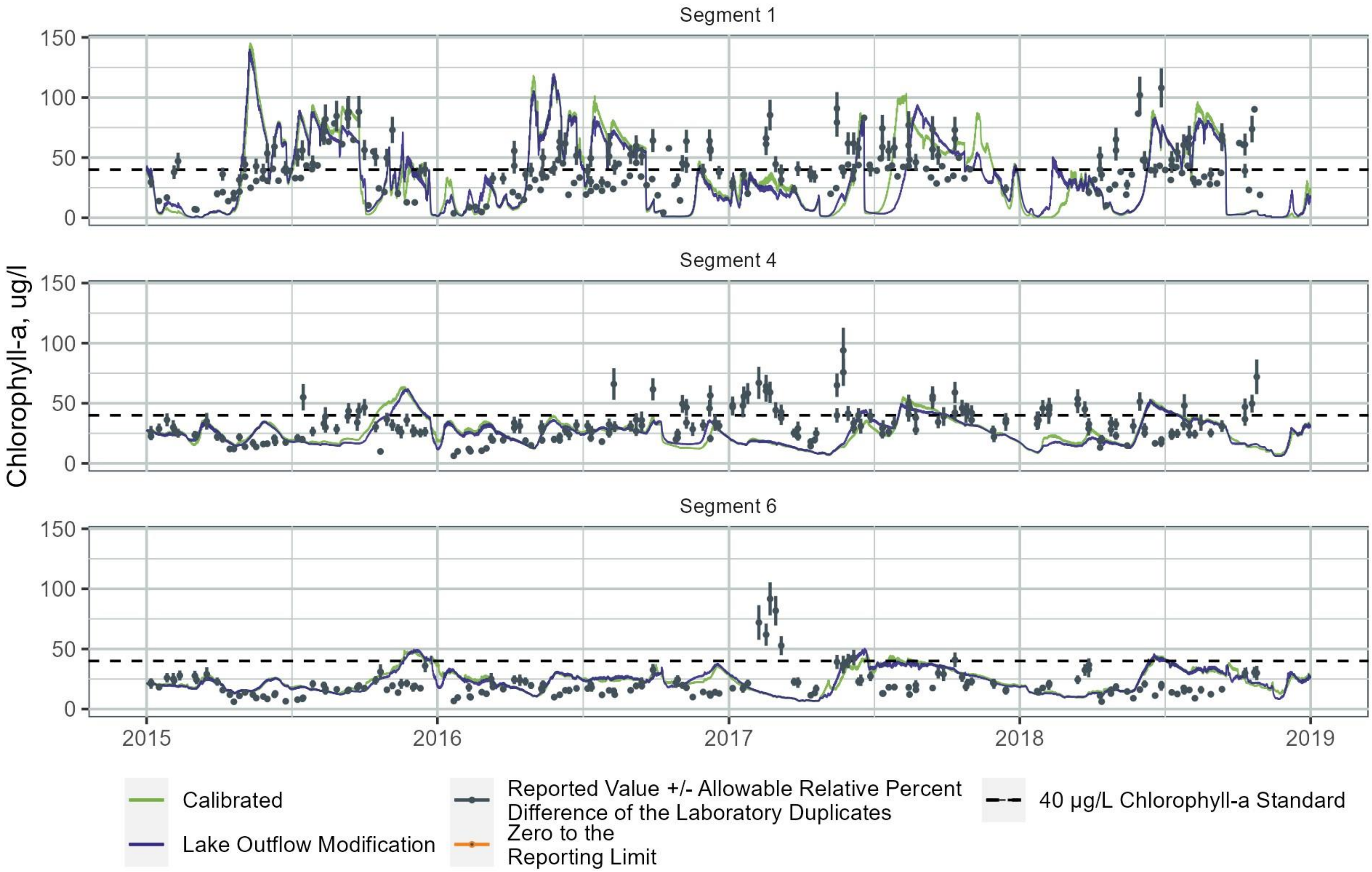

Figure B-118. WARMF Lake Simulated Chlorophyll-a Concentrations for the Calibrated Model Compared to the Dam Release Scenario with the Spillway Elevation Set to Normal Pool in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

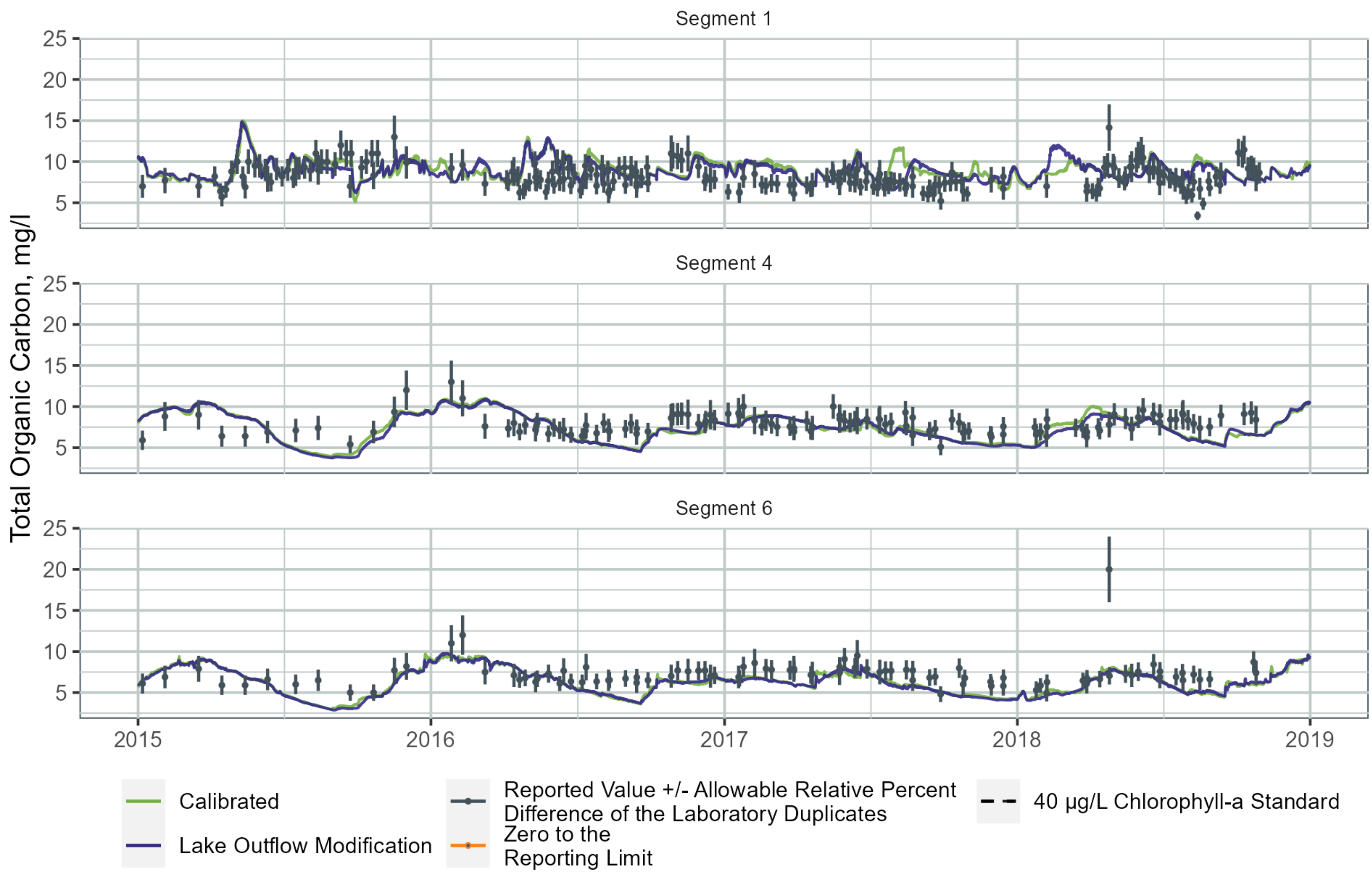

Figure B-119. WARMF Lake Simulated Total Organic Carbon Concentrations for the Calibrated Model Compared to the Dam Release Scenario with the Spillway Elevation Set to Normal Pool in Segment 1 (upper lake near Interstate 85), Segment 4 (middle lake near Highway 50), and Segment 6 (lower lake near the dam)

5.1.5 Comparison of Chlorophyll-a Statistics for the WARMF Lake Scenarios

Chlorophyll-a is the regulatory driver for the Falls Lake Rules. Comparison of simulated chlorophyll-a across model scenarios informs the reexamination of the Falls Lake Nutrient Management Strategy and revisions to the Falls Lake Rules by placing bounds on what is reasonably achievable for this system. Table B-11 provides the simulated percent exceedance of the chlorophyll-a standard for each main lake segment as well as annual and growing season means and geometric means. The statistics for the calibrated model are based on the calibration and validation years (2015 to 2018). The statistics for the scenarios are also evaluated for the four-year period. As previously discussed, each scenario was run five times in the WARMF watershed model to provide tributary inputs for the scenario. The initial conditions of the sediments in Falls Lake were reset for each iteration.

The percent exceedances of the chlorophyll-a criteria decrease from the upstream to downstream direction in Falls Lake. The upper end of the lake is wider and shallower and receives most of the nutrient loading from the watershed. None of the scenarios evaluated achieve the chlorophyll-a standard at least 90 percent of the time in Segments 1 through 3. In Segment 4, only the All Forest scenario could meet the standard at least 90 percent of the time. However, even this hypothetical scenario would not result in attainment of DWR's standard based on the current NC assessment methodology. **Not even this hypothetical scenario can meet the chlorophyll-a standard everywhere, all the time in Falls Lake. Therefore, it is not possible to achieve the chlorophyll-a standard in Falls Lake as currently applied.**

Segments 5 and 6 are located downstream of Highway 50 in the deeper, narrow part of the lake. Both of these segments are predicted to meet the chlorophyll-a standard at least 90 percent of the time under every scenario, including the calibrated model.

Table B-11. Chlorophyll-a Summary Statistics (2015 to 2018) by Lake Segment for WARMF Lake Model Scenarios

Main Lake Segment Order (upstream, to downstream)	Scenario	Percent Exceedance of 40 µg/L	Annual Mean	Annual Geometric Mean	Growing Season Mean	Growing Season Geometric Mean
1	All Forest	31.2	28.9	13.8	39.4	21.3
1	Calibrated Model	36.5	34.4	16.2	45.9	25.3
1	Calibrated with 20% more Precipitation	29.2	26.9	10.4	36.9	16.3
1	Calibrated with 25% more Atmospheric Deposition	36.9	34.9	16.7	46.5	26.0
1	Calibrated with 25% less Atmospheric Deposition	36.1	33.7	15.7	45.1	24.6
1	Calibrated with 20% less Precipitation	51.9	52.5	31.5	51.4	36.7
1	Spillway at Normal Pool Elevation	35.2	33.0	17.7	43.3	24.8
2	All Forest	20.9	25.7	18.0	30.5	22.9
2	Calibrated Model	35.7	31.6	21.9	35.7	27.3
2	Calibrated with 20% more Precipitation	30.9	28.0	15.3	34.9	21.3
2	Calibrated with 25% more Atmospheric Deposition	36.5	32.1	22.3	36.4	27.9
2	Calibrated with 25% less Atmospheric Deposition	34.4	30.9	21.3	35.1	26.6
2	Calibrated with 20% less Precipitation	35.3	41.2	32.0	35.6	30.8

Table B-11. Chlorophyll-a Summary Statistics (2015 to 2018) by Lake Segment for WARMF Lake Model Scenarios						
Main Lake Segment Order (upstream, to downstream)	Scenario	Percent Exceedance of 40 µg/L	Annual Mean	Annual Geometric Mean	Growing Season Mean	Growing Season Geometric Mean
2	Spillway at Normal Pool Elevation	33.7	32.6	24.4	37.0	29.1
3	All Forest	10.7	25.3	21.7	28.3	24.7
3	Calibrated Model	25.3	30.2	25.7	32.5	28.4
3	Calibrated with 20% more Precipitation	27.8	27.8	19.4	31.9	23.9
3	Calibrated with 25% more Atmospheric Deposition	26.7	30.8	26.2	33.2	28.9
3	Calibrated with 25% less Atmospheric Deposition	24.4	29.5	25.2	31.8	27.8
3	Calibrated with 20% less Precipitation	24.6	33.4	30.1	31.7	29.4
3	Spillway at Normal Pool Elevation	24.0	30.3	26.3	33.1	28.8
4	All Forest	8.1	23.6	21.6	25.6	23.4
4	Calibrated Model	11.1	25.8	23.5	27.1	24.8
4	Calibrated with 20% more Precipitation	15.0	25.7	21.5	28.3	24.0
4	Calibrated with 25% more Atmospheric Deposition	11.2	26.2	23.9	27.4	25.0
4	Calibrated with 25% less Atmospheric Deposition	10.5	25.4	23.2	26.8	24.5
4	Calibrated with 20% less Precipitation	11.7	24.6	22.1	24.2	22.4
4	Spillway at Normal Pool Elevation	11.0	25.3	23.1	26.5	24.3
5	All Forest	1.9	23.6	21.9	25.3	23.3
5	Calibrated Model	9.4	25.2	23.3	26.4	24.5
5	Calibrated with 20% more Precipitation	9.9	25.8	23.2	28.0	25.3
5	Calibrated with 25% more Atmospheric Deposition	9.8	25.6	23.6	26.7	24.7
5	Calibrated with 25% less Atmospheric Deposition	8.3	24.8	23.0	26.0	24.2
5	Calibrated with 20% less Precipitation	8.6	22.3	19.7	22.1	20.1
5	Spillway at Normal Pool Elevation	9.8	24.8	22.9	25.9	23.9
6	All Forest	0.6	22.2	20.7	23.5	21.8
6	Calibrated Model	5.9	23.8	21.9	24.8	23.0
6	Calibrated with 20% more Precipitation	5.1	24.6	22.6	26.8	24.7
6	Calibrated with 25% more Atmospheric Deposition	8.0	24.2	22.2	25.2	23.3
6	Calibrated with 25% less Atmospheric Deposition	3.4	23.3	21.6	24.5	22.7
6	Calibrated with 20% less Precipitation	5.0	19.7	17.3	19.5	17.5

Table B-11. Chlorophyll-a Summary Statistics (2015 to 2018) by Lake Segment for WARMF Lake Model Scenarios						
Main Lake Segment Order (upstream, to downstream)	Scenario	Percent Exceedance of 40 µg/L	Annual Mean	Annual Geometric Mean	Growing Season Mean	Growing Season Geometric Mean
6	Spillway at Normal Pool Elevation	5.5	23.5	21.6	24.7	22.8

Section 6: References

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