Prepared in cooperation with Bureau of Reclamation

Modeling the Water-Quality Effects to the Klamath River from Recirculation in Drains and Canals, Oregon and California, 2006–15

Scientific Investigations Report 2023–5059

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

Cover:

Front. Klamath Straits Drain east of Highway 97 and F-FF pumps looking east, June 9, 2021. Photograph by Katie Beauto (U.S. Geological Survey).

Back. Klamath Straits Drain at Highway 97 looking west, February 11, 2019. Photograph by Olivia Stoken (U.S. Geological Survey).

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U.S. Geological Survey, Reston, Virginia: 2023

Suggested citation:
Smith, E.A., and Sullivan, A.B., 2023, Modeling the water-quality effects to the Klamath River from recirculation in drains and canals, Oregon and California, 2006–15: U.S. Geological Survey Scientific Investigations Report 2023–5059, 87 p., https://doi.org/10.3133/sir20235059.

Associated data for this publication:
Smith, E.A., and Sullivan, A.B., 2023, CE–QUAL–W2 water-quality models for Klamath Straits Drain recirculation scenarios, Klamath River, Oregon, 2006–15: U.S. Geological Survey data release, https://doi.org/10.5066/P9RWP4F9.

ISSN 2328-0328 (online)

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	square hectometer (hm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
pound (lb)	0.45359	kilogram (kg)
pound per day (lb/day)	0.45359	kilogram per day (kg/day)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
kilogram (kg)	2.205	pound (lb)
kilogram per day (kg/day)	2.205	pound per day (lb/day)

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

°F = (1.8 × °C) + 32.

Datums

Horizontal coordinate information is referenced to the North American Datum of 1927.

A local vertical datum (Upper Klamath Lake Vertical Datum [UKLVD]) is used, established by the Bureau of Reclamation. For this report, the conversion is UKLVD – 1.78 feet = National Geodetic Vertical Datum of 1929 (NGVD 29).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

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

Abbreviations

BOD5	5-day biochemical oxygen demand
CBOD5	5-day carbonaceous biochemical oxygen demand
CE-QUAL-W2	Two-dimensional hydrodynamic and water-quality model
DMR	discharge monitoring report
GNIS	Geographic Names Information System
Link-Keno	Klamath River from Link River mouth to Keno Dam
NWR	National Wildlife Refuge
ODEQ	Oregon Department of Environmental Quality
Reclamation	Bureau of Reclamation
TDS	total dissolved solids
TMDL	Total Maximum Daily Loads
USGS	U.S. Geological Survey

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Abstract

The potential recirculation of Klamath Strait Drain (hereafter called by its local name, "Klamath Straits Drain") water into Ady Canal to reduce the drain discharge of high nutrient loads into the Klamath River was assessed by the U.S. Geological Survey for the Bureau of Reclamation. To study the feasibility of recirculation, this investigation evaluated three recirculation scenarios over a 10-year period from 2006 to 2015, as a series of 1-year model simulations. A combination of two existing hydrodynamic, water-temperature, and water-quality models (CE-QUAL-W2) were used, including (1) the Link-Keno reach of the Klamath River, using Klamath Straits Drain as a tributary and for calendar years 2006–11, and (2) the same Link-Keno model used for calendar years 2012–15 in combination with an independent Klamath Straits Drain model from 2012 to 2015. Model simulations using the water-quality models were configured for the base case conditions and three different sets of recirculation scenarios: the maximum year-round recirculation without limits (scenario 1), limited year-round recirculation fixed by the current pipe flow configuration (scenario 2), and limited seasonal recirculation (May–September) also fixed by the current pipe flow configuration (scenario 3).

In the base case, estimates of annual average daily total nitrogen loads and daily total phosphorus loads exported to the Klamath River from the Klamath Straits Drain were as much as 3,060 and 457 pounds per day (lbs/day), respectively. Currently (2023), the Total Maximum Daily Loads allocations for the Klamath Straits Drain are 21 and 268 lbs/day for total phosphorus and total nitrogen, respectively, so these maximum estimates exceed the current Total Maximum Daily Loads by greater than an order of magnitude. With scenario 1, load reductions occurred year-round for all constituents evaluated (total nitrogen, total phosphorus, 5-day biochemical oxygen demand [BOD5], 5-day carbonaceous biochemical oxygen demand) for the Klamath Straits Drain discharging to the Klamath River. Scenario 2 also had large reductions in total nitrogen, total phosphorus, and BOD5 loads. Substantial reductions did occur for scenario 3 but were constrained to only the active recirculation period from May through September. Despite the restricted period, the average reductions in the annual average daily load for total phosphorus and total nitrogen were 32.1 percent and 26.5 percent, respectively.

The Ady Canal diverts high nutrient loads from the Klamath River, so the loading tradeoffs to the Klamath River between no recirculation and the recirculation scenarios were calculated. On an annual basis, the overall net balance between the Klamath Straits Drain and Ady Canal resulted in more total nitrogen and total phosphorus load reductions to the Klamath River for the three recirculation scenarios than the base case, for most years. In contrast, the net balance for BOD5 loads was higher to the Klamath River for the three recirculation scenarios than the base case, for most years.

With the recirculation scenarios, the optimal recirculation periods to benefit Ady Canal, Klamath River, and Klamath Straits Drain did not always coincide. Recirculation would be most effective at reducing loads toward the Klamath Straits Drain Total Maximum Daily Load allocations in the spring (March–May) of each year. However, recirculation during these months would also increase salinity in the Ady Canal. In summer, recirculation would reduce Klamath Straits Drain loads toward the Total Maximum Daily Load allocations, though recirculation could decrease Klamath River water quality mostly because of decreased withdrawals of Klamath River water by the Ady Canal. Scenario 3 avoided recirculation into Ady Canal in the early spring months when salinity concerns would be the highest, while still decreasing nutrient loads exported from the Klamath Straits Drain to the Klamath River in the summer months.

Introduction

The Klamath River originates from Upper Klamath Lake and flows approximately 255 miles (410 km) through southern Oregon and northern California to the Pacific Ocean. The Klamath River watershed characteristics differ considerably between the first 65-mile segment, which is divided by a series of reservoir and river reaches controlled by four hydropower dams, and the final 190-mile segment with no other main-stem impoundments to the Pacific Ocean. The upper Klamath River has low gradients, less than 0.5 percent for some of the reaches and is mostly controlled by the dams, whereas the river downstream from the dams has higher gradients (Oliver and others, 2014; Rogers and others, 2016). Currently (2023), four of the six dams are planned for removal in the next several years, leaving only the northern most two dams: Link Dam, in Klamath Falls, Oregon, and Keno Dam near Keno, Oregon (Federal Energy Regulatory Commission, 2022).

The first 20 miles of the Klamath River flows from Link River mouth to Keno Dam, a part of the river commonly known as the Link-Keno reach or the Keno Reservoir. The State of Oregon has categorized the Link-Keno reach as having "very poor" water quality (Oregon Department of Environmental Quality, 2021). Many of the water-quality issues impacting the Klamath River originate from alteration of the hydrology and landscape surrounding and upstream from Upper Klamath Lake, such that nutrients and large algal blooms are exported out of the lake and directly into the Link-Keno reach (Oliver and others, 2014).

To improve the poor water quality for the Upper Klamath River, Total Maximum Daily Loads (TMDL) and a Water Quality Management Plan were established by the Oregon Department of Environmental Quality (ODEQ) to design water-quality goals for the subbasin (Oregon Department of Environmental Quality, 2019). The Water Quality Management Plan was designed as the implementation strategy. The TMDLs calculated the total pollutant load allocations that point and nonpoint sources could contribute to the stream to meet State water-quality standards.

A large amount of the area that drains within the Link-Keno reach is part of the Klamath Reclamation Project (hereinafter, "Klamath Project"), a water-management project operated by the Bureau of Reclamation (Reclamation) that converted a large area of seasonal wetlands to irrigated agriculture (Thorsteinson and others, 2011). The Link-Keno reach typically has poor water quality in the summer, including areas with elevated chlorophyll *a*, ammonia, and pH, and low dissolved oxygen, with water-quality impairments for ammonia toxicity, chlorophyll *a*, dissolved oxygen, and pH (Oregon Department of Environmental Quality, 2019). Although these water-quality issues could be partially related to large algal loads (mostly *Aphanizomenon flos-aquae*) exported out of Upper Klamath Lake that settle and decay within the Link-Keno reach, the poor water quality is also linked to inflows from point and non-point sources (Sullivan and others, 2014). To address water-quality issues attributed to inflows, the ODEQ established TMDLs for the Lost River Diversion Channel and Klamath Straits Drain, which both represent drainage water to the Klamath River from lands within the Klamath Project.

It should be noted for clarity that usage of Klamath Straits Drain throughout this report refers to two separate features within the Geographic Names Information System (GNIS), as developed by the U.S. Board on Geographic Names: Klamath Strait and Klamath Strait Drain. The GNIS is recognized as the official Federal standard for geographic nomenclature, so both names must be acknowledged within this report; however, the predominant local usage for these features is the Klamath Straits Drain. As such, and from hereafter in the report, we will use the local name, "Klamath Straits Drain" to describe this feature.

As part of the TMDLs, nonpoint source-load allocations were established for total phosphorus, total nitrogen, and the 5-day biochemical oxygen demand (BOD5). Additionally, load allocations were given for dissolved inorganic nitrogen and the 5-day carbonaceous biochemical oxygen demand (CBOD5) in the Lost River TMDL (U.S. Environmental Protection Agency, 2008).These load allocations have a direct effect on the Klamath Project because Reclamation has a leading role in the storage, delivery, and management of water in the surrounding areas, including nonpoint source load allocations that originate within Klamath Project boundaries (Schenk and others, 2018). Reducing loads toward the TMDLs is complicated by Klamath Project operations draining land within the Klamath Project, particularly from February through April before irrigation (Bureau of Reclamation, 2019). The highest nitrogen and phosphorus loads often occur in the spring (Mayer, 2005). Draining water off the land for spring planting to meet Klamath Project objectives often counteracts the TMDLs by adding high nitrogen and phosphorus loads to the Klamath River from the Klamath Straits Drain. Additionally, implementation plans to address the TMDLs must consider how hydrological flow modifications could impact Endangered Species Act-protected fish (Bureau of Reclamation, 2020). The Endangered Species Act obliges Reclamation to protect certain endangered fish, including suckers and salmon (U.S. Fish and Wildlife Service, 2019).

Previous studies have investigated operational alternatives to mitigate poor water quality for the Klamath River. These studies evaluated the effects on Klamath River water quality of decreasing particulate organic matter and cyanobacteria in the Link River (Sullivan and others, 2013a) and routing the Klamath River through treatment wetlands (Sullivan and others, 2013b; 2014). Sullivan and others (2014) simulated the potential recirculation of Klamath Straits Drain water into the Ady Canal so that water is recirculated in the Klamath Project instead of discharging into the Klamath River. Recirculation could conserve and reuse water, maintain or improve water quality, and help the Klamath Straits Drain meet TMDL load allocations. Scenarios used an existing water-quality and hydrodynamic model (CE-QUAL-W2) of the Link River to Keno Dam reach of the Klamath River, run as a series of 1-year simulations from 2006 through 2009, to evaluate recirculation for attaining TMDL goals. The model assumed maximum recirculation rates with year-round recirculation of Klamath Straits Drain water into the Ady Canal.

Laterally averaged two-dimensional hydrodynamic and water-quality models, such as CE-QUAL-W2, allow water-resource managers to assess alternative scenarios that balance mitigation strategies, such as recirculation, with the need to enable drainage water to flow out of the project area to the Klamath River. Currently (2023), two CE-QUAL-W2 models exist for simulating Klamath Straits Drain recirculation into Ady Canal. The original Klamath River CE-QUAL-W2 model for the Link-Keno reach included the Klamath Straits Drain as a tributary (Sullivan and others, 2011, 2013b). An independent CE-QUAL-W2 model for the Klamath Straits Drain was developed for 2012–15, comprising the entire Klamath Straits Drain from the headworks to the confluence with the Klamath River Link-Keno reach (Sullivan and Rounds, 2018). Because Sullivan and others (2014) only simulated year-round maximum recirculation rates for four years, this study was designed to consider a longer period having more variable flow, climate conditions, and alternative strategies that evaluated limited recirculation. This new study expands the original study period from 2006 to 2009 and 2006 to 2015.

Site Description

The Klamath River flows from the outlet of Upper Klamath Lake to the Pacific Ocean through southern Oregon and northern California. Upper Klamath Lake (fig. 1), a large 89.6 square miles (232 square kilometers), shallow (full pool mean depth 9 feet [ft]; 2.8 meters) lake, is just upstream from the study reach and tends to have dense summer harmful algal blooms, including the blue-green alga *Aphanizomenon flos-aquae* (Sullivan and others, 2011). The upstream flow enters from Upper Klamath Lake through the 1-mile-long Link River; on the downstream end, the Link-Keno reach is bounded by Keno Dam.

The start of the Klamath River is a wide and shallow area near Klamath Falls, Oregon (fig. 1). Channel widths in the upper section of the Klamath River measure up to 2,500 ft (about 800 m); in the rest of the reach down to Keno Dam, channel widths are 300–1,000 ft (about 100–300 m). Channel depths in the Link River to Keno Dam can be up to approximately 20 ft (6 m). In addition to the Link River, other Klamath River inflows through the Link-Keno reach include Klamath Straits Drain and three discrete point sources with National Pollutant Discharge Elimination System permits, the Klamath Falls and South Suburban wastewater treatment plants, and Columbia Forest Products (fig. 1). Gaged outflows include withdrawals through the Ady and North Canals to supply water for irrigation and wildlife refuges, and flow through Keno Dam to downstream reaches of the Klamath River. The Lost River Diversion Channel conveys water between the Klamath and Lost River systems. Water can be conveyed through the Lost River Diversion Channel in either direction, but typical operations divert water to the Klamath River in the winter and from the Klamath River in the summer.

Klamath Straits Drain is an unlined earthen channel, approximately 10.1 miles long, that transfers water north and west into the Klamath River (fig. 1). The Klamath Straits Drain functions as the primary outflow for Lower Klamath National Wildlife Refuge (NWR) return flow to the Klamath River. Klamath Straits Drain was originally constructed in the 1940s with Pump Plant E near Township Road and Pump Plant F near Highway 97. The E and F locations contain three pumps to help convey water. In the 1970s, the Klamath Straits Drain was enlarged with new pumps, pumps EE and FF co-located with pumps E and F, bringing the total number of pumps at each site to six (E-EE and F-FF, respectively, in fig. 1). Total flow capacity for Klamath Straits Drain is 600 cubic feet per second (ft^3/s) (17 cubic meters per second [m^3/s]). During 2006–15, daily median Klamath Straits Drain F-FF pump flows ranged from 0 to 399 ft^3/s (0–11.3 m^3/s). These flows represent an average of 6 percent and a range of 0–72 percent of the measured daily median streamflow at the Klamath River at Keno streamgage downstream (USGS station 11509500).

The area surrounding the Klamath Straits Drain was historically part of Lower Klamath Lake; the lake was drained as part of the Reclamation Klamath Project that converted land to irrigated agriculture. The drain originates at the Klamath Straits Drain headworks (KSDH; fig. 1) near the northern boundary of the Lower Klamath NWR, a 50,100-acre (78.3 square miles) refuge that encompasses part of the historical Lower Klamath Lake extent. Most of the Klamath Straits Drain and surrounding area is lower elevation than the Klamath River, so the E-EE and F-FF pump stations are sited along the Drain to move water uphill and toward the Klamath River. These two pump stations, operated by the Reclamation, lift water approximately 10 ft in elevation at each location.

Lower Klamath NWR, managed by the U.S. Fish and Wildlife Service, comprises open water, freshwater marshes, grassy uplands, and cropland (U.S. Fish and Wildlife Service, 2021). The Lower Klamath NWR comprises the Klamath Project, the Klamath Straits Drain, and the area surrounding the Klamath Straits Drain; it is an important stopover point for ducks, geese, and other migratory birds along the Pacific Flyway, including 25 species listed as threatened or sensitive by California and Oregon (U.S. Fish and Wildlife Service, 2021). The Lower Klamath NWR is managed through refuge units that include managed cropland units to support waterfowl, permanent wetland areas, and seasonally flooded wetlands that are allowed to go dry during spring and summer (Mayer, 2005). Each refuge unit is managed differently for a specific purpose (Risley and Gannett, 2006). Lower Klamath NWR is one of six national wildlife refuges that compose the Klamath Basin National Wildlife Refuge Complex. Tule Lake, another one of these six refuges, is east of Lower Klamath NWR and southeast of the Klamath Straits Drain headworks.

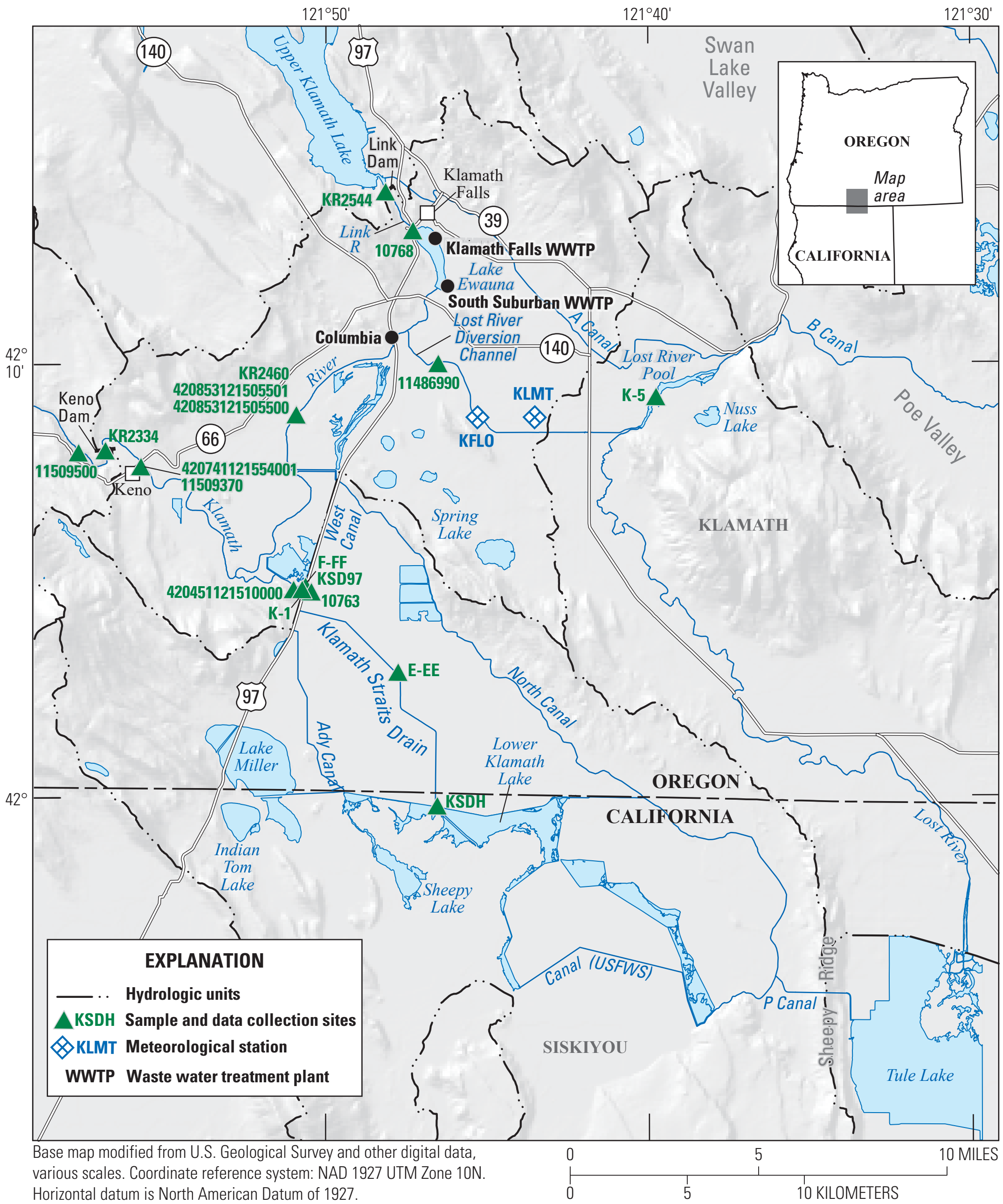


Figure 1. The study area, Klamath River, Oregon, and portions of the Klamath Project, Oregon and California.

Ady Canal conveys water from the Klamath River to the Klamath Project and Lower Klamath NWR (fig. 1). Ady Canal is one of the primary outside sources of water to the refuge and supplements many of the refuge units. Other sources of water to the refuge include ephemeral streams along the west side, precipitation, groundwater seepage, and the D Pumping Plant, which conveys water from the Tule Lake NWR (Mayer, 2005; Risley and Gannett, 2006). Additionally, pumps at Pump Plant F-FF lift water to afterbays from the Klamath Straits Drain, with gravity flow recirculating water from the afterbays through pipes to Ady Canal (R. Carlson, Bureau of Reclamation, written commun., April 8, 2022).

Under current operations, the Klamath Straits Drain conveys water from Lower Klamath NWR and irrigation return flows from agricultural land around Lower Klamath Lake. Ady Canal delivers water to the Lower Klamath NWR, diverting flow directly from the Klamath River (Mayer, 2005). Ady Canal inflows are a function of Klamath Project allotments to the refuge based on availability, delivering water for irrigation demand, and wetland habitat management.

The climate of the Upper Klamath River basin is typically dry in the summer, with most of the precipitation falling in the winter. Average annual precipitation at Klamath Falls is 13.5 inches, with two-thirds of that falling as snow between October and March (Oregon Department of Environmental Quality, 2019).

Purpose and Scope

The purpose of this study was to use an integrated hydrodynamic, water-temperature, and water-quality model for the Link-Keno reach of the Klamath River and the Klamath Straits Drain. This investigation focused on potential recirculation scenarios of Klamath Straits Drain water into Ady Canal to provide input for timing of recirculation and the feasibility of recirculation to reduce overall pollutant loads from Klamath Straits Drain into the Klamath River. Modeling focused on recirculation, in the absence of other restoration actions, in order to isolate the role of potential recirculation and identify both its expected positive and negative effects. Scenarios were configured for the base case conditions and three different recirculation scenarios:

- base case models simulating conditions from 2006 to 2015,
- maximum Klamath Straits Drain recirculation into Ady Canal from 2006 to 2015,
- limited Klamath Straits Drain recirculation into Ady Canal (year-round) from 2006 to 2015, and
- limited Klamath Straits Drain recirculation into Ady Canal (May–September) from 2006 to 2015.

Previous Klamath Straits Drain recirculation scenarios for the Link-Keno reach CE-QUAL-W2 model were from 2006 to 2009 and 2011 (Sullivan and others, 2014). This current study extended the calibration of the Link-Keno reach CE-QUAL-W2 model to 2010 and 2012–15. Additionally, the Klamath Straits Drain was simulated as an independent model into the main Link-Keno reach CE-QUAL-W2 model, using a newly integrated U.S. Geological Survey (USGS) model for 2012–15, thereby including in-stream processes in the Klamath Straits Drain before its confluence with the Klamath River (table 1). The new model combines the two previously published USGS models: the Link-Keno reach CE-QUAL-W2 model (Sullivan and others, 2011, 2013b, 2014) and the Klamath Straits Drain CE-QUAL-W2 model (Sullivan and others, 2014). This current report includes an evaluation of the effects of the three recirculation scenarios on the Klamath River at Keno, Oregon, downstream from the Klamath Straits Drain. This report is limited to assessing technical efficacy of recirculation scenarios on nutrient and BOD5 loads in the Klamath River and does not represent decisions on actual water management practices in the Klamath Straits Drain.

Table 1. Summary of model scenarios documented in this report.

[Also shown are the years the Klamath Straits Drain was simulated either as an input tributary within the Link-Keno model, or an independent simulation with the Klamath Straits Drain model]

Scenario number	Scenario name	Years	Klamath Straits Drain	Notes
0	Base	2006–11 2012–15	Input Independent	Actual environmental conditions from each simulated year.
1	Maximum Klamath Straits Drain Recirculation into Ady Canal	2006–11 2012–15	Input Independent	Year-round recirculation, maximum rate without pipe flow constraints at Pump Plants F and FF.
2	Limited Klamath Straits Drain Recirculation into Ady Canal (year-round)	2006–11 2012–15	Input Independent	Year-round recirculation, with limited recirculation rate based on total pipe flow of 120 cubic feet per second at Pump Plants F and FF.
3	Limited Klamath Straits Drain Recirculation into Ady Canal (May–September)	2006–11 2012–15	Input Independent	May–September recirculation only, with limited recirculation rate based on total pipe flow of 120 cubic feet per second at Pump Plants F and FF.

Methods

Calibrated CE-QUAL-W2 Models

CE-QUAL-W2 is a two-dimensional mechanistic flow, temperature, and water-quality model used to simulate water-body conditions from upstream to downstream (longitudinal) and from the water surface to the channel bottom (vertical). The third dimension, from bank to bank (lateral), is assumed to be well mixed and is not simulated by the model. CE-QUAL-W2 is capable of simulating water elevation, velocity, flow, water temperature, and many aspects of water quality, including total dissolved solids, dissolved oxygen, pH, nutrients, particulate and dissolved organic matter, and algae (Cole and Wells, 2015; Wells, 2020). At a reach scale, a long, narrow, pooled river is typically an appropriate usage for a two-dimensional, laterally averaged model. Certain required constituents, such as dissolved organic matter and particulate organic matter, were derived from measured dissolved organic carbon and particulate organic carbon. For more information on these derivations, see (1) appendix 1, which briefly discusses them and (2) the original model reports, which includes discussion on the partitioning into labile (quickly decomposing) and refractory (slowly decomposing) fractions (Sullivan and others, 2011; Sullivan and Rounds, 2018).

For this study, the Link-Keno model was used in all the base case and recirculation scenarios for a ten-year period, from January 1, 2006, through December 31, 2015, as a series of 1 calendar-year model simulations. For the years 2006 through 2009 and 2011, the Link-Keno model has been thoroughly documented and evaluated (Sullivan and others, 2011, 2013b, 2014). For the years 2010 and 2012 through 2015, this report includes the calibration for the Link-Keno model for each of the new calendar year simulations (app. 1). Calibration steps included a water balance to quantify and account for ungaged inputs and ensure proper simulation of water elevations, followed by temperature and water-quality calibrations between model predictions to measured data at selected locations (app. 1). Additionally, as part of the process to keep consistency between the previously calibrated simulations (2006–09, 2011) and the newly calibrated models (2010, 2012–15), minor modifications were completed for the older models in addition to rechecking the previous calibrations. The 2006–09 and 2011 models were updated to the CE-QUAL-W2 version 4.2, so that all models were consistent (Wells, 2020).

In addition to running the main-stem Klamath River water-quality models, the entire reach of the Klamath Straits Drain was simulated from 2012 through 2015 as individual calendar years. The development and calibration of the Klamath Straits Drain model was documented (Sullivan and Rounds, 2018), and the current set of simulations were used as input into the Link-Keno model. These models were linked using a new CE-QUAL-W2 functionality, with output from the Klamath Straits Drain model used as input into the Link-Keno model.

The full model archive for all CE-QUAL-W2 modeling scenarios described in this report, consists of the geospatial information, model inputs, model outputs, and scripts used to calculate loads for this study. The model archive is available via a USGS data release (Smith and Sullivan, 2023).

Model Scenario Setup

A summary of the model scenarios in this study are in table 1. A series of independent, 1-year model simulations were completed during the study period from 2006 through 2015.

Under current operations, the Klamath Straits Drain conveys water from Lower Klamath NWR, irrigated agricultural runoff, and (or) return flows near Lower Klamath Lake. Ady Canal delivers water to irrigated lands and the Lower Klamath NWR, diverting flow directly from the Klamath River (Mayer, 2005). The refuge is made up of individually diked wetlands, permanent and seasonally flooded wetlands, agricultural cropland, irrigated pasture, and upland habitat. Ady Canal inflows are based on Klamath Project allotments to the refuge and irrigated lands based upon availability, including some private land in the area not part of the refuge, delivering water for irrigation demand and sustaining wetland habitat. A water budget developed for years 2003–05 for the Lower Klamath NWR estimated that Ady Canal supplied 25 percent of refuge inflow (Risley and Gannett, 2006).

Maximum recirculation as a possible mitigation option for the Klamath Straits Drain was evaluated in an earlier USGS study (Sullivan and others, 2014). The strategy includes recirculating Klamath Straits Drain flows into the Ady Canal at Pump Plant FF. The maximum recirculation mitigation strategy would lessen the need to withdraw Klamath River water into Ady Canal and decrease Klamath Straits Drain return flows into the Klamath River.

Base Case

The base case was configured with the observed environmental conditions from each simulated year. The base case was constructed and calibrated on the Link-Keno reach of the Klamath River (Sullivan and others, 2011) and the Klamath Straits Drain (Sullivan and Rounds, 2018), with the model updates in appendix 1. Results from scenarios 1–3 were compared to base case results to simulate changes in specific recirculation scenarios.

Scenario 1—Maximum Klamath Straits Drain Recirculation into Ady Canal (Year-Round)

The maximum recirculation scenario (scenario 1) considered that (1) total Ady Canal flows would remain unchanged through flow balancing, meaning additional Klamath Straits Drain water added to Ady Canal would result in less Klamath River water withdrawn into Ady Canal, and (2) the maximum possible Klamath Straits Drain flow was recirculated into Ady Canal. No physical or operations limitations to the maximum amount of flow are evaluated in scenario 1 (for example, no pipe flow constraints at Pump Plants F and FF), with a maximum flow diverted of 304 ft^3/s. When Klamath Straits Drain flows were insufficient to meet Ady Canal flow needs, water was withdrawn to the Ady Canal from the Klamath River. If there was more flow in the Klamath Straits Drain than required by Ady Canal, Klamath Straits Drain flow constituted 100 percent of Ady Canal flow and excess Klamath Straits Drain flows were discharged to the Klamath River.

Total flows in the Ady Canal remained unchanged in scenario 1. The source of Ady Canal flows was (1) Klamath River water, (2) Klamath Strain Drain water, or (3) a mix of both, depending on interannual flow balancing requirements. This flow balancing meant that the water surface elevation in the Klamath River (downstream from Ady Canal and the Klamath Straits Drain) was unchanged in scenario 1 compared to the base case. The Link-Keno reach is typically managed to maintain a near-constant water surface elevation.

Scenario 1 was completed for individual calendar years 2006 through 2015. For the periods from 2006 through 2011, the following CE-QUAL-W2 input files were adjusted for scenario 1: the Klamath River input tributary discharge file for the Klamath Straits Drain and the withdrawal file, including the Ady Canal withdrawal rates from the Klamath River (Sullivan and others, 2014). For the periods from 2012 through 2015, the Ady Canal withdrawal rate from the Klamath River was still adjusted in the withdrawal file. The Klamath Straits Drain model was simulated independently and the resulting simulated Klamath Straits Drain total flow was used as an input into the Klamath River model. Potential cumulative effects over time were not assessed, because each 1-year simulation was independent.

Scenario 2—Limited Klamath Straits Drain Recirculation into Ady Canal (Year-Round)

The Bureau of Reclamation may add two pipes at the F-FF Pump Plants (fig. 1) to convey water from the Klamath Straits Drain into Ady Canal, with a maximum flow capacity of 120 ft^3/s. The limited year-round recirculation scenario (scenario 2) evaluates the fixed recirculation limitations of the pipe flow configuration on flow from the Klamath Straits Drain into Ady Canal. Recirculation was simulated year-round in scenario 2.

Scenario 3—Limited Klamath Straits Drain Recirculation into Ady Canal (May–September)

Late winter through early spring is an important period for draining the Klamath Project to prepare the agricultural land for spring planting. The Lower Klamath NWR contains intensively managed wetland units that include permanently flooded wetlands, seasonally flooded wetlands that cycle to seasonal agricultural lands used to grow moist soil annual vegetation, agricultural lands used for grain and alfalfa, and upland habitats flooded with local winter runoff. Because of the complex drainage requirements of the Klamath Project area, scenario 3 limited recirculation to only May through September to allow for early spring drainage while maintaining recirculation in the summer months.

Model Scenario Assumptions

All recirculation scenarios were completed for individual calendar years from 2006 through 2015. Potential cumulative effects over time were not assessed because the model only included 1-year simulations. Water quality of the Klamath Straits Drain flows to the Klamath River was simulated to dynamically change from recirculation for the years with a paired Klamath Straits Drain model (2012–15). For the years 2006–11, water quality was assumed to have no changes from recirculation because there was no independent Klamath Straits Drain model. Load differences between the base case and the recirculation scenarios from the Klamath Straits Drain to the Klamath River were calculated as a function of changes in discharge only for 2006–11.

Load Estimation—Instantaneous and Daily Load Averaging

Constituent loads were calculated for the Klamath Straits Drain for total phosphorus, total nitrogen, BOD5, and CBOD5. Load calculations were based upon the Klamath Straits Drain model output for water quality and discharge near the Klamath Straits Drain and Highway 97, which functions as the best available proxy for loading into the Klamath River at the mouth of Klamath Straits Drain. When there was no velocity at the site, the instantaneous load was assumed to be zero and incorporated in the overall average. Instantaneous loads were calculated with equation 1, using an approach similar to Schenk and others (2018):

$$L_i = C \times Q \times c, \qquad (1)$$

where

L_i is instantaneous load, in kilograms per day;

C is constituent concentration, in milligrams per liter;

Q is streamflow, in cubic feet per second (ft^3/s) or cubic meters per second (m^3/s); and

c conversion factor = 2.45 for Q in ft^3/s, and 86.4 for Q in m^3/s.

Streamflow data were recorded at Klamath Straits Drain near Highway 97, Oregon (KSD97; USGS station 11509340). Load calculations were initially calculated for all available streamflow measurements and then averaged to either daily, monthly, or annual loads. Additionally, the loads were converted from kilograms per day to pounds per day for easier comparison to the existing TMDLs. The concentrations of total phosphorus, total nitrogen, BOD5, and CBOD5 were multiplied by these instantaneous streamflow measurements, and used to calculate instantaneous loads using equation 1 (Smith and Sullivan, 2023).

Model Results

To assess changes in loads, scenario-specific results were compared to results from the base case (current conditions). At the completion of each scenario, the simulated water-surface elevation at Keno Dam was assessed to ensure that it was unchanged from the base case. This assessment allowed base case and scenario results to be directly compared without confounding travel-time or storage effects from water stage differences. Scenarios 1 and 2 are exploratory in nature and include end member cases to examine the range of possible effects, whereas scenario 3 is the closest to the proposed recirculation scenario by Reclamation.

Hydrologic Conditions

Klamath Straits Drain flow had a pattern of higher flows earlier in the year, with the 7-day centered moving average of daily discharge peaking in March and April (fig. 2), mainly because of the drainage of agricultural lands and wetlands from the Klamath Project area. A few of the years, such as 2010, 2014, and 2015, deviated from this pattern because these were drier years. For 2010, minimal flow occurred throughout the year, with the typical early spring drainage not occurring. Because the Klamath Straits Drain is mostly controlled by pumping and the water-surface elevations in the Klamath Straits Drain was kept relatively constant, the flow characteristics of the Klamath Straits Drain can be different than the Klamath River.

Ady Canal flow did not show strong seasonal patterns in the same way as Klamath Straits Drain. The 7-day centered moving average of daily withdrawals from the Klamath River into the Ady Canal was generally smaller earlier in the year and higher withdrawals later in the year coinciding with warmer temperatures, higher evapotranspiration, and more crop demand for irrigation water in the Klamath Project (fig. 3). This tendency did not hold every year: 2014 had high withdrawals earlier in the year with negligible withdrawals

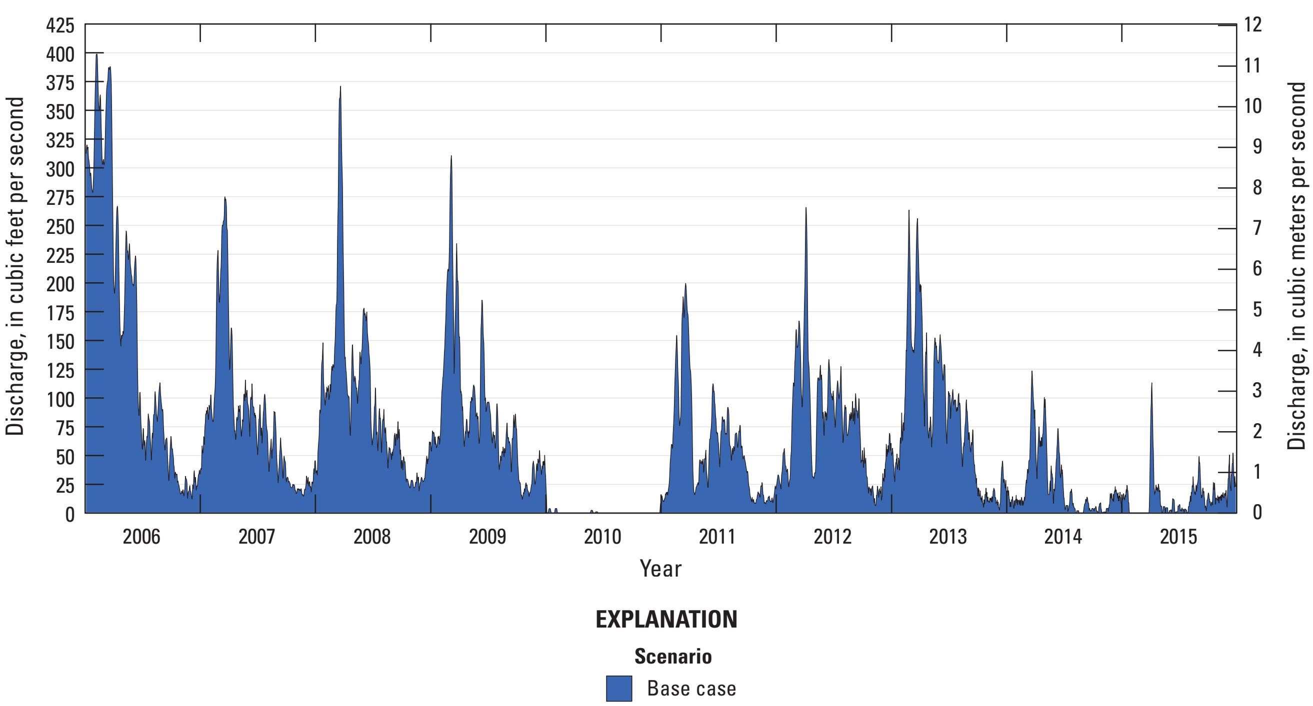


Figure 2. Klamath Straits Drain discharge, as 7-day centered moving averages of daily data (base case), from January 1, 2006 to December 31, 2015.

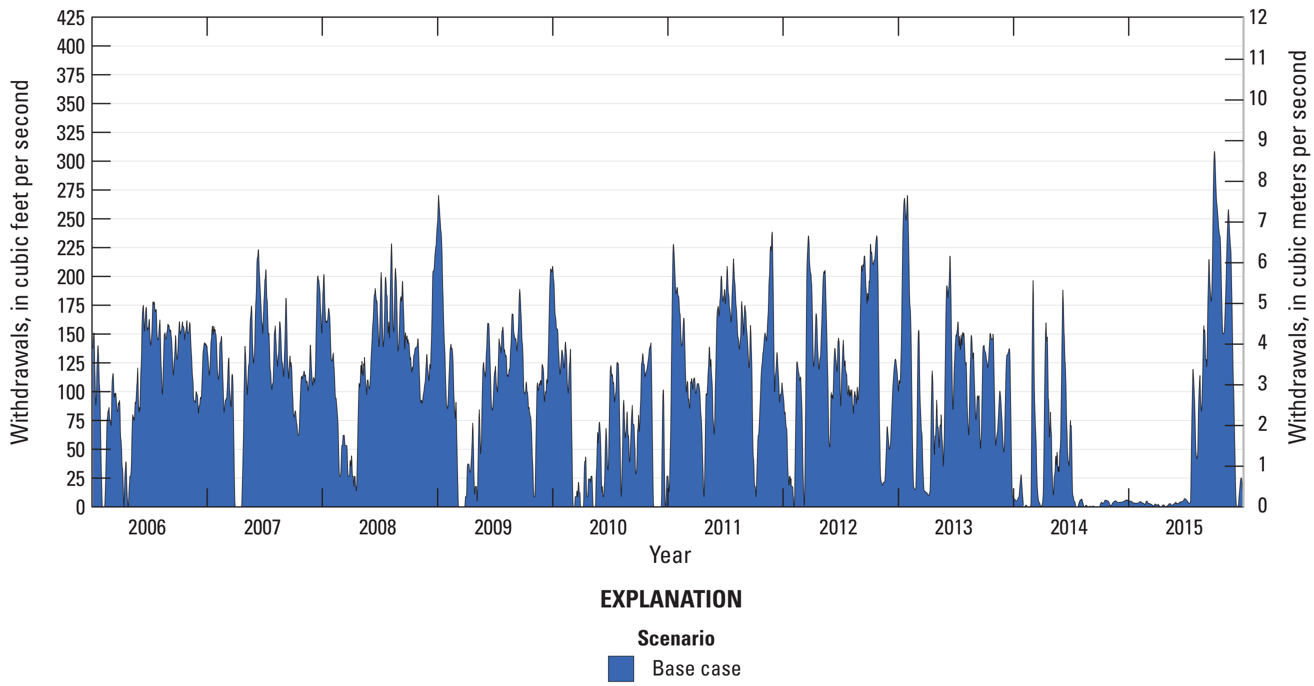


Figure 3. Klamath River withdrawals to the Ady Canal, as 7-day centered-moving averages of daily data, from January 1, 2006 to December 31, 2015.

later in 2014 up to the second half of 2015 when that year's drought and associated restrictions in irrigation flows persisted.

In comparison to the overall Klamath Straits Drain discharge, the three different recirculation scenarios had varying effects on the overall Klamath Straits Drain discharge to the Klamath River. Figure 4 shows the base case Klamath Straits Drain discharge (fig. 2) with the scenarios 1–3 plotted as the 7-day centered moving average of daily discharge.

Because there were no limits placed on how much Ady Canal water could be replaced by Klamath Straits Drain water, the maximum recirculation resulted in the largest decrease in Klamath Straits Drain discharge to the Klamath River. In the early months of the year, scenarios 1 and 2 had a high proportion of the Klamath Straits Drain discharge pass through, because little water was pulled from the Klamath River for the Ady Canal. The differences later in each calendar year also differed for scenarios 1 and 2 with reductions in discharge to the Klamath River, whereas scenario 3 showed the limitations in flow reduction from May through September.

Klamath Straits Drain Load Allocation and Scenario Results

Total nitrogen, total phosphorus, BOD5, and CBOD5 were calculated for the Klamath Straits Drain for the base case and three recirculation scenarios. Constituent loads were then compared to the nonpoint source load allocations for the Klamath Straits Drain from the Upper Klamath and Lost River Subbasins TMDL (Oregon Department of Environmental Quality, 2019). Daily allocations for Klamath Straits Drain to the Klamath River allow a maximum of 268 lbs/day for total nitrogen, 21 lbs/day for total phosphorus, and 1,329 lbs/day for BOD5. All scenarios were completed for individual calendar years from 2006 through 2015. TMDL allocations for CBOD5 were not established but a calculated annual allocation is shown for comparison between the different scenarios. Overall, these comparisons are important for Reclamation to determine how much recirculation could decrease the export of nutrient loads to the Klamath River.

Base Case

As the Klamath Straits Drain flows to and Ady Canal flows from the Klamath River, nutrient loads are transported into and out of the Klamath River. In the base case, annual average total phosphorus loads exported to the Klamath River from the Klamath Straits Drain were estimated at 149 lbs/day (maximum annual average: 457 lbs/day) and annual average total nitrogen loads at 1,310 lbs/day (maximum annual average: 3,060 lbs/day) (tables 2–3). In comparison, the total phosphorus and total nitrogen loads removed from the Klamath River by Ady Canal were generally less on an annual average basis, with total phosphorus loads estimated at 77 lbs/day (maximum annual average: 115 lbs/day), and total nitrogen loads at 958 lbs/day (maximum annual average: 1,500 lbs/day) (tables 2–3). However, the year-to-year variabilities for phosphorus and

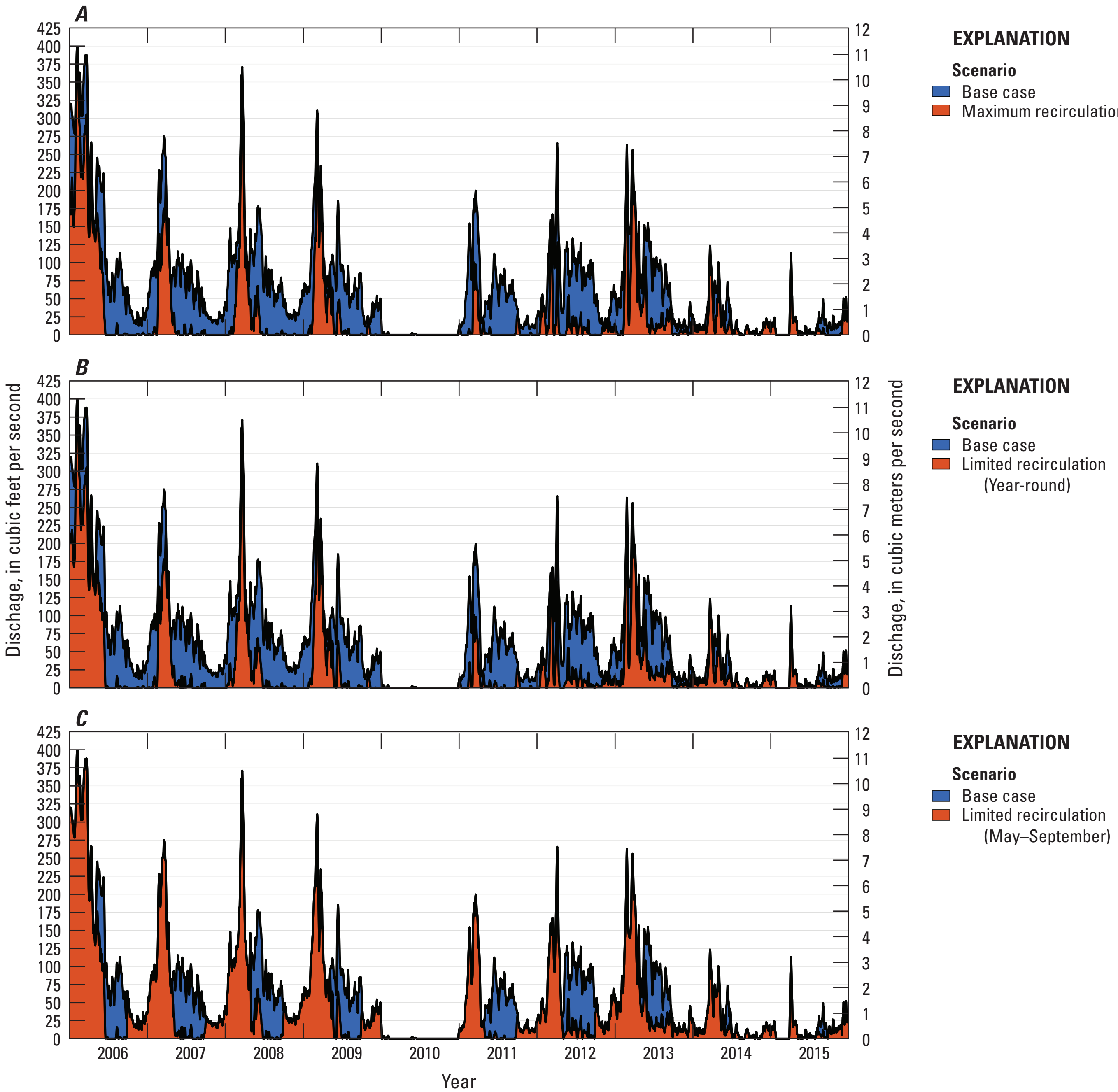


Figure 4. Klamath Straits Drain discharge, as 7-day centered-moving averages of daily data, from January 1, 2006 to December 31, 2015. The base case (fig. 2) is plotted with *A*, Klamath Straits Drain maximum recirculation discharge (scenario 1), *B*, Klamath Straits Drain limited year-round recirculation discharge (scenario 2), and *C*, Klamath Straits Drain limited seasonal recirculation discharge (scenario 3).

nitrogen loads into the Klamath River from the Klamath Straits Drain were greater than an order of magnitude between 2006 and 2015, excluding 2010, which had little or no Klamath Straits Drain flow (fig. 2). Likewise, the overall phosphorus and nitrogen loads out of the Klamath River to the Ady Canal varied greater than an order of magnitude during the same period. In contrast to the total phosphorus and nitrogen loads, BOD5 loads to the Klamath River from the Klamath Straits Drain were less than the BOD5 loads diverted from the Klamath River to the Ady Canal except for 2014 (tables 2.1–2.3). Annually, average BOD5 loads exported to the Klamath River from the Klamath Straits Drain were estimated at up to 854 lbs/day (CBOD5: 817 lbs/day) (tables 4–5), whereas BOD5 loads removed from the Klamath River by Ady Canal were estimated at up to 1,920 lbs/day (CBOD5: 1,870 lbs/day) (tables 4–5)

Table 2. Total nitrogen loads (in pounds per day) withdrawn from the Klamath Straits Drain to the Klamath River and from the Klamath River to the Ady Canal (including average and maximum annual loads), as simulated in base case conditions and the three recirculation scenarios.

[The percentage of reduction between the base-case loads and the three scenarios was calculated for the Klamath Straits Drain to the Klamath River and from the Klamath River to the Ady Canal. Loads are annual average daily loads, calculated using all days of the year whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Combinations of scenarios and years exceeding the TMDL for Klamath Straits Drain are **bold.** Abbreviations: TMDL, Total Maximum Daily Load; N/A, not applicable]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	Maximum
From Klamath Straits Drain to Klamath River												
Base Case	**3,060**	**1,720**	**1,920**	**1,680**	4	**1,100**	**1,420**	**1,560**	**431**	196	1310	3,060
Scenario 1	**1,880**	**557**	**720**	**719**	0	168	**316**	**704**	**290**	138	549	1,880
Scenario 2	**1,940**	**583**	**764**	**738**	0	191	**375**	**768**	**298**	142	580	1,940
Scenario 3	**2,440**	**1,110**	**1,310**	**1,180**	4	**666**	**898**	**1,110**	**377**	167	926	2,440
TMDL	268	268	268	268	268	268	268	268	268	268	N/A	N/A
From Klamath River to Ady Canal												
Base Case	1,170	1,350	1,500	1,130	607	1,220	954	881	188	586	958	1,500
Scenario 1	575	758	825	605	606	788	397	435	101	457	555	825
Scenario 2	599	768	847	613	606	797	423	486	118	473	573	847
Scenario 3	848	1,040	1,180	858	607	1,020	677	643	141	529	753	1,180
Percent reduction relative to base case (from Klamath Straits Drain to Klamath River)												
Scenario 1	38.4	67.6	62.5	57.2	89.8	84.7	77.8	54.9	32.7	29.6	59.5	89.8
Scenario 2	36.4	66.1	60.2	56.1	89.8	82.7	73.7	50.8	30.9	27.7	57.4	89.8
Scenario 3	20.0	35.2	32.1	29.8	15.3	39.4	36.9	28.9	12.4	14.8	26.5	39.4
Percent reduction relative to base case (from Klamath River to Ady Canal)												
Scenario 1	50.7	43.9	45.2	46.5	0.3	35.1	58.4	50.6	46.2	22.0	39.9	58.4
Scenario 2	48.7	43.1	43.7	45.8	0.3	34.4	55.7	44.8	37.2	19.3	37.3	55.7
Scenario 3	27.3	23.4	22.1	24.1	0.0	16.3	29.1	27.0	25.0	9.8	20.4	29.1

Table 3. Total phosphorus loads (in pounds per day) withdrawn from the Klamath Straits Drain to the Klamath River and from the Klamath River to the Ady Canal (including average and maximum annual loads), as simulated in base case conditions and the three recirculation scenarios.

[The percentage of reduction between the base-case loads and the three scenarios was calculated for the Klamath Straits Drain to the Klamath River and from the Klamath River to the Ady Canal. Loads are annual average daily loads, calculated using all days of the year whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Combinations of scenarios and years exceeding the TMDL for Klamath Straits Drain are **bold.** Abbreviations: TMDL, Total Maximum Daily Load; N/A, not applicable]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	Maximum
From Klamath Straits Drain to Klamath River												
Base Case	**457**	**190**	**193**	**184**	0	**100**	**136**	**161**	**45**	**22**	149	457
Scenario 1	**291**	**61**	**66**	**78**	0	14	**26**	**58**	**29**	15	64	291
Scenario 2	**300**	**64**	**71**	**80**	0	16	**31**	**65**	**30**	16	67	300
Scenario 3	**371**	**110**	**113**	**115**	0	**51**	**76**	**102**	**39**	19	100	371
TMDL	21	21	21	21	21	21	21	21	21	21	N/A	N/A
From Klamath River to Ady Canal												
Base Case	104	107	115	81	47	80	86	78	22	52	77	115
Scenario 1	52	59	63	41	46	51	35	37	12	40	44	63
Scenario 2	54	60	64	42	46	51	37	42	14	42	45	64
Scenario 3	74	77	84	56	47	65	57	54	16	46	57	84
Percent reduction relative to base case (from Klamath Straits Drain to Klamath River)												
Scenario 1	36.3	68.1	65.8	57.7	82.1	86.0	80.7	63.7	34.2	31.7	60.6	86.0
Scenario 2	34.4	66.5	63.2	56.4	82.1	84.3	77.0	59.3	32.2	29.0	58.4	84.3
Scenario 3	18.9	42.1	41.5	37.5	26.9	49.3	43.9	36.8	12.0	12.2	32.1	49.3
Percent reduction relative to base case (from Klamath River to Ady Canal)												
Scenario 1	50.1	44.9	45.3	48.7	0.2	36.1	59.2	52.2	47.6	22.7	40.7	59.2
Scenario 2	48.4	44.0	43.9	47.8	0.2	35.4	56.8	45.9	39.4	19.9	38.2	56.8
Scenario 3	29.3	28.7	26.5	30.5	0.0	18.9	34.2	30.8	30.1	11.7	24.1	34.2

Table 4. The 5-day biochemical oxygen demand loads (in pounds per day) withdrawn from the Klamath Straits Drain to the Klamath River and from the Klamath River to the Ady Canal (including average and maximum annual loads), as simulated in base case conditions and the three recirculation scenarios.

[The percentage of reduction between the base-case loads and the three scenarios was calculated for the Klamath Straits Drain to the Klamath River and the Ady Canal from the Klamath River. Loads are annual average daily loads, calculated using all days of the year whether flow occurred]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	Maximum
From Klamath Straits Drain to Klamath River												
Base Case	854	619	681	576	1	421	690	717	209	98	487	854
Scenario 1	373	131	161	163	0	44	79	199	106	60	132	373
Scenario 2	386	138	174	168	0	49	93	216	109	62	140	386
Scenario 3	537	284	352	304	1	166	305	407	150	68	257	537
From Klamath River to Ady Canal												
Base Case	1,380	1,490	1,920	1,450	580	1,280	1,030	895	145	1,150	1,130	1,920
Scenario 1	763	884	1,180	786	580	919	393	371	74	861	681	1,180
Scenario 2	774	892	1,200	793	580	923	410	442	90	903	701	1,200
Scenario 3	893	973	1,339	905	580	1,030	550	511	100	997	788	1339
Percentage of reduction relative to base case (from Klamath Straits Drain to Klamath River)												
Scenario 1	56.3	78.9	76.4	71.7	79.8	89.5	88.6	72.3	49.3	38.4	70.1	89.5
Scenario 2	54.8	77.7	74.4	70.8	79.8	88.3	86.5	69.9	48.1	37.1	68.7	88.3
Scenario 3	37.1	54.1	48.3	47.3	20.8	60.6	55.8	43.3	28.0	30.6	42.6	60.6
Percentage of reduction relative to base case (from Klamath River to Ady Canal)												
Scenario 1	44.9	40.8	38.6	45.9	0.1	28.4	61.6	58.5	49.2	24.9	39.3	38.6
Scenario 2	44.1	40.3	37.7	45.3	0.1	28.1	60.0	50.6	37.8	21.3	36.5	37.7
Scenario 3	35.5	34.9	30.4	37.6	0.0	19.8	46.3	42.9	31.1	13.1	29.2	30.4

Table 5. The 5-day carbonaceous biochemical oxygen demand loads (in pounds per day) withdrawn from the Klamath Straits Drain to the Klamath River and from the Klamath River to the Ady Canal (including average and maximum annual loads), as simulated in base case conditions and the three recirculation scenarios.

[The percentage of reduction between the base-case loads and the three scenarios was calculated for the Klamath Straits Drain to the Klamath River and the Ady Canal from the Klamath River. Loads are annual average daily loads, calculated using all days of the year whether flow occurred]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	Maximum
From Klamath Straits Drain to Klamath River												
Base Case	817	593	655	555	1	410	667	693	201	96	469	817
Scenario 1	353	124	154	156	0	42	74	186	100	59	125	353
Scenario 2	365	131	167	161	0	48	87	203	102	60	132	365
Scenario 3	511	268	334	289	1	160	292	390	142	66	245	511
From Klamath River to Ady Canal												
Base Case	1,350	1,450	1,870	1,410	561	1,250	1,000	869	141	1,130	1,100	1,870
Scenario 1	745	856	1,150	761	560	897	383	359	72	847	663	1,150
Scenario 2	755	864	1,170	768	560	901	400	428	88	888	682	1,170
Scenario 3	867	934	1,290	868	560	1,000	533	493	97	981	763	1,290
Percentage of reduction relative to base case (from Klamath Straits Drain to Klamath River)												
Scenario 1	56.8	79.1	76.5	71.8	79.3	89.6	88.9	73.1	50.3	38.6	70.4	89.6
Scenario 2	55.4	77.9	74.5	70.9	79.3	88.4	86.9	70.8	49.0	37.3	69.1	88.4
Scenario 3	37.5	54.8	49.0	47.9	20.7	60.9	56.3	43.7	29.0	31.1	43.1	60.9
Percentage of reduction relative to base case (from Klamath River to Ady Canal)												
Scenario 1	44.8	40.8	38.5	45.9	0.1	28.4	61.7	58.7	49.3	25.0	39.3	38.5
Scenario 2	44.1	40.3	37.6	45.4	0.1	28.0	60.1	50.8	37.9	21.4	36.6	37.6
Scenario 3	35.8	35.4	30.9	38.3	0.0	19.9	46.7	43.3	31.2	13.1	29.5	30.9

On a monthly basis, the loads had an even wider range, particularly for the total phosphorus and total nitrogen loads for the Klamath Straits Drain (fig. 5). The monthly trends show higher loads into the Klamath River through June, and smaller loads into the Klamath River during the second half of the individual years. While this pattern holds for total phosphorus and total nitrogen, the year 2006 stood out from the other years for total phosphorus loads through May. The year 2010 had no or very low loads (less than 4 lbs/day for total nitrogen, less than 1 lbs/day for total phosphorus and BOD5), so 2010 appears to be missing for most months in figure 5 and subsequent figures. BOD5 loads showed slightly different patterns, with the monthly phosphorous load trends more evenly distributed from March through September and October through January generally smaller.

For total phosphorus and nitrogen loads, the TMDL allocations were typically exceeded in the months from January to September, with the loads approaching or falling below the TMDL allocations from October through December. BOD5 did not meet the TMDL allocation in five individual months during the 10-year period, with four out of five exceedances in either 2006 or 2013.

Scenario 1—Maximum Klamath Straits Drain Recirculation into Ady Canal (Year-Round)

Scenario 1 evaluated the maximum possible recirculation of Klamath Straits Drain water into the Ady Canal, with no limitations to the maximum amount of transfer to Ady Canal except for the available Klamath Straits Drain water. Compared to the base case, annual average daily loads were substantially lower for total phosphorus, total nitrogen, and BOD5 (tables 6–8). Total phosphorus loads were estimated at up to 291 lbs/day compared to the base case high of 457 lbs/day, with an average reduction in the annual average daily load of 60.6 percent. Total nitrogen loads were estimated at up to 1,880 lbs/day compared to the base case high of 3,060 lbs/day, with an average reduction in the annual average daily load of 59.5 percent. For the Ady Canal loads, the total phosphorus and nitrogen loads removed from the Klamath River by Ady Canal were reduced because less water was pulled from the Klamath River. Ady Canal total phosphorus loads were estimated at up to 63 lbs/day compared to the base case high of 115 lbs/day, with an average reduction in the annual average daily load of 40.7 percent. Total nitrogen loads were estimated at up to 825 lbs/day compared to the base case high of 1,500 lbs/day, with an average reduction in the annual average daily load of 39.9 percent. BOD5 loads to the Klamath River from the Klamath Straits Drain were estimated at up to 373 lbs/day (CBOD5: 353 lbs/day) compared to the base case high of 854 lbs/day, with an average reduction of 70.1 percent; comparably, the BOD5 from the Klamath River to the Ady Canal were estimated at up to 1,180 lbs/day (CBOD5: 1,150 lbs/day) compared to the base case high of 1,920 lbs/day, with an average reduction in the annual average daily load of 39.3 percent.

On a monthly basis, the load reductions occurred year-round for all constituents for the Klamath Straits Drain (fig. 6). In particular, the scenario 1 load reductions after the spring high flows were often below the current TMDL allocations, because the total nitrogen and total phosphorus loads typically were at or below the TMDL allocations after June with scenario 1. For BOD5 loads, scenario 1 led to the same annual trend in reductions, and the BOD5 TMDL allocation was not exceeded for a single month.

Scenario 2—Limited Klamath Straits Drain Recirculation into Ady Canal (Year-Round)

Scenario 2 evaluated the year-round recirculation of Klamath Straits Drain water into the Ady Canal with the current pipe flow configuration at the F-FF Pump Plant, constricted by a maximum flow capacity of 120 ft^3/s. Despite the limitations, Scenario 2 had substantially lower annual average daily loads for total phosphorus, total nitrogen, and BOD5 compared to the base case (tables 6–8). Total phosphorus loads were estimated at up to 300 lbs/day compared to the base case high of 457 lbs/day, with an average reduction in the annual average daily load of 58.4 percent. Total nitrogen loads were estimated at up to 1,940 lbs/day compared to the base case high of 3,060 lbs/day, with an average reduction in the annual average daily load of 57.4 percent. The total phosphorus and nitrogen loads removed from the Klamath River by Ady Canal were also reduced in similar amounts to Scenario 1. Ady Canal total phosphorus loads were estimated at up to 64 lbs/day compared to the base case high of 115 lbs/day, with an average reduction in the annual average daily load of 38.2 percent. Total nitrogen loads were estimated at up to 847 lbs/day compared to the base case high of 1,500 lbs/day, with an average reduction in the annual average daily load of 37.3 percent. BOD5 loads to the Klamath River from the Klamath Straits Drain were estimated at up to 386 lbs/day (CBOD5: 365 lbs/day) compared to the base case high of 854 lbs/day, with an average reduction of 68.7 percent. The BOD5 from the Klamath River to the Ady Canal were estimated at up to 1,200 lbs/day (CBOD5: 1,166 lbs/day) compared to the base case high of 1,920 lbs/day, with an average reduction in the annual average daily load of 36.5 percent.

Scenarios 1 and 2 load reductions occurred in all months for all constituents (total nitrogen, total phosphorus, BOD5) for the Klamath Straits Drain (fig. 7). Also, both scenarios had load reductions after the spring high flows that were often below the current TMDL allocations for total nitrogen and total phosphorus after June. For BOD5 loads, scenario 2 had similar annual reduction trends as scenario 1 and the BOD5 TMDL allocation was not exceeded during any single month.

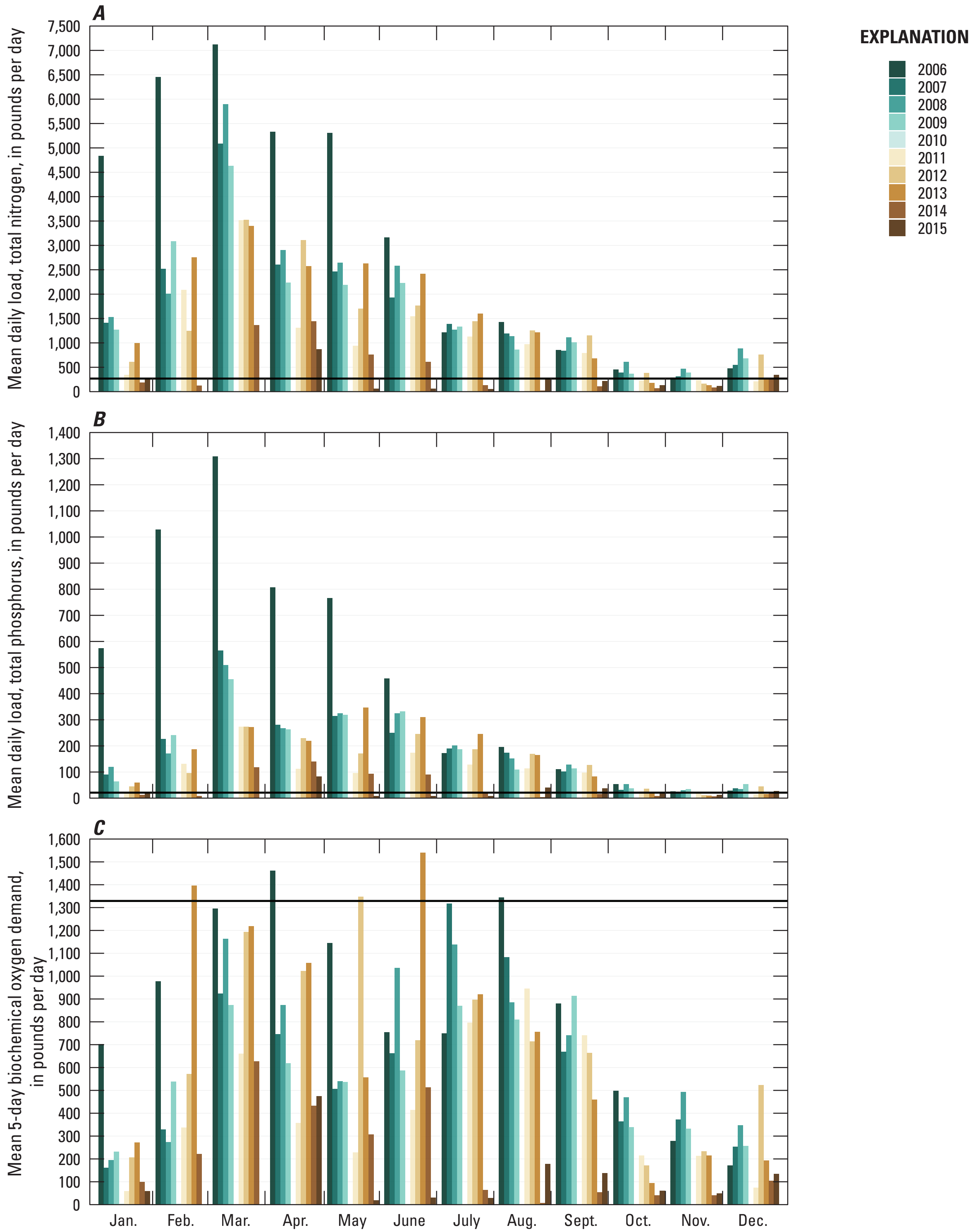


Figure 5. Klamath Straits Drain monthly average daily loads to the Klamath River from 2006 through 2015 for the base case for *A*, total nitrogen, *B*, total phosphorus, and *C*, the 5-day biochemical oxygen demand. The horizontal bar denotes the Klamath Straits Drain Total Maximum Daily Load allocations of 268, 21, and 1,329 lbs/day for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand, respectively.

Table 6. Monthly averages of daily total nitrogen loads withdrawn from the Klamath River to the Ady Canal, as simulated in base case conditions and the three recirculation scenarios.

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Abbreviation: lbs/day, pounds per day]

Month of year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total nitrogen load, base case (lbs/day)										
January	1,050	1,510	1,910	2,460	1,320	1,550	459	1,790	79	28
February	298	1,180	1,040	1,130	1,140	1,390	750	912	23	30
March	618	717	606	100	133	1,020	1,140	573	442	15
April	173	125	319	210	141	629	965	297	431	8
May	442	875	745	411	227	685	759	369	170	12
June	1,080	1,380	1,210	888	243	1,080	755	1,150	545	34
July	1,910	2,250	2,130	1,550	950	1,320	1,240	1,560	226	448
August	1,810	2,130	2,680	1,650	622	1,520	1,160	1,220	34	915
September	1,820	1,910	2,040	1,810	631	1,340	1,540	637	9	1,750
October	1,990	982	1,550	916	959	679	1,500	887	22	1,530
November	1,440	1,320	1,560	984	589	2,210	307	509	26	1,710
December	1,280	1,810	2,270	1,460	360	1,190	860	643	37	222
Total nitrogen load, scenario 1 (lbs/day)										
January	0	780	946	1,680	1,310	1,380	266	1,240	57	22
February	0	278	174	96	1,140	513	326	430	8	29
March	0	0	0	0	133	53	410	58	282	14
April	0	31	33	58	141	261	328	84	277	2
May	0	357	128	90	224	447	359	64	115	11
June	325	757	294	190	243	575	210	346	274	28
July	1,120	1,080	1,220	686	951	827	322	571	116	425
August	685	1,200	1,730	994	622	911	290	393	20	542
September	1,000	1,320	1,300	1,020	631	811	906	313	2	1,370
October	1,530	687	1,160	664	959	599	923	778	16	1,370
November	1,200	1,100	1,190	716	589	2,010	160	423	21	1,540
December	999	1,480	1,730	1,010	360	1,060	266	500	23	130
Total nitrogen load, scenario 2 (lbs/day)										
January	130	787	1,040	1,680	1,310	1,380	266	1,290	66	23
February	0	286	181	135	1,130	578	328	465	10	29
March	25	40	0	0	133	75	523	79	314	14
April	0	31	37	58	141	261	383	107	332	4
May	30	371	134	90	224	447	374	86	142	11
June	413	788	410	242	243	593	217	452	313	33
July	1,120	1,100	1,250	688	951	830	328	753	138	444
August	692	1,200	1,730	994	622	918	292	482	22	643
September	1,000	1,320	1,300	1,030	631	811	924	335	5	1,390
October	1,530	687	1,160	664	959	599	938	808	20	1,370
November	1,200	1,100	1,190	716	589	2,010	195	436	24	1,570
December	999	1,480	1,730	1,010	360	1,060	305	512	29	139
Total nitrogen load, scenario 3 (lbs/day)										
January	1,050	1,511	1,910	2,460	1,320	1,550	459	1,790	79	28
February	298	1,180	1,040	1,130	1,140	1,390	750	912	23	30

Table 6. Monthly averages of daily total nitrogen loads withdrawn from the Klamath River to the Ady Canal, as simulated in base case conditions and the three recirculation scenarios.—Continued

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Abbreviation: lbs/day, pounds per day]

Month of year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total nitrogen load, scenario 3 (lbs/day)—Continued										
March	618	717	606	100	133	1,020	1,140	573	442	15
April	167	125	292	210	141	625	958	295	429	8
May	30	371	134	90	224	447	374	88	137	11
June	413	788	410	242	243	592	217	453	298	33
July	1,120	1,100	1,250	688	952	830	328	754	135	444
August	692	1,200	1,730	994	622	918	292	476	22	644
September	1,020	1,330	1,340	1,040	631	811	941	335	5	1,390
October	1,990	982	1,550	916	959	679	1,500	879	22	1,540
November	1,440	1,320	1,560	984	589	2,210	307	507	26	1,690
December	1,280	1,810	2,270	1,460	360	1,190	859	643	37	221

Table 7. Monthly averages of daily total phosphorus loads withdrawn from the Klamath River to the Ady Canal, as simulated in base case conditions and the three recirculation scenarios.

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Abbreviation: lbs/day, pounds per day]

Month of year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total phosphorus load, base case (lbs/day)										
January	64	83	86	114	72	70	24	111	5	64
February	24	71	49	64	75	66	53	99	2	24
March	58	44	47	7	9	67	95	39	40	58
April	17	9	24	19	12	43	71	23	36	17
May	40	82	70	35	22	49	75	38	23	40
June	104	128	111	86	26	72	89	106	87	104
July	187	194	169	137	87	87	130	169	39	187
August	171	220	245	151	53	105	125	117	5	171
September	182	201	205	159	61	140	152	69	1	182
October	192	91	160	80	87	63	127	83	2	192
November	110	81	97	48	35	126	16	34	2	110
December	94	81	107	67	22	67	70	43	3	94
Total phosphorus load, scenario 1 (lbs/day)										
January	0	42	42	77	72	63	14	77	4	2
February	0	16	8	5	74	23	22	49	1	3
March	0	0	0	0	9	3	36	4	26	1
April	0	2	3	5	12	18	25	7	24	0
May	0	32	12	8	21	32	34	6	16	1
June	31	69	24	17	26	39	25	31	43	3
July	109	87	97	61	87	55	34	61	20	57
August	66	124	159	91	53	63	31	36	3	63
September	102	139	131	90	61	85	90	35	0	150
October	147	63	119	58	87	56	79	74	2	114
November	92	68	74	35	35	115	8	29	2	79
December	73	66	81	47	22	60	21	33	2	6

Table 7. Monthly averages of daily total phosphorus loads withdrawn from the Klamath River to the Ady Canal, as simulated in base case conditions and the three recirculation scenarios.—Continued

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Abbreviation: lbs/day, pounds per day]

Month of year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total phosphorus load, scenario 2 (lbs/day)										
January	8	42	46	77	72	63	14	81	5	2
February	0	17	8	7	74	26	22	53	1	3
March	2	3	0	0	9	5	45	6	29	1
April	0	2	3	5	12	18	29	9	28	0
May	3	34	12	8	21	32	36	8	20	1
June	40	72	34	23	26	40	26	42	48	3
July	109	89	99	61	87	55	35	81	23	60
August	67	124	159	91	53	63	32	46	3	75
September	102	139	131	91	61	85	91	37	0	151
October	147	63	119	58	87	56	80	76	2	114
November	92	68	74	35	35	115	10	30	2	80
December	73	66	81	47	22	60	25	34	2	7
Total phosphorus load, scenario 3 (lbs/day)										
January	64	83	86	114	72	70	24	111	5	2
February	24	71	49	64	75	66	53	99	2	3
March	58	44	47	7	9	67	95	39	40	1
April	17	9	22	19	12	43	71	23	36	1
May	3	34	12	8	21	32	36	8	19	1
June	40	72	34	23	26	40	26	42	47	3
July	109	89	99	61	87	55	35	81	23	60
August	66	124	159	91	53	63	32	46	3	75
September	104	139	136	92	61	85	93	36	0	151
October	192	91	160	80	87	63	127	83	2	128
November	110	81	97	48	35	126	16	35	2	86
December	94	81	107	67	22	67	70	43	3	11

Table 8. Monthly averages of the 5-day biochemical oxygen demand loads withdrawn from the Klamath River to the Ady Canal, as simulated in base case conditions and the three recirculation scenarios.

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Abbreviation: lbs/day, pounds per day]

Month of year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
5-day biochemical oxygen demand (BOD5), base case (lbs/day)										
January	166	223	298	440	343	302	90	517	25	9
February	54	178	164	204	306	440	214	232	11	13
March	165	128	114	17	37	302	430	166	218	10
April	94	43	160	111	60	207	737	180	221	5
May	278	445	353	303	121	285	366	227	101	7
June	1,773	1,997	1,496	1,132	180	513	450	1,798	522	36
July	3,600	5,890	5,410	3,680	1,750	2,000	3,290	3,360	362	1,230
August	2,860	3,600	6,580	4,090	1,050	2,470	2,630	2,060	54	2,390
September	3,000	2,730	3,680	4,170	1,040	2,370	1,940	440	8	4,110

Table 8. Monthly averages of the 5-day biochemical oxygen demand loads withdrawn from the Klamath River to the Ady Canal, as simulated in base case conditions and the three recirculation scenarios.—Continued

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Abbreviation: lbs/day, pounds per day]

Month of year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
5-day biochemical oxygen demand (BOD5), base case (lbs/day)—Continued										
October	2,620	1,030	2,530	1,740	1,120	891	1,480	775	27	3,060
November	1,340	894	1,300	806	800	4,790	271	536	33	2,010
December	521	599	790	578	121	839	334	373	20	130
5-day biochemical oxygen demand (BOD5), scenario 1 (lbs/day)										
January	0	117	148	302	341	267	52	371	19	7
February	0	41	27	17	304	153	93	108	4	13
March	0	0	0	0	37	18	161	17	137	9
April	0	11	15	31	60	87	297	51	145	1
May	0	176	68	71	119	186	201	39	69	6
June	748	1,160	564	237	180	270	134	522	236	29
July	2,110	3,090	3,090	1,650	1,750	1,240	838	1,140	180	1,180
August	1,050	2,070	4,260	2,460	1,050	1,450	641	630	30	1,390
September	1,640	1,890	2,360	2,350	1,040	1,430	1,140	195	1	3,080
October	2,000	724	1,930	1,240	1,120	786	880	619	19	2,710
November	1,120	746	990	594	800	4,360	137	417	26	1,790
December	406	488	602	389	122	770	126	312	13	84
5-day biochemical oxygen demand (BOD5), scenario 2 (lbs/day)										
January	21	118	163	302	341	267	52	386	21	7
February	0	42	29	24	304	174	93	117	5	13
March	5	7	0	0	37	25	204	23	155	9
April	0	11	17	31	60	87	327	66	171	3
May	19	183	70	71	119	186	207	51	97	6
June	822	1,180	647	296	180	279	140	670	307	34
July	2,110	3,150	3,170	1,650	1,750	1,250	857	1,550	215	1,230
August	1,070	2,070	4,270	2,460	1,050	1,470	645	764	32	1,670
September	1,640	1,890	2,360	2,370	1,040	1,430	1,170	217	4	3,170
October	2,000	724	1,930	1,240	1,120	786	893	665	25	2,730
November	1,120	746	990	594	800	4,360	168	441	30	1,830
December	406	488	602	389	122	770	154	305	16	89
5-day biochemical oxygen demand (BOD5), scenario 3 (lbs/day)										
January	166	223	298	440	343	302	90	517	25	9
February	54	178	164	204	306	440	214	232	11	13
March	165	128	114	17	37	302	430	166	218	10
April	90	43	150	111	60	205	731	179	220	5
May	19	183	70	71	119	186	207	55	82	6
June	822	1,180	647	296	180	279	139	683	265	34
July	2,110	3,150	3,170	1,650	1,750	1,250	857	1,630	216	1,230
August	1,070	2,070	4,270	2,460	1,050	1,470	644	767	33	1,670
September	1,670	1,900	2,430	2,400	1,040	1,430	1,190	223	4	3,180
October	2,620	1,030	2,530	1,740	1,120	891	1,480	742	27	3,070
November	1,330	894	1,300	806	801	4,790	271	523	33	1,980
December	521	599	790	578	122	839	334	382	20	133

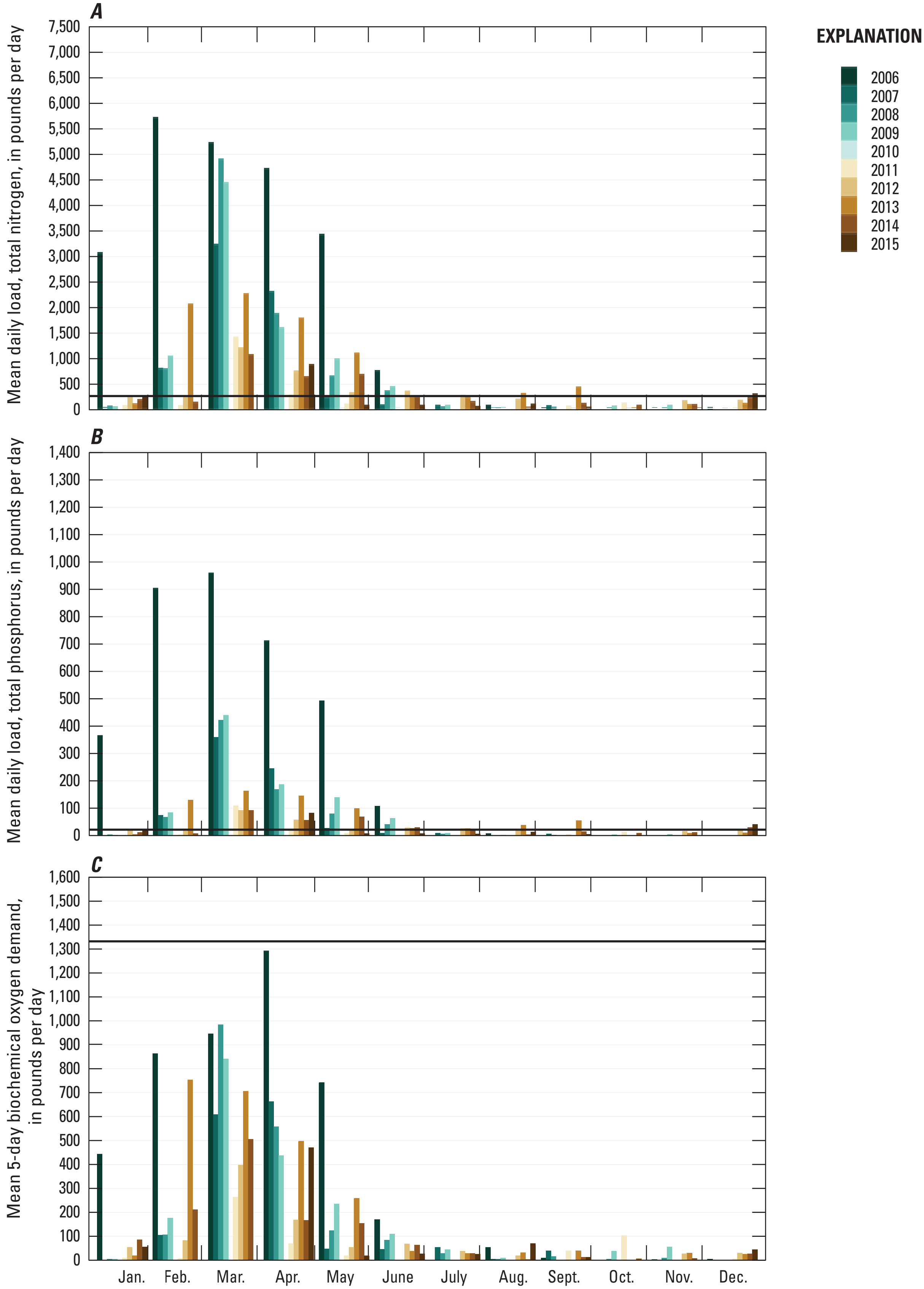


Figure 6. Klamath Straits Drain monthly average daily loads to the Klamath River from 2006 through 2015 for scenario 1 for *A*, total nitrogen, *B*, total phosphorus, and *C*, the 5-day biochemical oxygen demand. The horizontal bar denotes the Klamath Straits Drain Total Maximum Daily Load allocations of 268, 21, and 1,329 lbs/day for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand, respectively.

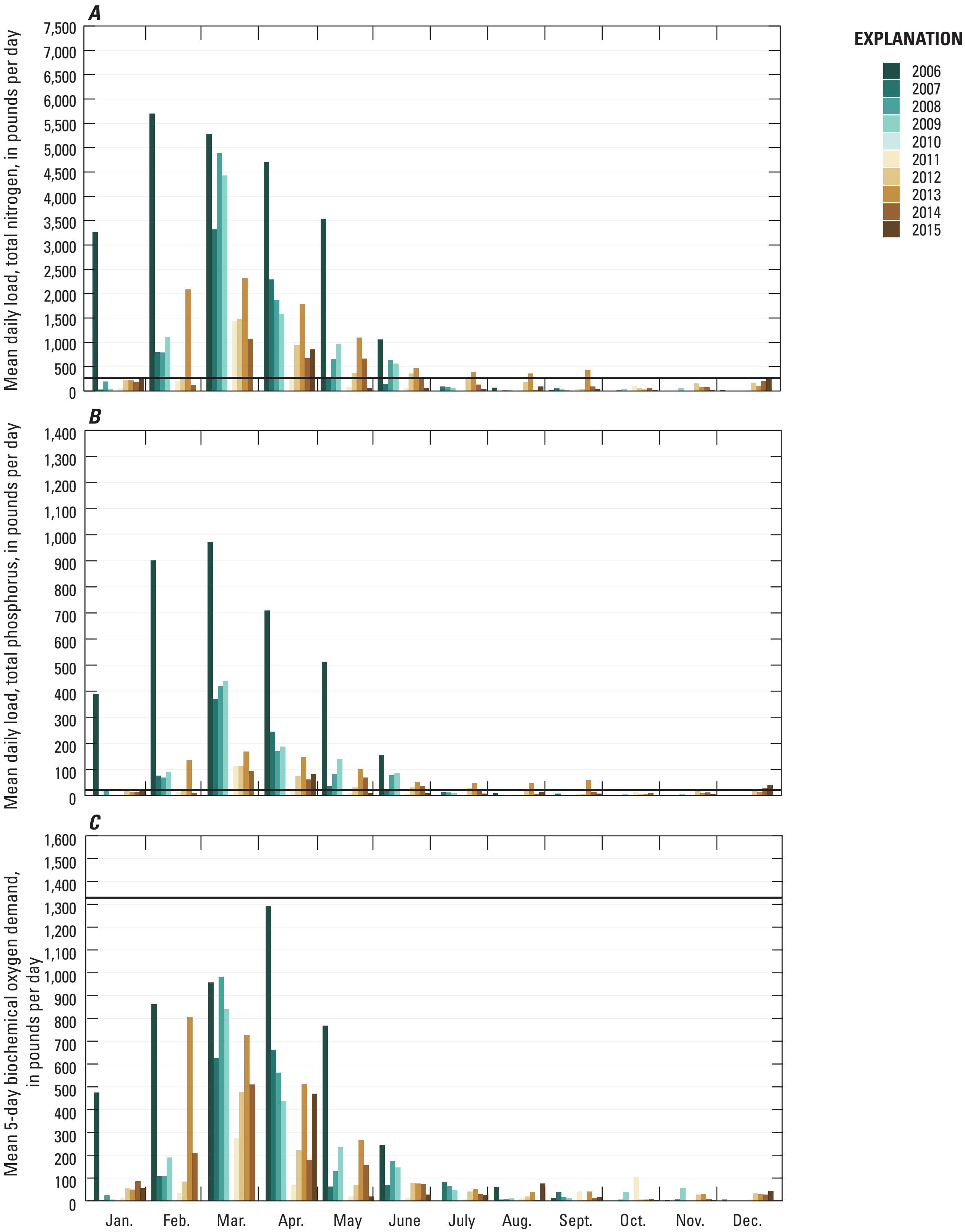


Figure 7. Klamath Straits Drain monthly average daily loads to the Klamath River from 2006 through 2015 for scenario 2 for *A*, total nitrogen, *B*, total phosphorus, and *C*, the 5-day biochemical oxygen demand. The horizontal bar denotes the Klamath Straits Drain Total Maximum Daily Load allocations of 268, 21, and 1,330 lbs/day for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand, respectively.

Scenario 3—Limited Klamath Straits Drain Recirculation into Ady Canal (May–September)

Scenario 3 evaluated the Reclamation plans to limit recirculation to only May through September. Although scenario 3 had the lowest load reductions of the three recirculation scenarios, the limited season led to reductions toward the TMDL load allocations. Total phosphorus loads from Klamath Straits Drain were estimated at up to 371 lbs/day compared to the base case high of 457 lbs/day, with a reduction in the annual average daily load of 32.1 percent. Total nitrogen loads were estimated at up to 2,440 lbs/day compared to the base case high of 3,060 lbs/day, with an average reduction in the annual average daily load of 26.5 percent. Ady Canal total phosphorus loads were estimated at up to 84 lbs/day compared to the base case high of 115 lbs/day, with an average reduction in the annual average daily load of 24.1 percent. Total nitrogen loads were estimated at up to 1,170 lbs/day compared to the base case high of 1,500 lbs/day, with an average reduction in the annual average daily load of 20.4 percent. BOD5 loads to the Klamath River from the Klamath Straits Drain were estimated at up to 537 lbs/day (CBOD5: 511 lbs/day) compared to the base case high of 854 lbs/day, with an average reduction of 42.6 percent. The BOD5 from the Klamath River to the Ady Canal were estimated at up to 1,340 lbs/day (CBOD5: 1,290 lbs/day) compared to the base case high of 1,920 lbs/day, with an average reduction in the annual average daily load of 29.2 percent.

On a monthly basis, the load reductions were approximately identical to the base outside the months May through September, because the limited seasonal recirculation only occurred in the summer months (fig. 8). The summer months did show reductions, similar to scenarios 1 and 2, although the highest loads occurred in the months when recirculation was not active (October–April). The monthly average daily total nitrogen and total phosphorus TMDL allocations for the active period were often met for scenario 3, and monthly average daily BOD5 TMDL allocations were met every month, except in April 2006 and February 2013.

Model Application

The established TMDLs outline the necessary levels to reduce nitrogen, phosphorus, and BOD5 loads from the Klamath Straits Drain (Oregon Department of Environmental Quality, 2019). However, the Klamath Straits Drain also drains the Klamath Project, so it was important to consider the implications of balancing the drainage requirements with the necessity to reduce nutrient loads. The calibrated CE-QUAL-W2 models were simulated under varying recirculation scenarios to examine the water-quality changes that might occur in the Link-Keno reach by altering the allocation of Klamath Straits Drain flow into Ady Canal. The primary goal was to examine the potential reduction in loads from the three recirculation scenarios in comparison to the current flow allocation (the base case).

The scope of the application was limited to only Klamath Straits Drain recirculation into Ady Canal rather than the entire Klamath Project area. As such, this publication did not include the loads diverted into and out of the Klamath River for the A Canal, Lost River Diversion Channel, or the North Canal (fig. 1). For a more comprehensive assessment of nutrient loads across the entire Klamath Project area, Schenk and others (2018) characterized water-quality trends and calculated a nutrient budget for the Klamath Project from March 2012 to March 2015.

Klamath Straits Drain Load Variations Throughout the Year

Recirculated flow from Klamath Straits Drain into Ady Canal occurred at the highest rates in the early spring months for scenario 1 and 2 when the Klamath Straits Drain discharge was higher because of Klamath Project drainage in late winter and early spring (fig. 2). These higher discharge rates also coincided with high concentrations of nitrogen and phosphorus species, such as nitrate, ammonia, and orthophosphate, in addition to high organic loads. Therefore, the largest reductions in loads due to recirculating Klamath Straits Drain water into Ady Canal, rather than discharging into the Klamath River, was the highest for these scenarios during the late winter and early spring (figs. 7–8). Load reductions for scenario 3 were constrained to the summer period when available Klamath Straits Drain discharge was lower. However, scenario 3 still reduced nutrient and BOD5 loads because Klamath River water was still being pulled into the Ady Canal during this time. From October through December of each year, total nitrogen, total phosphorus, and BOD5 monthly average daily loads were reduced across the three different scenarios, although these reductions generally coincided with the lower load observed in the base case during the same time of year.

The pipe flow limitations only had a small effect on the amount of recirculated flow into Ady Canal, because the pipe configuration capacity was rarely exceeded when comparing scenario 1 to scenario 2 (fig. 9). The most discernable differences, which were small, occurred in the early months of 2006 and 2007 (fig. 9). Comparing the daily mean discharge diverted from the Klamath River into Ady Canal for the two scenarios, the average daily discharges were 56.3 and 58.6 ft^3/s for scenario 1 and scenario 2, respectively. The pipe flow limitation was generally reached during January–May when available Klamath Straits Drain flow was higher because of Klamath Project drainage. During these periods, a reduced amount of Klamath River water had to be diverted for scenario 2 to maintain the same Ady Canal flow as the base case scenario. Flow in the Ady Canal was mostly recirculated Klamath Straits Drain water in scenario 1.

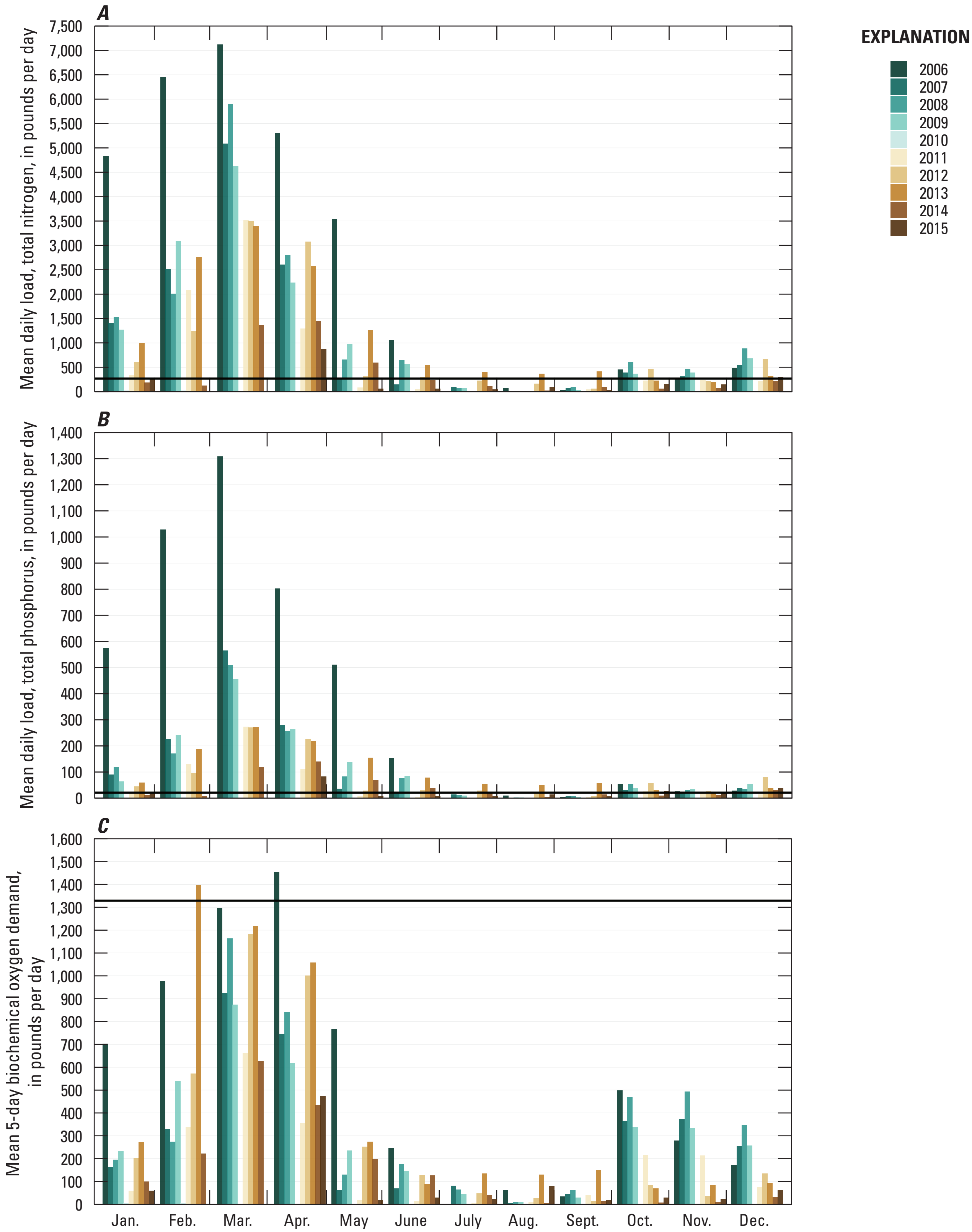


Figure 8. Klamath Straits Drain monthly average daily loads to the Klamath River from 2006 through 2015 for scenario 3 for *A*, total nitrogen, *B*, total phosphorus, and *C*, the 5-day biochemical oxygen demand. The horizontal bar denotes the Klamath Straits Drain Total Maximum Daily Load allocations of 268, 21, and 1,329 lbs/day for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand, respectively.

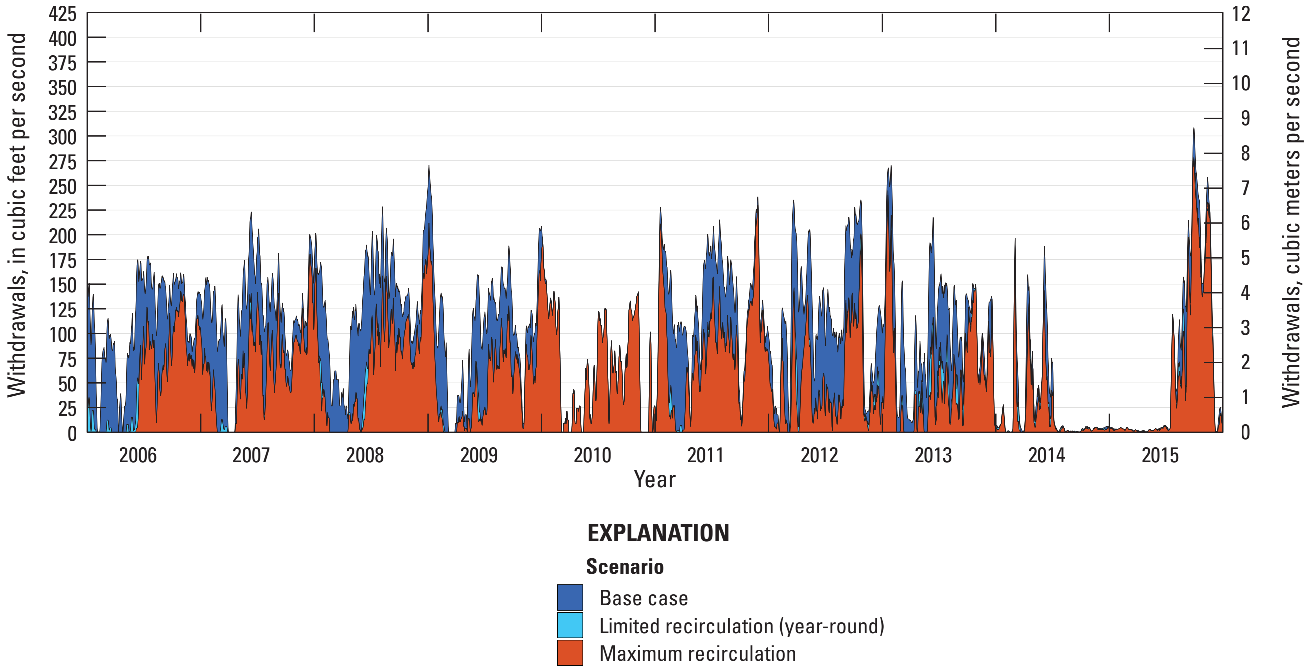


Figure 9. Klamath River withdrawals to the Ady Canal, as 7-day centered-moving averages of daily data, from January 1, 2006 to December 31, 2015. The base case is plotted with the Ady Canal maximum recirculation (scenario 1) and the Ady Canal limited year-round recirculation discharge.

Load reductions across all scenarios were still high in the summer months despite the reduced discharge from the Klamath Straits Drain. In all three scenarios, the monthly average daily total nitrogen and total phosphorus loads frequently fell below the TMDL allocations of 268 and 21 lbs/day, respectively (figs. 6–8). The base case shows the total nitrogen was typically exceeded across the summer months from June through September, except for the dry years of 2010, 2014, and 2015 (fig. 5). However, the TMDL allocation was typically met for those months for all three scenarios except from 2006 through 2009 and 2013. Reductions in the monthly average daily total nitrogen load (lbs/day) were often greater than 1,000 lbs/day (figs. 6–8). For total phosphorus, the same trend in load reductions occurred with reductions in the average monthly daily total phosphorus loads (lbs/day) greater than 150 lbs/day (figs. 5–8). The monthly average daily BOD5 loads were consistently below the TMDL allocation of 1,329 lbs/day across all three scenarios, as noted earlier, with loads fewer than 100 lbs/day after May, during most years.

Ady Canal Load Variations throughout the Year

The replacement of Ady Canal flow with water from the Klamath Straits Drain reduces the loads diverted from the Klamath River, a tradeoff to the load reductions from recirculation. Typically, the largest loads out of the Klamath River into the Klamath Project area from the Ady Canal occurred from May through November for the base case (tables 6–8). Peaks loads diverted from the Klamath River generally occurred in July, coinciding with the summer *Aphanizomenon flos-aquae* peak in Upper Klamath Lake (tables 6–8).

For scenarios 1 and 2, much lower nutrient loads were diverted out of the Klamath River in the early months of a typical year, particularly for 2006 and 2008. Available Klamath Straits Drain discharge rates were also high for 2006 and 2008 (fig. 2); therefore, a high amount of Klamath Straits Drain water was available to replace Ady Canal water instead of withdrawing water from the Klamath River to Ady Canal. In contrast, 2014–15 coincided with low drainage rates out of the Klamath Project from the Klamath Straits Drain, so less Klamath Straits Drain water was available to replace Ady Canal water (fig. 2) and therefore the loads withdrawn from the Klamath River to the Ady Canal were not as reduced from March through May for scenarios 1 and 2.

For all three recirculation scenarios, the peak of available Klamath Straits Drain water occurred in the early months from February through May. From May through September, when all three recirculation scenarios were active, a substantial portion of Ady Canal water was replaced by recirculated Klamath Straits Drain water. This replacement led to large reductions in the flux of nutrient loads diverted from the Klamath River into Ady Canal during those months, leading to tradeoffs between reducing Klamath Straits Drain loads into the Klamath River and Klamath River loads being drawn into Ady Canal. Table 6 shows these large absolute reductions for total nitrogen, total phosphorus, and BOD5 for all three scenarios monthly for every year.

Components of the Nutrient and BOD5 Loads

The bulk of the total nitrogen load was from refractory organic matter for the base case and the three recirculation scenarios. In figure 10, the base case is shown with the simulated amount of the total nitrogen loads contributed by the following constituents for individual calendar year simulations: refractory organic matter, labile organic matter, nitrate, ammonia, and algal biomass. These loads are based on model output for the base case, calculated as instantaneous loads and then averaged to either daily, monthly, or annual loads. An average of approximately 73 percent of the base-case load for total nitrogen was contributed by refractory organic matter (based on the monthly average daily load across all years), followed by ammonia at approximately 13.5 percent, nitrate at approximately 9 percent, labile organic matter at 3 percent, and algal biomass less than 2 percent. These percentages did vary across the months in every year, but generally the refractory organic matter dominated the total nitrogen load.

The larger difference in the distribution of constituents occurred between the years with a paired Klamath Straits Drain model (2012–15) as opposed to the years with only the Link-Keno model (2006–11). Small differences did occur for the distribution of labile organic matter, ammonia, nitrate, and algal biomass, likely because of simulating biogeochemical processes in the Klamath Straits Drain as an independent standalone model, not as the static water quality for the Klamath Straits Drain from 2006 to 2011. The years 2012–15 tended to have a slightly higher amount of algal biomass, with a slightly smaller pool of labile organic matter, lower nitrate, and a slightly higher ammonia pool, although these differences generally only varied by 1–3 percent.

In addition to total nitrogen, the amount of the total phosphorus load contributed by the following constituents for individual calendar year model simulations is shown for the base case (fig. 10): refractory organic matter, labile organic matter, orthophosphorus, and algal biomass. Unlike the total nitrogen load, the total phosphorus load was approximately equal between orthophosphorus and refractory organic matter at approximately 47 percent and 49 percent, respectively, for the average monthly daily load across all years for the base case. Phosphorus derived from labile organic matter and algal biomass was small, at approximately 2 percent and less than 1.5 percent, respectively. Similar to total nitrogen, these percentages did vary across the months in every year and slightly varied across the different types of hydrologic years, but generally the orthophosphorus and refractory organic matter dominated the total phosphorus load.

For BOD5, the amount of the contributing constituents to the BOD5 as the monthly average daily load for individual calendar year model simulations is shown for the base case (fig. 10): refractory organic matter, labile organic matter, ammonia, and algal biomass. Unlike the total nitrogen and total phosphorus loads, more dynamic differences occurred between the contributing distributions to BOD5 between the earlier standalone Link-Keno simulations (2006–11) to the years paired with an independent Klamath Straits Drain simulation (2012–15). For example, in the earlier simulations, an average of 64 percent of the contributing load was derived from labile organic matter across all months for the base case, whereas less than 40 percent was derived from labile organic matter for the years 2012–15 (fig. 10).

Similar figures to fig. 10 are in appendix 3 for each of the three recirculation scenarios, with monthly average daily total nitrogen, total phosphorus, and BOD5 split by the individual constituents.

Lack of Accounting for the Recycling of Constituents

Overall, the recirculation scenarios did not account for the recycling of constituents to the Klamath Straits Drain that were recirculated to the Ady Canal, then returned to the Klamath Straits Drain after cycling through the greater Klamath Project area. For constituents that act conservatively and are impacted only by sources, evaporation, and dilution (such as, total dissolved solids), concentrations could increase under continuous recirculation although the specific levels of cumulative effects is difficult to estimate. Concentration and dilution were impacted by factors such as evaporation, precipitation, dissolution from soils, type of interannual and seasonal variability (wet/dry), and residence time, all of which could vary spatially. For instance, Mayer (2005) found that estimated hydraulic residence times within the Lower Klamath NWR were 210 days for seasonal wetlands, 60 days for farmed units, and 6.6 days for permanent wetlands. For nutrients and constituents impacted by biogeochemical processes in addition to sources and mixing, it is more difficult to simulate or predict concentration changes because recirculated water is cycled from Klamath Straits Drain into Ady Canal and eventually back to the Klamath Straits Drain after cycling through the Klamath Project. For example, ammonia could be taken up by aquatic plants, algae, or crops. Also, ammonia could be transformed through nitrification and denitrification into other forms of nitrogen like nitrate or even nitrogen gas. Fertilizer application also varies depending on crop type and time of year, although Danosky and Kaffka (2002) theorized that drainage water recirculation should decrease the amount of nutrients returned to the Klamath Straits Drain, because wetlands and agriculture likely result in the net removal of nutrients.

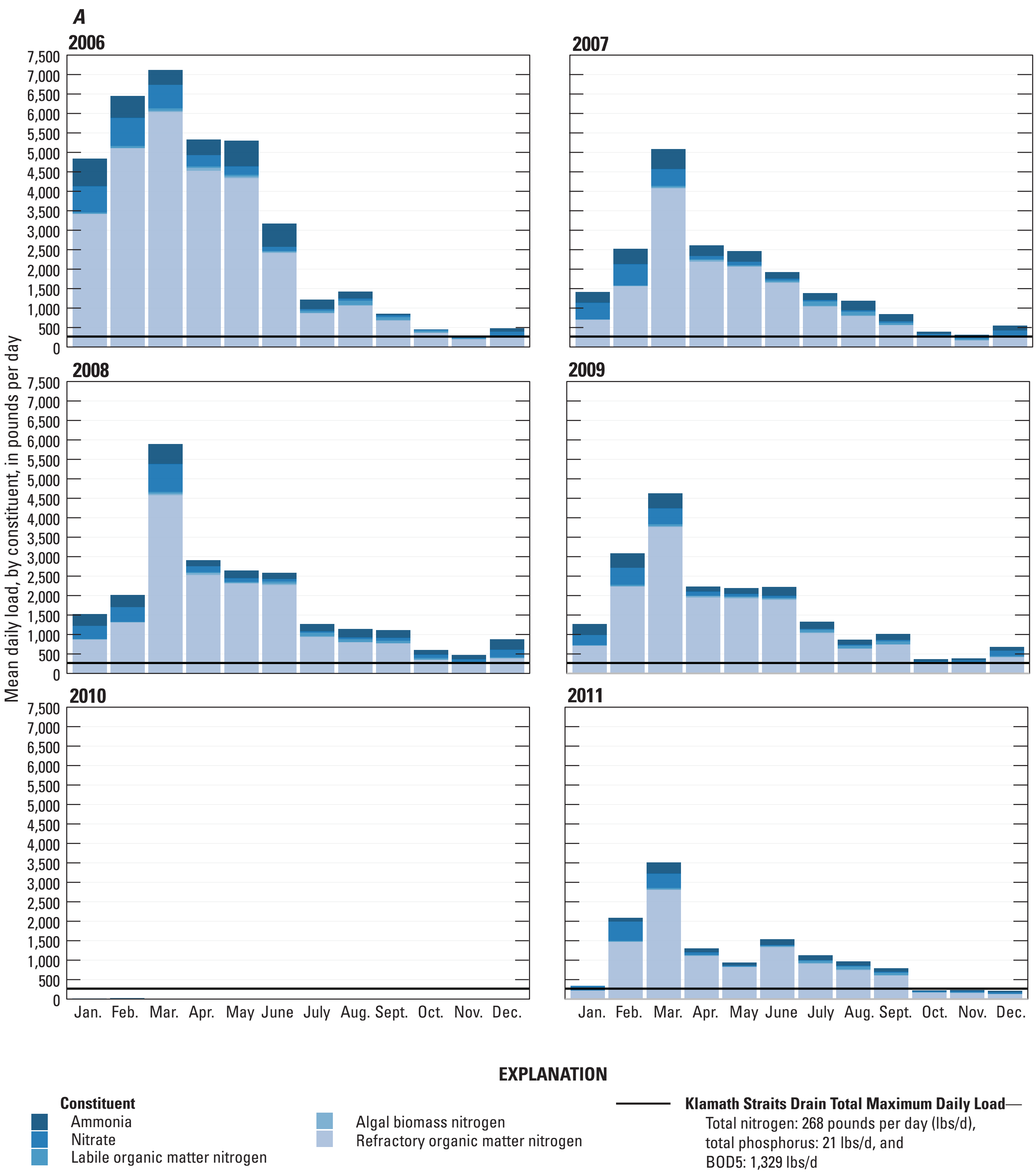


Figure 10. Klamath Straits Drain monthly average daily total nitrogen, total phosphorus, and 5-day biochemical oxygen demand (BOD5) loads for each year from 2006 through 2015 for the base case, broken up by the individual constituents that compose the total loads. *A*, monthly average daily total nitrogen: ammonia, nitrate, labile organic matter nitrogen, algal biomass nitrogen, and refractory organic matter nitrogen. *B*, monthly average daily total phosphorus: orthophosphorus, labile organic matter phosphorus, algal biomass phosphorus, and refractory organic matter phosphorus. *C*, monthly average daily BOD5: ammonia, labile organic matter, refractory organic matter, and algal biomass. These loads are based on simulated output for the different scenarios, calculated as instantaneous loads and then averaged to either daily, monthly, or annual loads.

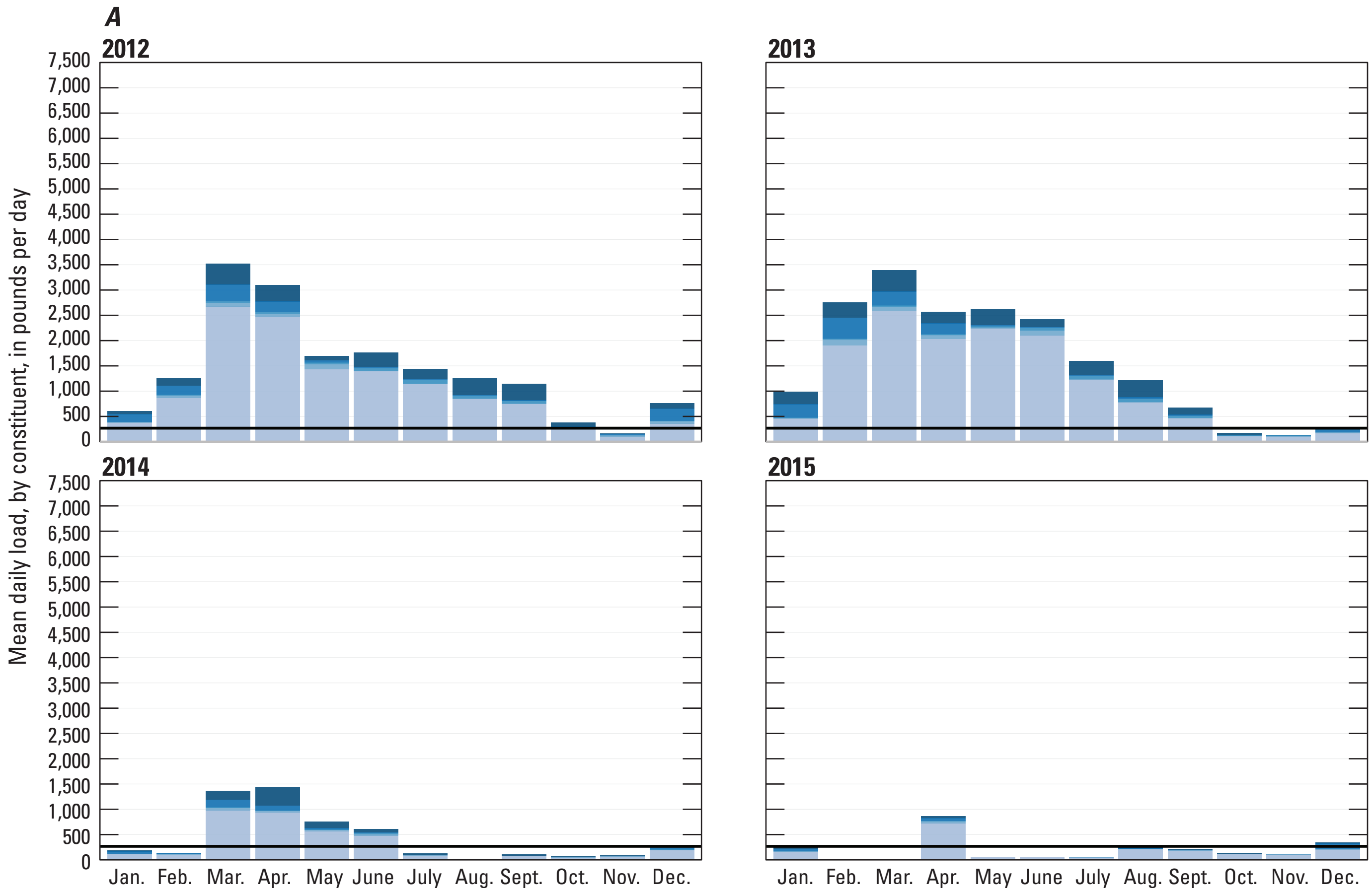
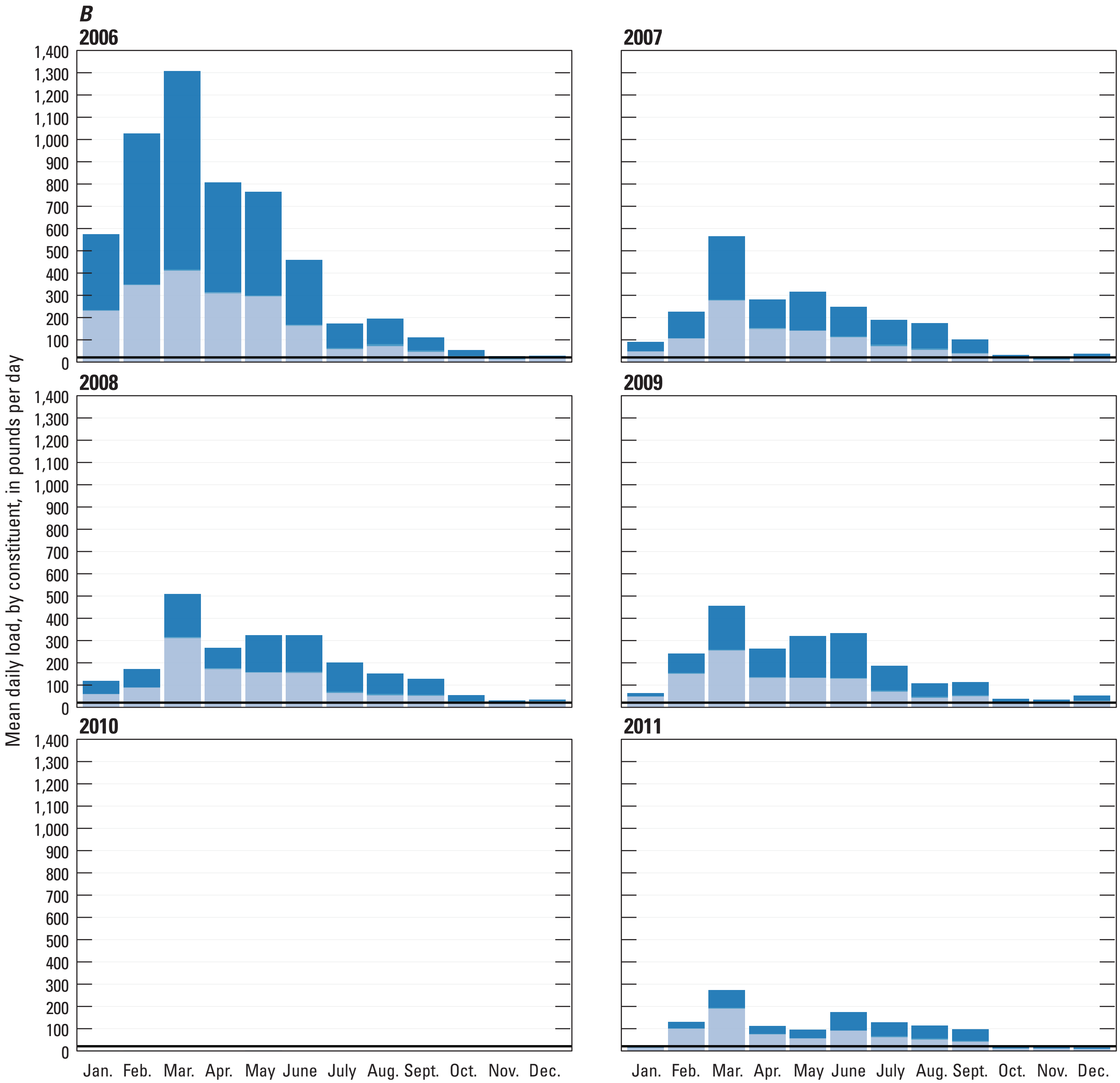


Figure 10.—Continued



EXPLANATION

Constituent

- Orthophosphorus
- Labile organic matter phosphorus
- Algal biomass phosphorus
- Refractory organic matter phosphorus

Klamath Straits Drain Total Maximum Daily Load—
Total nitrogen: 268 pounds per day (lbs/d),
total phosphorus: 21 lbs/d, and
BOD5: 1,329 lbs/d

Figure 10.—Continued

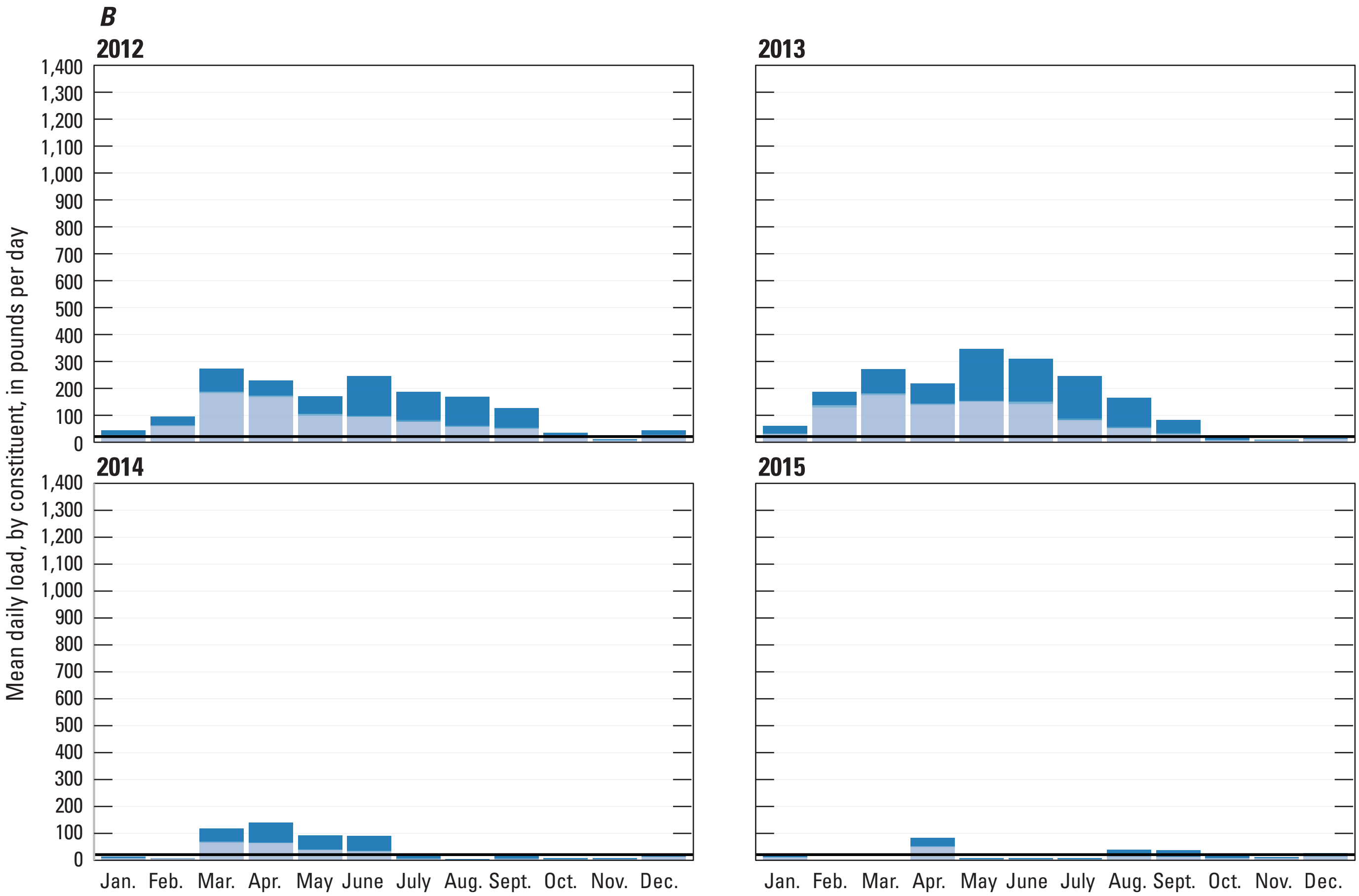


Figure 10.—Continued

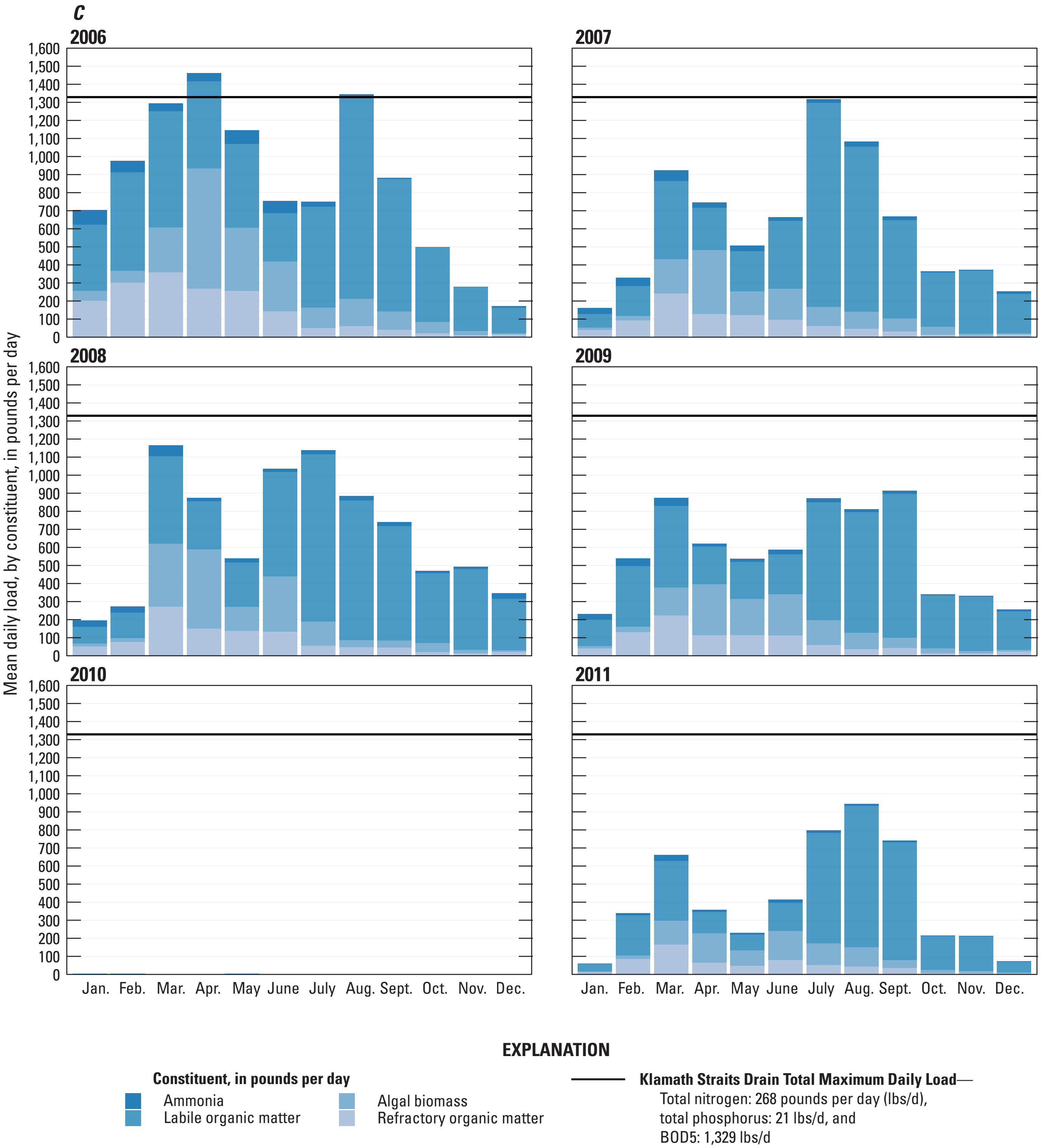


Figure 10.—Continued

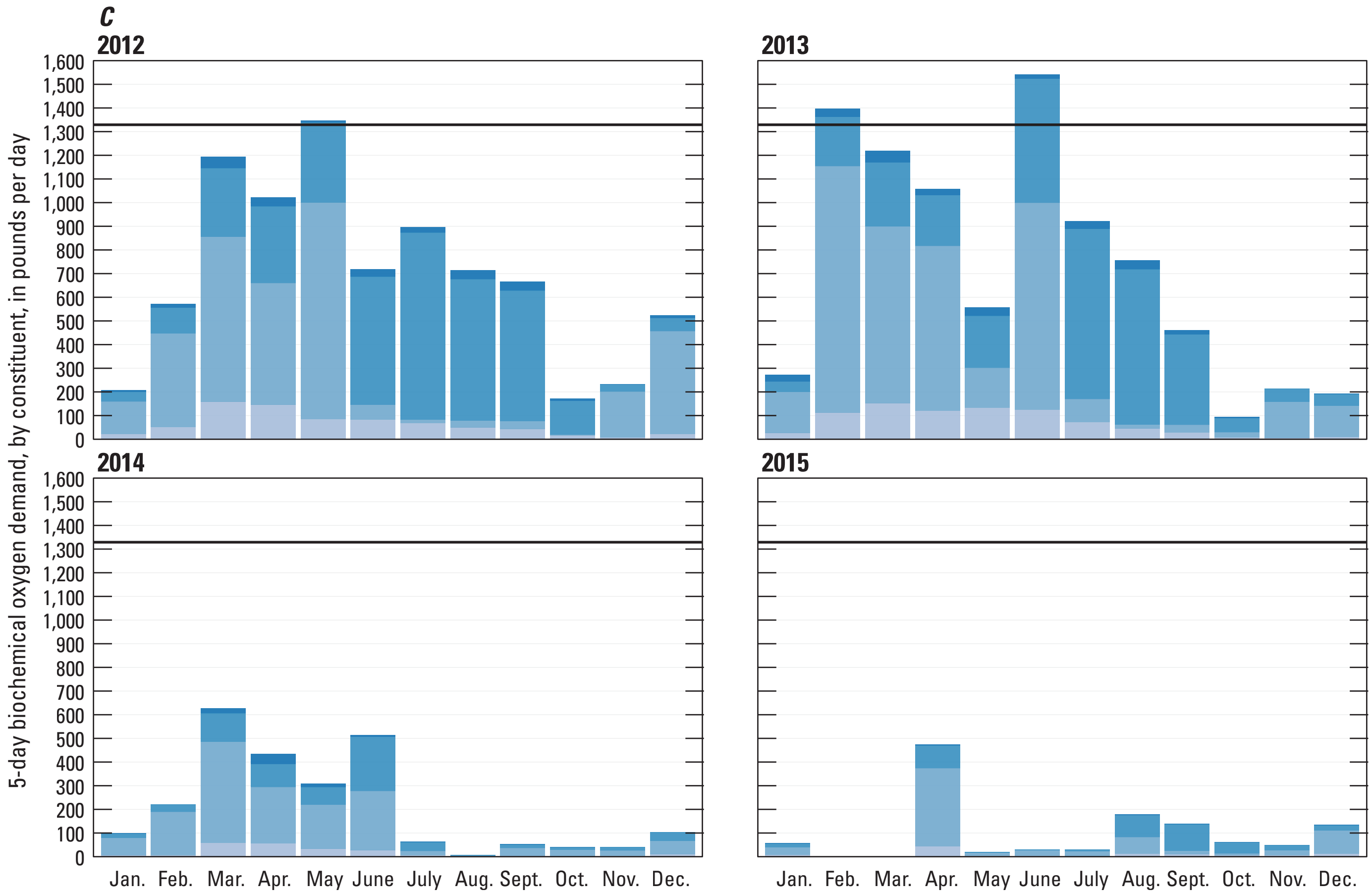


Figure 10.—Continued

Net Balance Between Klamath Straits Drain and Ady Canal Loads

Loads are calculated from flow and concentration, which vary from year-to-year and month-to-month. On a monthly basis, there were periods when Ady Canal was removing more nutrients from the Klamath River than Klamath Straits Drain was contributing to the river. For the base case, total nitrogen and phosphorus loads removed by Ady Canal were generally greater than exports to the Klamath River from July through January (fig. 11). This difference with larger loads removed from the Klamath River by Ady Canal than exports to the Klamath River from the Klamath Straits Drain was due in part to the generally smaller flows in the Klamath Straits Drain (fig. 2) and higher withdrawals by the Ady Canal from the Klamath River (fig. 3) during the latter half of the year. The refractory and labile organic concentrations, and orthophosphorus, were lower in the Klamath Straits Drain in January than from February to June (figs. 11–14). For BOD5 loads, the base case often had higher BOD5 loads removed from the Klamath River by Ady Canal than exports to the Klamath River through Klamath Straits Drain from May through December compared to all three recirculation scenarios (figs. 11–14), although the net BOD5 load addition to the Klamath River from January to May was generally lower with recirculation. Because the Klamath River algal load of *Aphanizomenon flos-aquae* was generally high in the summer and fall months, the smaller withdrawals of Klamath River water to the Ady Canal with recirculation led to a smaller net decrease in the BOD5 loads during those months.

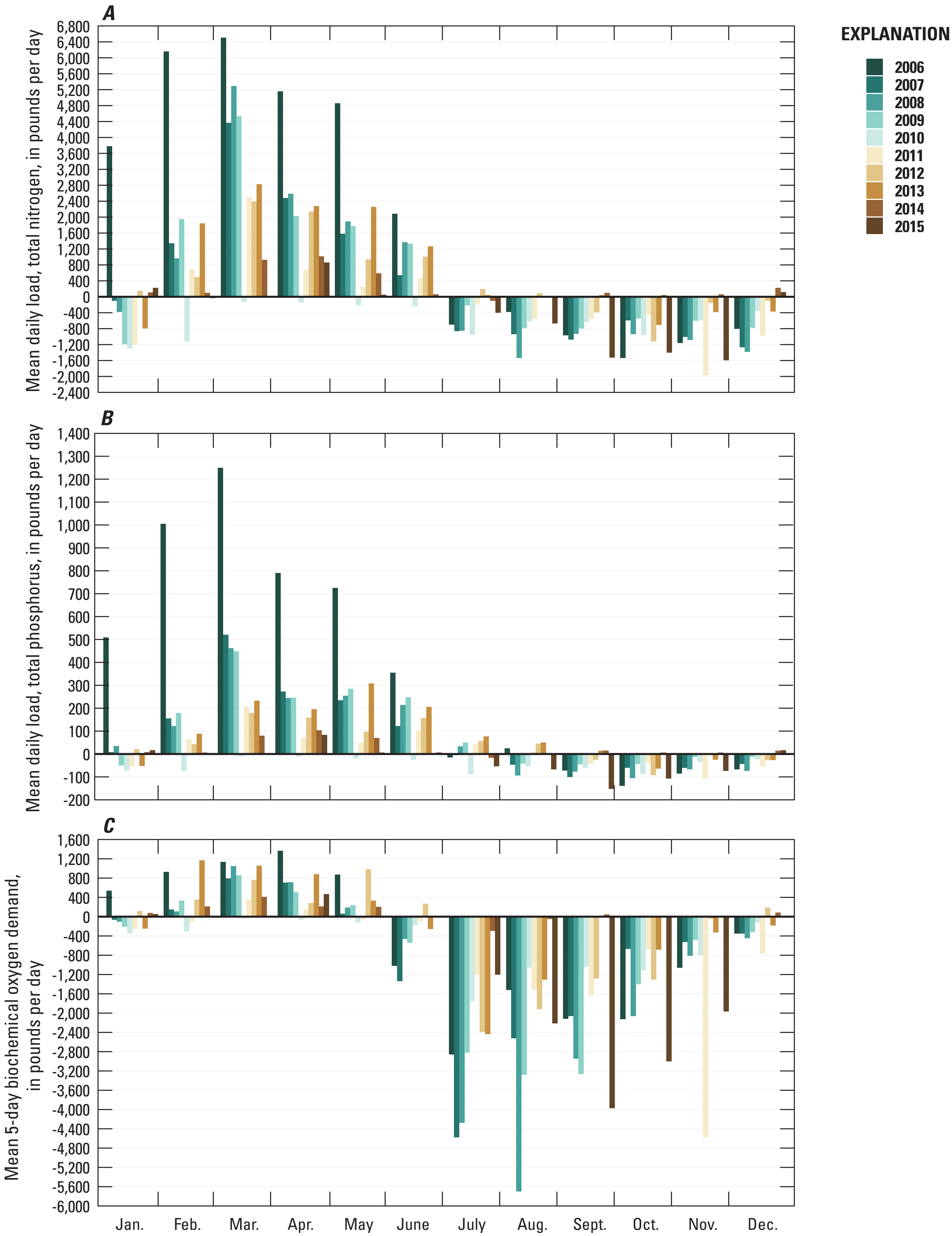


Figure 11. The differences between the monthly average daily loads for the Klamath Straits Drain to the Klamath River and the Ady Canal from the Klamath River from 2006 through 2015 for the base case, for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand. Positive numbers denote net loading to the Klamath River and negative numbers denote net reductions in loads to the Klamath River.

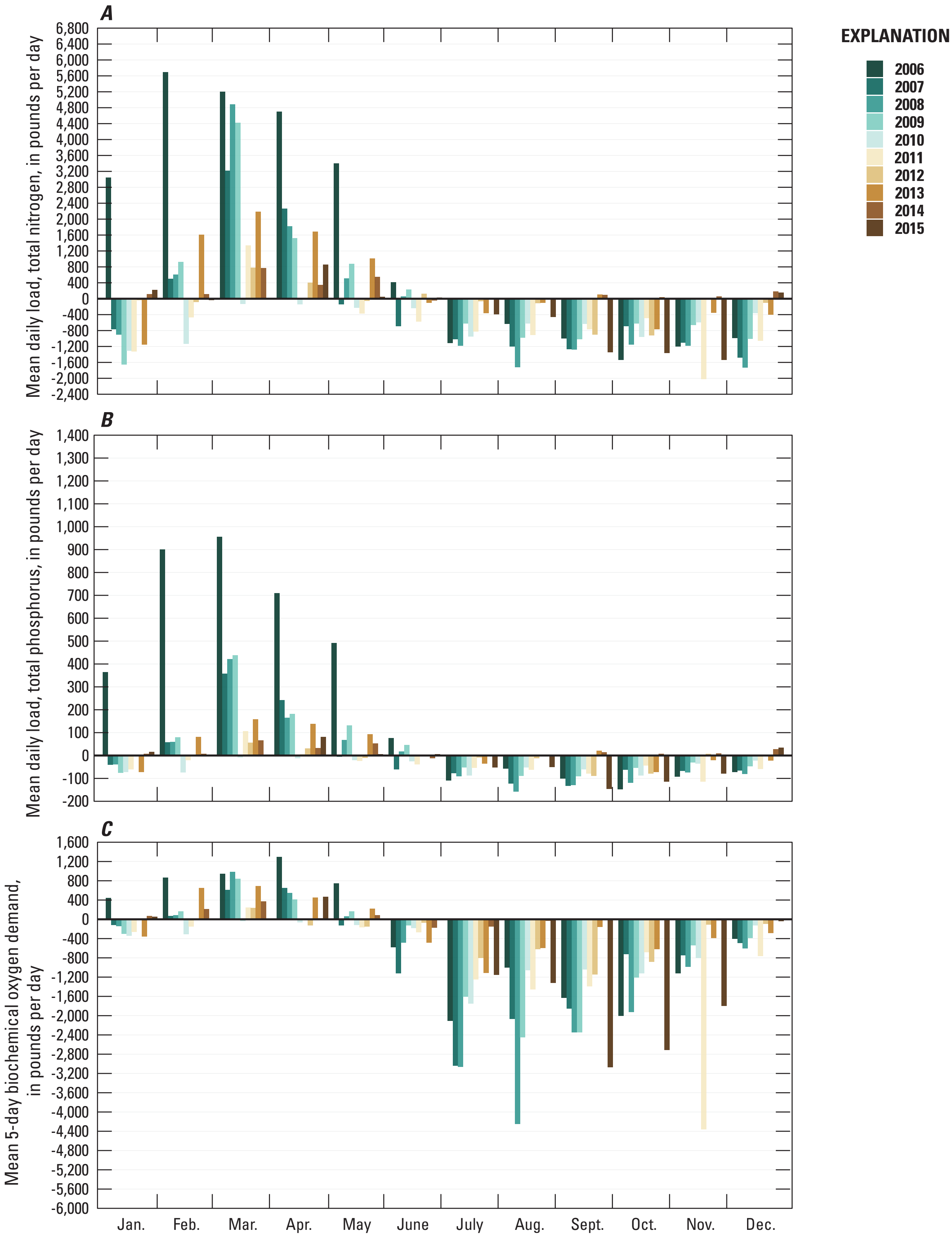


Figure 12. The differences between the monthly average daily loads for the Klamath Straits Drain to the Klamath River and the Ady Canal from the Klamath River from 2006 through 2015 for scenario 1, for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand. Positive numbers denote net loading to the Klamath River and negative numbers denote net reductions in loads to the Klamath River.

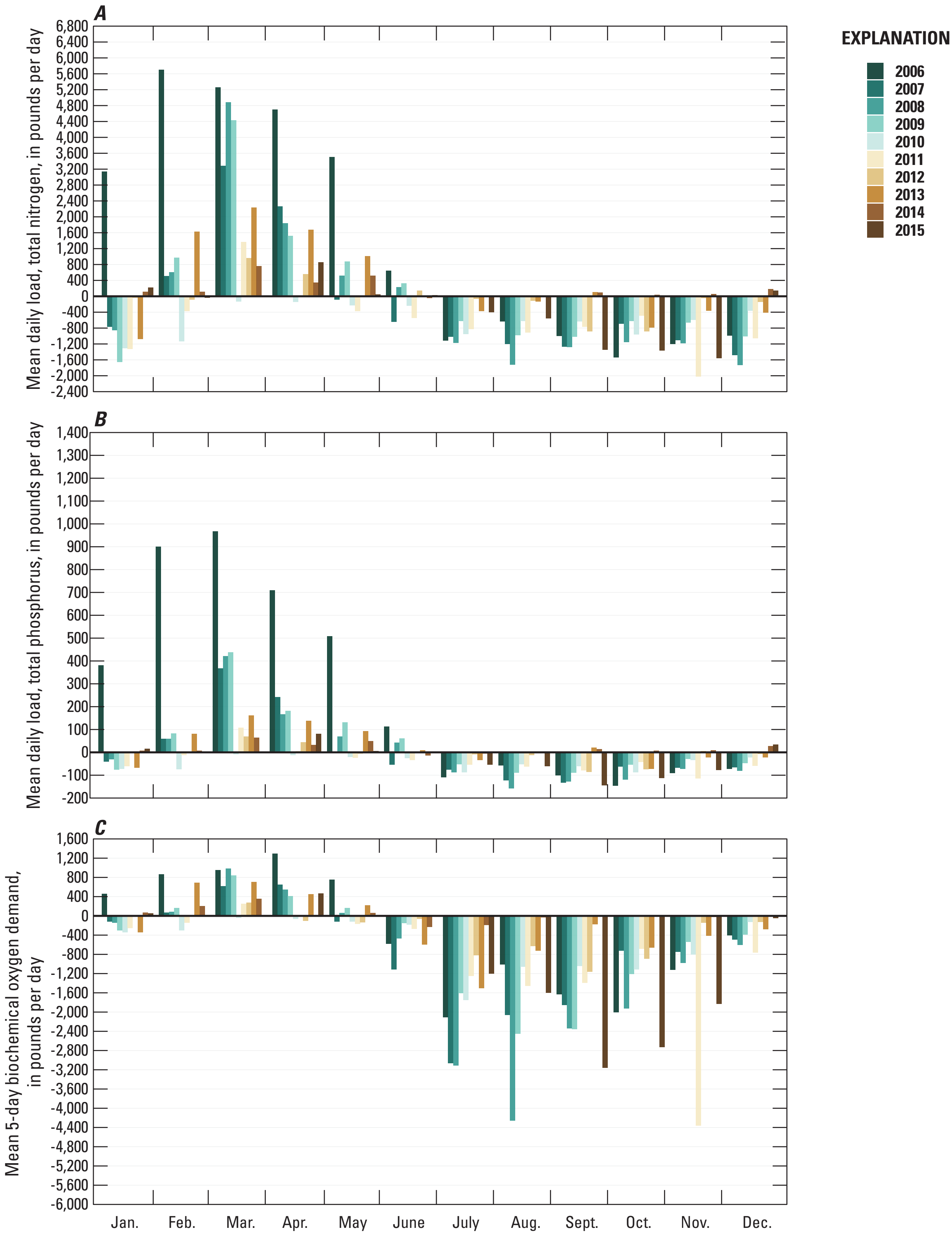


Figure 13. The differences between the monthly average daily loads for the Klamath Straits Drain to the Klamath River and the Ady Canal from the Klamath River from 2006 through 2015 for scenario 2, for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand. Positive numbers denote net loading to the Klamath River and negative numbers denote net reductions in loads to the Klamath River.

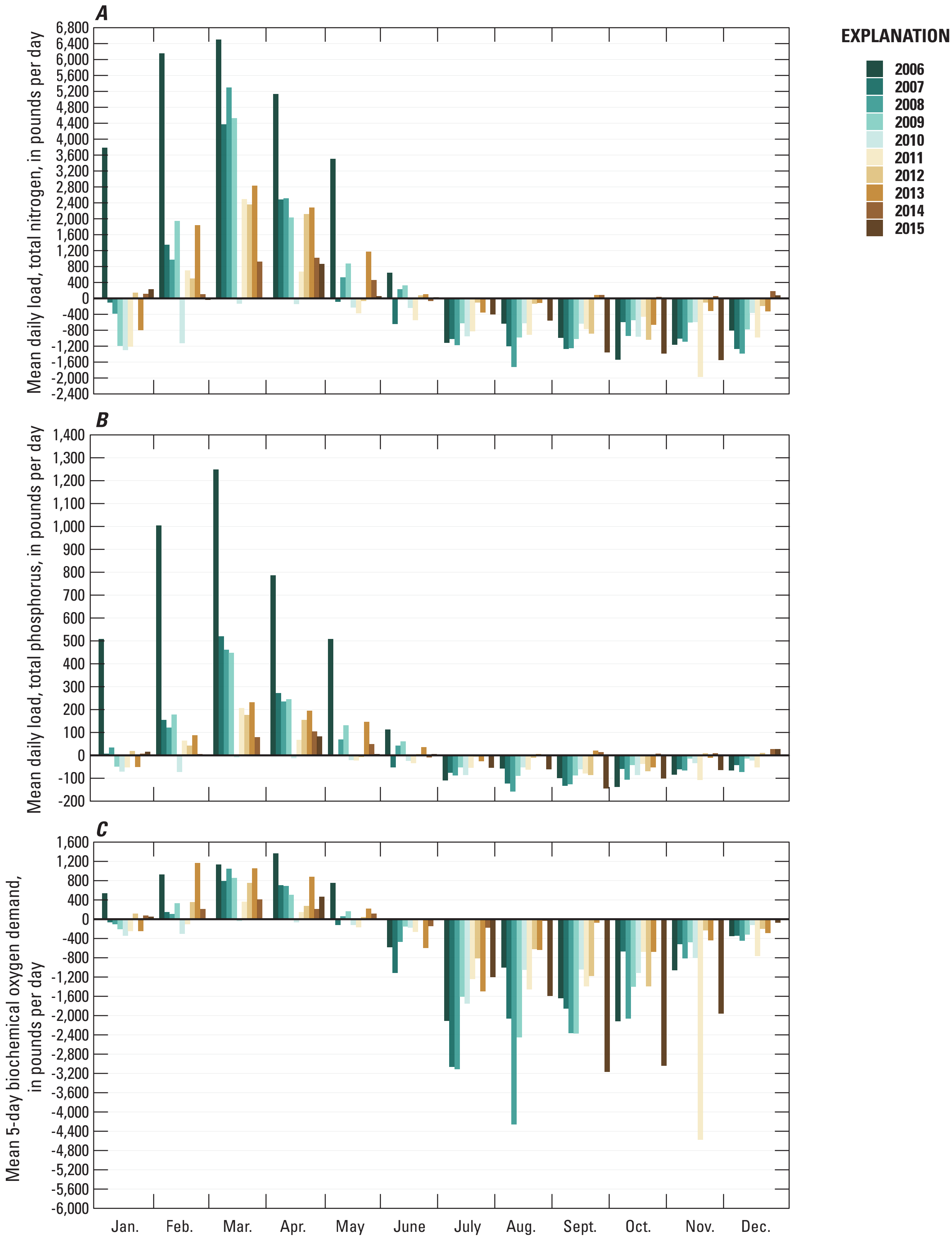


Figure 14. The differences between the monthly average daily loads for the Klamath Straits Drain to the Klamath River and the Ady Canal from the Klamath River from 2006 through 2015 for scenario 3, for total nitrogen, total phosphorus, and the 5-day biochemical oxygen demand. Positive numbers denote net loading to the Klamath River and negative numbers denote net reductions in loads to the Klamath River.

Recirculation Effects on Downstream Klamath River Loads

Downstream effects of the recirculation scenarios were evaluated to determine if the recirculation scenarios influenced the loads calculated at the Keno Dam. The Klamath River at the Keno Dam loads were similar to the net balance discussed between Klamath Straits Drain and Ady Canal (tables 9–11). For the base case, average daily total nitrogen loads varied annually from 9,920 to 20,700 lbs/day (table 9). All three scenarios generally showed a reduction on an annual basis in average daily total nitrogen loads, ranging from an average of 1.5 percent for scenario 3–3.1 percent for scenario 1. However, some of the years with less Klamath Straits Drain water available, such as 2010, 2013, and 2014, showed smaller reductions in average daily total nitrogen loads or slight increases on an annual basis. Total phosphorus exhibited similar trends as total nitrogen loads. Average daily total phosphorus loads varied from 838 to 1,980 lbs/day for the base case, with an average of a 3.0 percent reduction for scenario 3 to a 5.3 percent reduction for scenario 1 (table 10). BOD5 loads generally increased on an annual basis for all three recirculation scenarios (table 11). Of the three recirculation scenarios, scenario 3 had the smallest negative (increase in average daily load) percent reduction relative to the base case at -1.5 percent compared to -1.9 and -2.7 percent for scenarios 1 and 2, respectively.

When evaluated year-to-year for the base case, the total nitrogen loads added to the Klamath River (from the Klamath Straits Drain) minus the loads removed from the Klamath River (from the Ady Canal) resulted in a net addition to the Klamath River, except for 2010, 2011, and 2015 (table 12). Klamath Straits Drain flow in 2010 was negligible, with average flow in 2011 and low flow in 2015 (fig. 2), whereas the flow diverted into Ady Canal in 2010 was smaller than 2011, and almost negligible in the first half of 2015 (fig. 3). For scenarios 1 and 2, the net difference between the total nitrogen loads exported by the Klamath Straits Drain and the total nitrogen loads removed from the Klamath River by Ady Canal was lower relative to the base case, resulting in more years with negative annual differences. Annual net total nitrogen loads added to the Klamath River (Klamath Straits Drain exports minus Ady Canal removal) ranged from -603 to 1,890 lbs/day for the base case, -620 to 1,310 lbs/day for scenario 1, -607 to 1,350 lbs/day for scenario 2, and -604 to 1,600 lbs/day for scenario 3. When comparing the annual net total nitrogen loads between the base case and the three recirculation scenarios, only 2015 had more net removal of total nitrogen loads for the base case.

For phosphorus loads added to the Klamath River from the Klamath Straits Drain minus the loads removed from the Klamath River from the Ady Canal resulted in a net addition to the Klamath River, except for 2010 and 2015 (table 12). Similar to total nitrogen, the net difference between the total phosphorus loads exported by the Klamath Straits Drain and the total phosphorus loads removed from the Klamath River by Ady Canal was even smaller relative to the base case for scenarios 1 and 2. Overall, annual net total phosphorus loads added to the Klamath River (Klamath Straits Drain exports minus Ady Canal removal) were -46–353 lbs/day for the base case, -46–239 lbs/day for scenario 1, -46–246 lbs/day for scenario 2, and -46–297 lbs/day for scenario 3. When comparing the annual net total phosphorus loads between the base case and the three recirculation scenarios, only the year 2015 had more net removal of total phosphorus loads for the base case. Additionally, 2014 had slightly more net removal of total phosphorus for the base case than scenario 3.

BOD5 loads added to the Klamath River from the Klamath Straits Drain minus the loads removed from the Klamath River from the Ady Canal often resulted in more removal for the base case than the recirculation scenarios. As noted with the monthly trends, the removal of the large loads of *Aphanizomenon flos-aquae* from Ady Canal often resulted in large reductions in BOD5 for the Klamath River relative to the additions by Klamath Straits Drain. Relative to the base case, only the years 2011 and 2014 had more removal by the three recirculation scenarios and 2013 had slightly more removal by scenario 2 relative to the base case. Overall, annual net total BOD5 loads added to the Klamath River (Klamath Straits Drain exports minus Ady Canal removal) were -1,240–64 lbs/day for the base case, -1,020–32 lbs/day for scenario 1, -1,020–18 lbs/day for scenario 2, and -987–51 lbs/day for scenario 3. For additions to the Klamath River, only 2014 had a positive annual average daily BOD5 load.

Recirculation Effects on Ady Canal Total Dissolved Solids Concentrations

Recirculating Klamath Straits Drain into Ady Canal would change the water quality in Ady Canal. In the base case, Ady Canal water quality would be wholly representative of Klamath River water quality; under recirculation, varying amounts of Klamath Straits Drain water would be mixed in. The different volumes of Klamath River-sourced and Klamath Straits Drain-sourced water and their different total dissolved solids (TDS) concentrations were used to calculate the estimated total dissolved solids concentration in Ady Canal after recirculation (table 13). Total dissolved solids are mostly conservative or non-reactive (Wells, 2020), so simple mixing calculations were used for this estimation, considering only days when Ady Canal was flowing. One limitation of this analysis that was not evaluated was anoxic conditions, which could alter the redox conditions and thereby change the dissolved ion chemistry. Other water-quality constituents, such as nutrients or organic matter, are subject to biogeochemical changes, settling, or other non-conservative reactions and thus were not estimated for Ady Canal under recirculation for this study.

Table 9. Total nitrogen loads at the Klamath River at the Keno Dam (including average and maximum annual loads), as simulated in base case conditions and the three recirculation scenarios, and the percentage of reduction between the base-case loads and the three scenarios.

[Loads are annual average daily loads, calculated using all days of the year whether flow occurred. Abbreviation: lbs/day, pounds per day]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	Maximum
Total nitrogen load, (lbs/day)												
Base Case	20,700	11,400	12,600	9,650	7,780	12,800	8,510	5,970	4,830	4,920	9,920	20,700
Scenario 1	20,200	10,900	12,100	9,230	7,780	12,300	8,090	5,610	4,780	4,930	9,590	20,200
Scenario 2	20,200	10,900	12,200	9,240	7,780	12,300	8,110	5,650	4,780	4,920	9,610	20,200
Scenario 3	20,500	11,100	12,400	9,430	7,780	12,500	8,360	5,810	4,820	4,930	9,760	20,500
Percent reduction relative to base case (Klamath Straits Drain to Klamath River)												
Scenario 1	2.7	4.8	3.9	4.3	0.0	3.9	4.9	6.1	1.1	−0.3	3.1	6.1
Scenario 2	2.5	4.6	3.8	4.2	0.0	3.8	4.7	5.4	1.0	−0.2	3.0	5.4
Scenario 3	1.3	2.4	2.2	2.3	0.0	1.8	1.7	2.7	0.2	−0.2	1.5	2.7

Table 10. Total phosphorus loads at the Klamath River at the Keno Dam (including average and maximum annual loads), as simulated in base case conditions and the three recirculation scenarios, and the percentage of reduction between the base-case loads and the three scenarios.

[Loads are annual average daily loads, calculated using all days of the year whether flow occurred. Abbreviation: lbs/day, pounds per day]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	Maximum
Total phosphorus load (lbs/day)												
Base Case	1,980	928	1,010	771	592	874	741	518	526	454	838	1,980
Scenario 1	1,860	849	931	705	591	817	697	467	521	456	790	1,860
Scenario 2	1,870	851	934	707	591	818	699	470	521	455	792	1,870
Scenario 3	1,920	880	955	727	592	840	722	490	526	456	811	1,920
Percent reduction relative to base case (Klamath Straits Drain to Klamath River)												
Scenario 1	5.7	8.5	7.4	8.5	0.0	6.5	6.0	9.7	1.0	−0.5	5.3	9.7
Scenario 2	5.3	8.3	7.1	8.3	0.0	6.3	5.7	9.2	0.9	−0.3	5.1	9.2
Scenario 3	2.8	5.2	5.0	5.7	0.0	3.9	2.7	5.3	0.0	−0.6	3.0	5.7

Table 11. The 5-day Biochemical Oxygen Demand loads at the Klamath River at the Keno Dam (including average and maximum annual loads), as simulated in base case conditions and the three recirculation scenarios, and the percentage of reduction between the base-case loads and the three scenarios.

[Loads are annual average daily loads, calculated using all days of the year whether flow occurred. Abbreviation: lbs/day, pounds per day]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	Maximum
5-day biochemical oxygen demand (lbs/day)												
Base Case	11,500	8,000	9,030	7,810	5,450	8,190	6,270	3,900	3,840	5,380	6,930	11,500
Scenario 1	11,500	8,050	9,150	7,950	5,450	8,160	6,420	4,170	3,930	5,560	7,040	11,500
Scenario 2	11,500	8,050	9,150	7,950	5,450	8,160	6,420	4,030	4,430	5,510	7,070	11,500
Scenario 3	11,600	8,100	9,180	7,970	5,450	8,170	6,430	4,010	3,910	5,490	7,030	11,600
Percent reduction relative to base case (Klamath Straits Drain to Klamath River)												
Scenario 1	−0.7	−0.6	−1.4	−1.8	0.0	0.4	−2.4	−6.9	−2.4	−3.3	−1.9	0.4
Scenario 2	−0.7	−0.7	−1.3	−1.8	0.0	0.4	−2.3	−3.3	−15.4	−2.4	−2.7	0.4
Scenario 3	−1.0	−1.3	−1.7	−2.1	0.0	0.2	−2.5	−2.9	−1.7	−2.1	−1.5	0.2

Table 12. Annual net difference load calculated as the difference between loads added to the Klamath River from the Klamath Straits Drain and the loads removed from the Klamath River to the Ady Canal.

[Loads are annual average daily loads, calculated using all days of the year regardless of flow conditions. Positive (negative) numbers denote years/scenarios when more (less) load was added to the Klamath River. Relative to the base case, positive (negative) numbers denote periods when a higher (lower) load was added to the Klamath River. Abbreviation: lbs/day, pounds per day]

Scenario	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total nitrogen load (lbs/day)										
Annual net difference load (delivery to Klamath River)										
Base Case	1,890	368	417	548	−603	−115	468	680	242	−390
Scenario 1	1,310	−201	−105	114	−605	−620	−82	269	189	−319
Scenario 2	1,350	−186	−83	125	−605	−607	−49	282	179	−331
Scenario 3	1,600	80	134	321	−604	−351	221	467	236	−361
Relative to the base case										
Scenario 1	−583	−570	−522	−434	−2	−505	−550	−411	−54	71
Scenario 2	−544	−554	−500	−423	−2	−492	−517	−398	−63	59
Scenario 3	−293	−288	−283	−227	0	−236	−247	−213	−6	29
Total phosphorus load (lbs/day)										
Annual net difference load (delivery to Klamath River)										
Base Case	353	83	79	103	−46	20	50	83	22	−30
Scenario 1	239	2	3	36	−46	−37	−9	21	18	−25
Scenario 2	246	4	7	38	−46	−36	−6	23	17	−26
Scenario 3	297	33	29	59	−46	−14	20	48	24	−27
Relative to the Base Case										
Scenario 1	−114	−81	−75	−67	0	−57	−59	−62	−5	5
Scenario 2	−107	−79	−72	−65	0	−56	−56	−60	−6	4
Scenario 3	−56	−49	−50	−44	0	−34	−30	−35	1	3
5-day biochemical oxygen demand (lbs/day)										
Annual net difference load (delivery to Klamath River)										
Base Case	−529	−876	−1,240	−875	−579	−863	−336	−178	64	−1,050
Scenario 1	−389	−753	−1,020	−622	−580	−875	−314	−172	32	−801
Scenario 2	−388	−754	−1,020	−625	−580	−874	−317	−226	18	−841
Scenario 3	−355	−688	−987	−601	−579	−864	−245	−105	51	−929
Relative to the base case										
Scenario 1	140	123	223	252	0	−12	21	6	−32	248
Scenario 2	142	122	220	250	0	−12	19	−48	−46	208
Scenario 3	174	187	257	274	0	−2	90	73	−14	120

On average, over the 10-year period, the base case Ady Canal TDS was estimated at 101 mg/L, with a range of 95–108 mg/L as individual year averages (table 13). Under scenario 1, Ady Canal TDS was estimated at 255 mg/L as a 10-year average, with annual averages ranging from 109 to 340 mg/L. Scenarios 2 and 3 had TDS concentrations between those of the base case and scenario 1, with the 10-year period averages of 232 mg/L for scenario 2 and 155 mg/L for scenario 3. Daily values of estimated TDS for three representative years (fig. 15) show typical seasonal variation, with base case TDS remaining relatively constant through the year. Of the three example years, 2008 followed the most typical pattern with the most elevated TDS concentrations in early to mid-spring months. For 2006, the high amount of recirculation in January elevated TDS concentrations slightly earlier in the year, whereas 2015 showed some of the highest TDS concentrations. Scenarios 1 and 2 typically had higher estimated TDS concentrations in winter through April.

Table 13. Annual average total dissolved solids concentration for Ady Canal, either for the base case or after recirculation (scenarios 1–3).

[Different volumes of Klamath River-sourced and Klamath Straits Drain-sourced water and their different total dissolved solids concentrations were used to calculate the estimated total dissolved solids concentration in Ady Canal after recirculation]

Year	Total dissolved solids, in milligrams per liter			
	Base case	Maximum recirculation (scenario 1)	Limited year-round recirculation (scenario 2)	Limited season recirculation (scenario 3)
2006	103	301	293	181
2007	97	217	215	148
2008	105	238	234	165
2009	95	220	218	156
2010	108	109	109	109
2011	100	197	196	135
2012	104	277	267	167
2013	99	327	309	193
2014	101	325	230	141
2015	96	340	246	158
All years (average)	101	255	232	155

Considering Multiple Water-Quality Requirements (Load Analysis)

With the current recirculation scenarios, the optimal recirculation periods to benefit Ady Canal, Klamath River, and Klamath Straits Drain did not always occur at the same time. For instance, recirculation in the spring would be most effective at reducing loads toward the Klamath Straits Drain TMDL targets. This was also confirmed by earlier recirculation simulations for Klamath Straits Drain (Sullivan and others, 2014). However, recirculation at that time of year could increase salinity in the Ady Canal. During the summer, recirculation would help Klamath Straits Drain approach the TMDL targets but could lead to slight decreases in Klamath River water quality because of the decreased withdrawals of Klamath River water by the Ady Canal. Scenario 3 balances the need to avoid recirculation into Ady Canal in the early spring months because of salinity concerns while enabling the Klamath Straits Drain to deliver smaller loads in the summer months.

Model Limitations

A full understanding of model limitations is necessary to better evaluate the performance of any water-quality model. Because the CE–QUAL–W2 model is averaged laterally, processes that could impose lateral variations (perpendicular to the primary flow axis of the water body) will not be represented in the model. Structural selections, such as segment geometry, the number of vertical layers, and the numerical transport scheme, could potentially impose a bias in the outcome of the model. Water-quality limitations include the simplification of a complex aquatic ecosystem into a series of kinetic reactions expressed in source and loss terms (Cole and Wells, 2015). Potential cumulative effects over time were not assessed, because each 1-year simulation was independent. The derivation of the organic matter pools was based on transforming dissolved organic carbon and particulate organic carbon into dissolved organic matter and particulate organic matter, respectively, with a static stochiometric ratio of 0.46 between carbon and organic matter.

Data limitations also impact model representation and accuracy. Boundary conditions are not fixed in nature; however, boundary conditions are limited by the availability of data. The extrapolation of the data was necessary to fit the requirements of the CE–QUAL–W2 model. For example, water-quality data were linearly interpolated between sampling dates or the sampling data were used as input into load-estimation software to generate daily time steps for the model.

No simulated output from the Link-Keno model provided feedback upstream into the Klamath Straits Drain model. This was an important caveat to this study because the earlier Klamath Straits Drain studies found that upstream flow from Link-Keno reach occurred into the Klamath Straits Drain downstream from the F-FF pumps, when the Klamath Straits Drain F-FF pumps were off (Sullivan and Rounds, 2018). This upstream flow is not simulated in the current study.

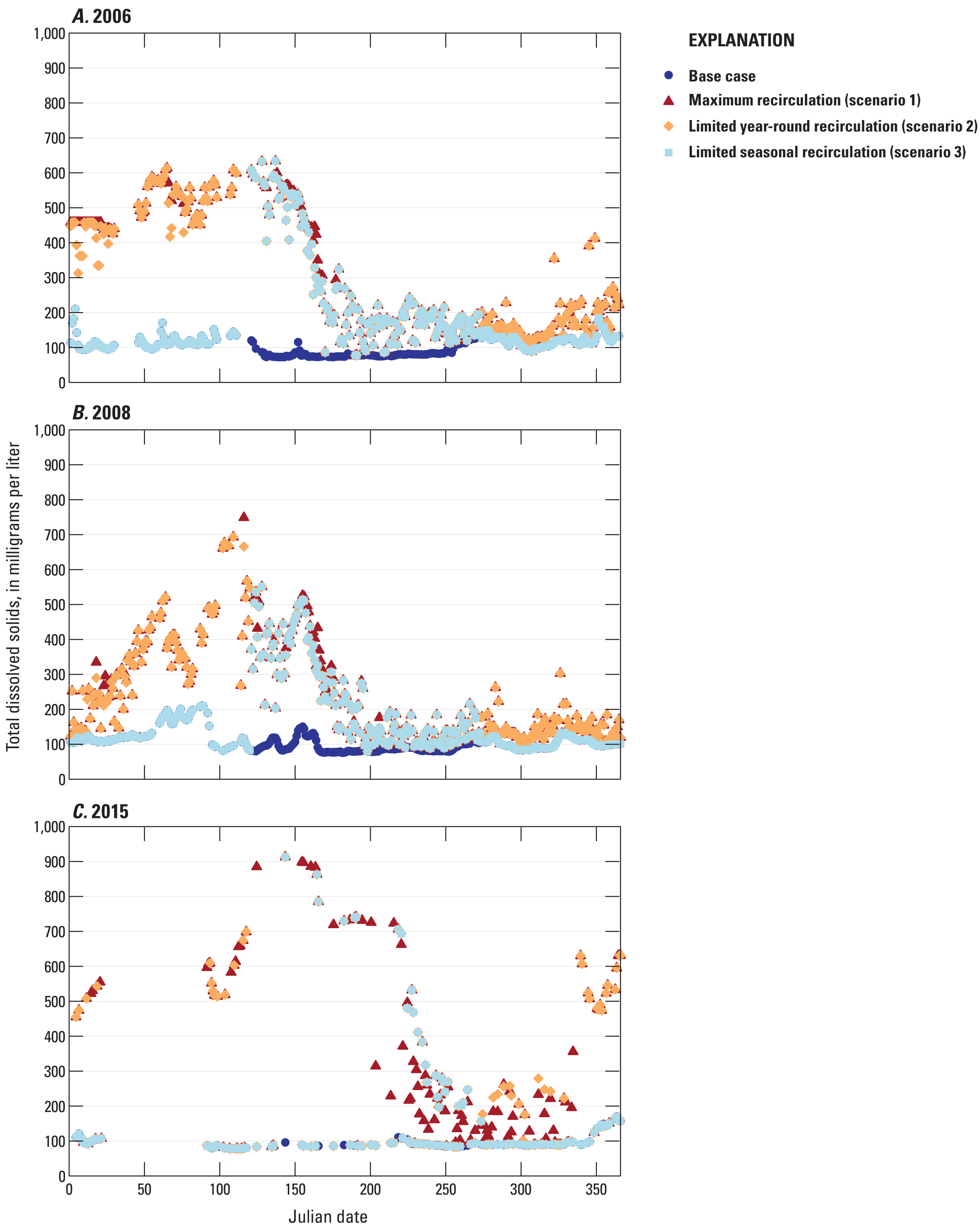


Figure 15. Ady Canal total dissolved solids concentration, for 2006, 2008, and 2015 in Julian days (from beginning of year), for the base case and three recirculation scenarios.

Summary

Poor water quality has been well-documented in the first 20 miles of the Klamath River above the Keno Dam (Link-Keno reach). To improve the poor Klamath River water quality, multiple Total Maximum Daily Loads have been established for this subbasin, including several for the Klamath Strait Drain (hereafter called by its local name, “Klamath Straits Drain”). Multiple investigations have been explored to remediate Klamath Straits Drain water quality, including the potential recirculation of Klamath Straits Drain water into the Ady Canal.

To study the feasibility of recirculation, this investigation expanded on earlier work by evaluating three recirculation scenarios over a ten-year period from 2006 to 2015, as a series of 1-year simulations. Scenarios using the water-quality models were configured for the base case conditions and three different sets of recirculation scenarios: the maximum year-round recirculation without limits (scenario 1), limited year-round recirculation fixed by the current pipe flow configuration (scenario 2), and limited seasonal recirculation (May–September) fixed by the current pipe flow configuration (scenario 3).

Previous Klamath Straits Drain recirculation scenarios for the Link-Keno reach CE-QUAL-W2 model were from 2006 to 2009 and 2011. This new work extended the calibration of the Link-Keno reach CE-QUAL-W2 model to 2010 and 2012–15. Additionally, the Klamath Straits Drain was simulated as an independent model into the main Link-Keno reach CE-QUAL-W2 model, using a newly integrated USGS model for 2012–15, thereby including in-stream processes in the Klamath Straits Drain before its confluence with the Klamath River (table 1). The new model combines the two previously published USGS models: the Link-Keno reach CE-QUAL-W2 model and the Klamath Straits Drain CE-QUAL-W2 model. Water quality of the Klamath Straits Drain flows to the Klamath River was simulated to dynamically change from recirculation for the years with a paired Klamath Straits Drain model (2012–15). Water quality was assumed to have no changes from recirculation from 2006 to 2011 because there was no independent Klamath Straits Drain model for 2006–11. Load differences between the base case and the recirculation scenarios from the Klamath Straits Drain to the Klamath River were calculated as a function of changes in discharge only for 2006–11.

In the base case, annual average total phosphorus loads exported to the Klamath River from the Klamath Straits Drain were estimated at up to 457 lbs/day and annual average total nitrogen loads at up to a maximum annual average of 3,060 lbs/day. These maximums exceed the Total Maximum Daily Loads by more than an order of magnitude. With scenario 1, load reductions occurred year-round for all constituents evaluated (total nitrogen, total phosphorus, BOD5, CBOD5) for the Klamath Straits Drain water discharging to the Klamath River. In particular, load reductions often fell below the current TMDL allocations after spring high flows, whereas BOD5 loads had the same annual trend and did not meet the BOD5 Total Maximum Daily Load allocation for a single month after May. Similar to scenario 1, scenario 2 also included large reductions in total nitrogen, total phosphorus, and BOD5 loads. Substantial reductions did occur in scenario 3 but were constrained to only the active recirculation period from May through September.

To maintain unaltered Klamath River water elevations compared to the base case condition, Ady Canal water replaced by Klamath Straits Drain water was then retained in the Klamath River. Potential cumulative effects over time were not assessed, because each 1-year simulation was independent. Because the Ady Canal diverts high constituent loads from the Klamath River, the tradeoffs (between no recirculation and the different recirculation scenarios) on loading in the Klamath River were explored. On an annual basis, the overall net balance between the Klamath Straits Drain and Ady Canal resulted in larger total nitrogen and total phosphorus load reductions to the Klamath River for the three recirculation scenarios than the base case, for most years. Alternatively, the net balance for BOD5 loads was higher to the Klamath River for the three recirculation scenarios than the base case, for most years. Elevated BOD5 loads may be in part because of the removal of large loads of *Aphanizomenon flos-aquae* from the Ady Canal during the base case, which is diminished with recirculation.

With the current recirculation scenarios, the optimal recirculation periods to benefit Ady Canal, Klamath River, and Klamath Straits Drain did not always occur at the same time. Recirculation would be most effective at reducing loads toward the Klamath Straits Drain Total Maximum Daily Load allocations in the spring. However, recirculation at that time of year would increase salinity as TDS in the Ady Canal. In summer, recirculation would help Klamath Straits Drain reduce loads toward TMDL allocations but could decrease Klamath River water quality mostly because of decreased withdrawals of Klamath River water by the Ady Canal. Scenario 3 balances the need to avoid recirculation into Ady Canal in the early spring months because of salinity concerns while enabling the Klamath Straits Drain to deliver smaller loads in the summer months.

The work presented in this report provides insights into the effects of recirculation solely on water quality (specifically, nutrients, BOD5, CBOD5) in the Klamath River and Klamath Straits Drain, in the absence of other changes in water management. This work does not account for potential restoration or water-quality improvement projects in the Klamath Project beyond the indicated recirculation scenarios or areas, nor does it assess results if recirculation were combined with other such actions. However, the updated model represents a new tool that can be used to better evaluate the degree to which other-water quality improvements and recirculation might interact under different future scenarios with a goal toward improving water quality in the Klamath River.

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Appendix 1. Model Development for the Klamath River from Link River to Keno Dam, Oregon, 2010 and 2012–15

Abstract

A hydrodynamic, water temperature, and water-quality model was constructed for a 20-mile reach of the Klamath River downstream from Upper Klamath Lake, from Link River to Keno Dam, for calendar years 2010 and 2012–15. The two-dimensional, laterally averaged model CE-QUAL-W2 was used to simulate water velocity, ice cover, water temperature, specific conductance, dissolved and suspended solids, dissolved oxygen, total nitrogen, ammonia, nitrate, total phosphorus, orthophosphate, dissolved and particulate organic matter, and three algal groups. The amount of water-quality data for tributary inflows, used as model input, varied between years. Those years with greater density of input water-quality data produced closer matches between model output and measured data. The model successfully simulated the most important spatial and temporal patterns in the measured data for the five years. Models for calendar years 2006–09 and 2011 had been constructed previously (Sullivan and others, 2014, https://dx.doi.org/10.3133/ofr20141185), so with the five additional years in this report, calibrated models encompassing years 2006–15 are now available.

Introduction

The extension of a water-quality model to additional years tests the model in different hydrologic, climatic, and water-quality conditions, permitting management scenarios to be investigated under a wider range of conditions. In this study, two-dimensional flow, water temperature, and water-quality models of the upper Klamath River from the mouth of Link River to Keno Dam (Link-Keno; fig. 1) were developed for calendar years 2010 and 2012–15. These new models extend the U.S. Geological Survey (USGS)-developed models for this reach to encompass a 10-year period from 2006 through 2015.

Early Link-Keno reach models were built by PacifiCorp (2004) and Tetra Tech, Inc. (2009). The USGS, Reclamation, and Watercourse Engineering collaborated to conduct field and experimental work that informed new models. This effort produced flow, water temperature, and water-quality models of the Link-Keno reach for calendar years 2006–09 that were used to analyze the water-quality effects of management and other options. This team built additional models and calendar years including Link-Keno 2011 (Sullivan and others, 2014), Link River 2006–09 and 2011 (Sullivan and Rounds, 2016), and Klamath Straits Drain 2012–15 (Sullivan and Rounds, 2018).

Methods

CE-QUAL-W2 Model

The Link-Keno models were developed with CE-QUAL-W2 version 4.2, a two-dimensional mechanistic flow, temperature, and water-quality model (Wells, 2020). The version used for this work included improvements to the pH algorithm (Sullivan and others, 2013). The model simulates water velocity, ice cover, water temperature, specific conductance, dissolved and suspended solids, dissolved oxygen, total nitrogen, ammonia, nitrate, total phosphorus, orthophosphate, dissolved and particulate organic matter, and three algal groups.

Many components of the previously developed Link-Keno model (Sullivan and others, 2011) were used for the 2010 and 2012–15 models, including the model grid and the previously calibrated model parameters. Measured data from 2010 and 2012–15 were compiled, used to update the model input files, and used for calibration data that were used to check model performance. These measured data included meteorology, flow, stage, water temperature, and water-quality data, compiled from various sources, as detailed in table 1.1. The data availability for different sites and years varied.

The previous model reports that covered the Klamath River CE-QUAL-W2 model (Sullivan and others, 2011) and the standalone Klamath Straits Drain CE-QUAL-W2 model (Sullivan and Rounds, 2018) discussed the partition of the dissolved organic matter for CE-QUAL-W2 in detail. Measured dissolved organic carbon was transformed into dissolved organic matter, with a stochiometric ratio of 0.46 between carbon and organic matter. The dissolved organic matter was further separated into labile (quickly decomposing) and refractory (slowly decomposing) compartments. Measured particulate organic carbon was transformed into particulate organic matter for the model with the same stoichiometric ratio between carbon and organic matter of 0.46. The particulate organic matter was then divided between labile and refractory components. For further details on the subsequent derivations for the model, including seasonal differences and differences for other tributaries to the Link-Keno model (see Sullivan and others, 2011; Sullivan and Rounds, 2018).

Table 1.1. Location of water-quality monitors, sample sites, and type of data used for the development of model input files or calibration checks for the calendar year 2010 and 2012–15 models in the upper Klamath River, Oregon.

[Abbreviations: KHSA, Klamath Hydroelectric Settlement Agreement; ODEQ, Oregon Department of Environmental Quality; USGS, U.S. Geological Survey; D, discrete sample; S, data from multiparameter sonde; I, model input; C, calibration check; PC, PacifiCorp; m, meters]

Site name	Source	Site ID	Latitude longitude	Data source type	Use
Link Dam	Reclamation, KHSA	KR2544	42° 14' 1.75" −121° 48' 8.6"	D	I
Link River at mouth	ODEQ	10768	42° 13' 08" −121° 47' 18"	D	I
Lost River Diversion Channel at Tingley Lane near Klamath Falls, OR	USGS	11486990	42° 10' 04" −121° 46' 31"	D	I
Lost River Diversion Dam	Reclamation	K-5	42° 09' 18" −121° 39' 46"	D	I
Klamath River at Miller Island Boat Ramp [top]	Reclamation, USGS	420853121505500	42° 08' 53" −121° 50' 55"	S	C
Klamath River at Miller Island Boat Ramp [bottom]	Reclamation, USGS	420853121505501	42° 08' 53" −121° 50' 55"	S	C
Miller Island	Reclamation, KHSA	KR2460	42° 08' 53" −121° 50' 55"	D	C
Klamath Straits Drain at Reclamation Pump Station F	ODEQ	10763	42° 04' 48" −121° 50' 27"	D	I
Klamath Straits Drain near Hwy 97	Reclamation, USGS	420451121510000	42° 04' 51" −121° 51' 00"	S	I
Klamath Straits Drain at Highway 97	Reclamation	K-1	42° 04' 51" −121° 50' 44"	D	I
Klamath River above Keno Dam nr Keno, OR [top]	Reclamation, USGS	11509370	42° 07' 41" −121° 55' 44"	S	C
Klamath River above Keno Dam nr Keno, OR [bottom]	Reclamation, USGS	420741121554001	42° 07' 41" −121° 55' 44"	S	C
Klamath River below Keno Dam	Reclamation, KHSA	KR2334	42° 08' 03" −121° 56' 50"	D	C
Klamath River below Keno Dam at Keno, OR	USGS	11509500	42° 08' 00" −121° 57' 40"	S	C

Meteorological and Flow Data

Measurements of air temperature, dew point temperature, wind speed, wind direction, precipitation, and cloud cover, which were used for model input, were obtained from the Klamath Falls airport (site KLMT; fig. 1) at approximately hourly intervals (National Climatic Data Center, 2016). Cloud cover was converted to CE-QUAL-W2 model units (Sullivan and others, 2011). The temperature of precipitation was assumed equal to air temperature; when air temperature was below 0° Celsius, precipitation temperature was set to zero. Hourly measurements of solar radiation were obtained from the Klamath Falls Agrimet station (site KFLO; fig. 1) (National Climatic Data Center, 2016).

The water inflow to the Link-Keno reach at the upstream end was from Upper Klamath Lake through Link River (fig. 1). Other tributary inflows to the system included the Lost River Diversion Channel, the Klamath Straits Drain, and the Klamath Falls and South Suburban wastewater treatment plants. Withdrawals from the system included Lost River Diversion Channel (in summer), North Canal, and Ady Canal. The downstream outflow was at Keno Dam. These inflows and outflows in the model were defined with measured data (table 1.1) from USGS and Reclamation datasets, and from point source discharge monitoring reports (DMRs) submitted to Oregon Department of Environmental Quality (ODEQ).

Water Temperature and Water-Quality Data

The water-quality conditions of inflows to the Link-Keno reach were defined using data from samples and continuous sondes. These data were obtained from USGS, Reclamation, ODEQ, and from DMRs submitted to ODEQ (table 1.1). Some data were collected as part of the Klamath Hydroelectric

Settlement Agreement (Watercourse Engineering, Inc., 2018a–d). Water-quality data-collection methods are described here briefly and followed the methods in Sullivan and others (2011).

Discrete samples were collected from the water column and were analyzed for constituents, such as total and dissolved nutrients, organic matter, and algae. When more than one source of data was available for a constituent for the same site, all data were plotted together for initial analysis. Typically, the dataset with the most frequent data was used to construct the input file or calibration dataset if its temporal pattern was consistent with data from the other sources (table 1.1). Data from other sources were used to fill in data gaps for periods with less frequent collection (table 1.1).

The collection frequency of discrete sample datasets varied depending on the data source and year. For example, data for Link River were available about 20 times per year, but data for Lost River Channel water quality were available between 5 and 26 times per year. The data from the DMRs were available at various frequencies; for example, pH data were available daily to several times per week, but nutrient data were often available at monthly frequencies.

Continuous sonde data were mostly from instruments deployed at fixed depth that collected hourly or half-hourly water temperature, specific conductance, pH, and dissolved oxygen measurements. Sondes were deployed and maintained by Reclamation, and the USGS processed the data to correct for fouling and instrument drift following methods modified from Wagner and others (2006).

Water Balance

The major inflows to and outflows from the model reach were defined with measured data, and evaporative losses were calculated within the model. However, there were other unmeasured sources and sinks of water including small tributaries, overland flow, or seepage loss to groundwater. To account for unmeasured sources and sinks of water and complete the water balance, a distributed tributary was applied within the model; the distributed tributary was calculated so that the model surface elevation matched the measured water surface elevation (fig. 1.1). The total flow in the distributed tributary was small compared to gaged flows, constituting on average less than 4 percent of the gaged flow downstream from Keno Dam in all years simulated.

Model Performance

Model performance was evaluated by comparing model output to measured data at the same time, location, and depth. This evaluation was done visually (figs. 1.2–1.12) as well as through the calculation of mean error and mean absolute error statistics that summarize the difference between model output and measured data (table 1.2). Error statistics from previous year USGS models of the reach are included for comparison.

Ideally, the comparison between model output and measured data would be at the same date and time, location, and characterizing the same water volume. With data and model limitations, that was not always possible. For instance, model water-quality output is averaged through the volume of a model cell that is 2 ft high, approximately 1000 feet long, and between 2500 and 16 ft wide depending on depth in the channel. Measured water-quality data are from a discrete sample or a sonde, which characterize the conditions of a much smaller volume of the river. The measured data from USGS station 11509500 are approximately 1 mile downstream from Keno Dam, outside the model boundaries. Data from these measurement sites are compared to model results in figures 1.2–1.12 and in the error statistics in table 1.2. Thus, while the model should capture temporal and spatial patterns measured in the river, exact matches between measured data and model output are not expected. The 2010 and 2012–15 models simulated conditions with measured-simulated error statistics similar to that in previous model years (table 1.2).

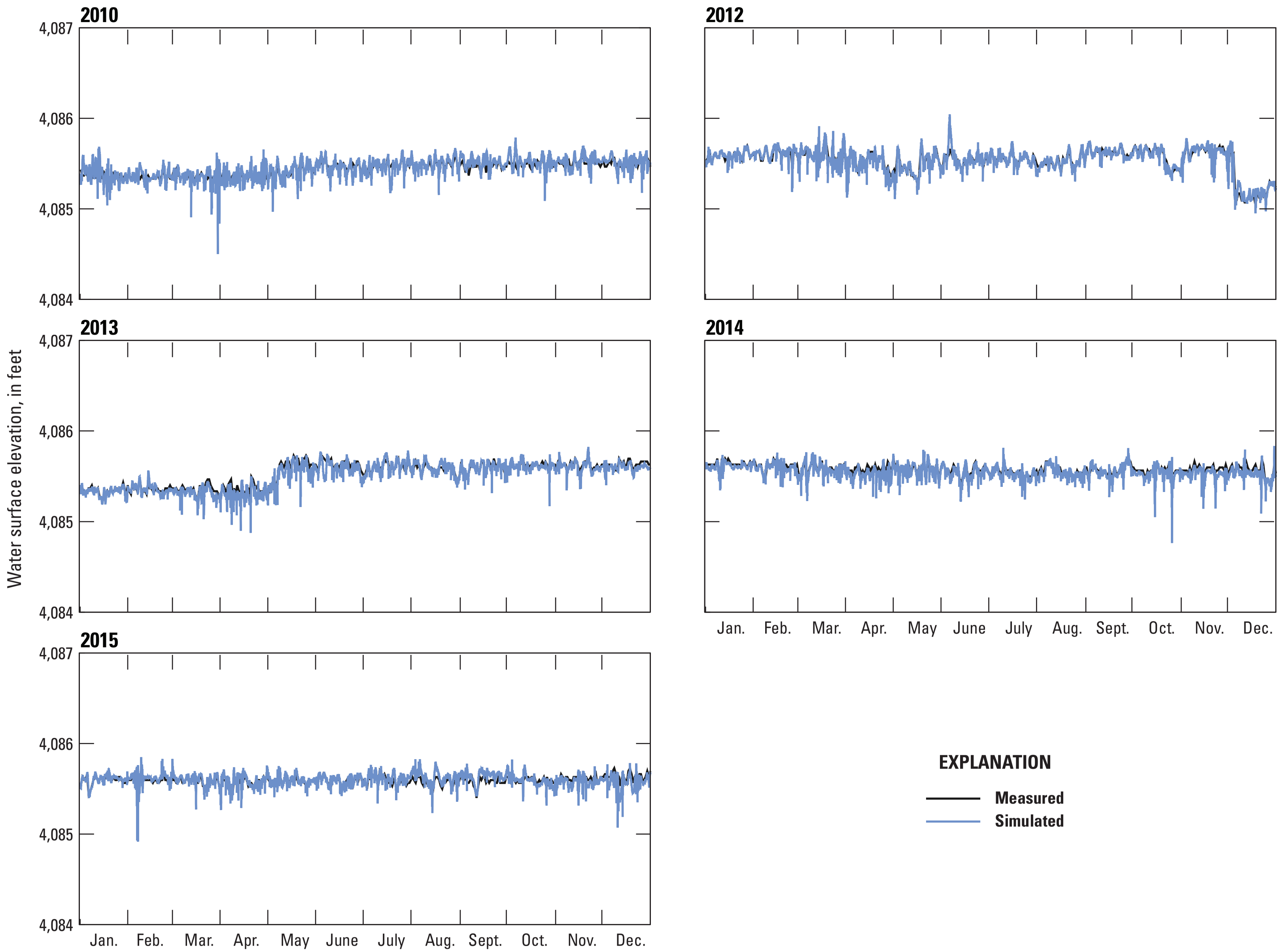

Figure 1.1. Measured and simulated water-surface elevations at Keno Dam forebay, Oregon, for calendar years 2010 and 2012–15.

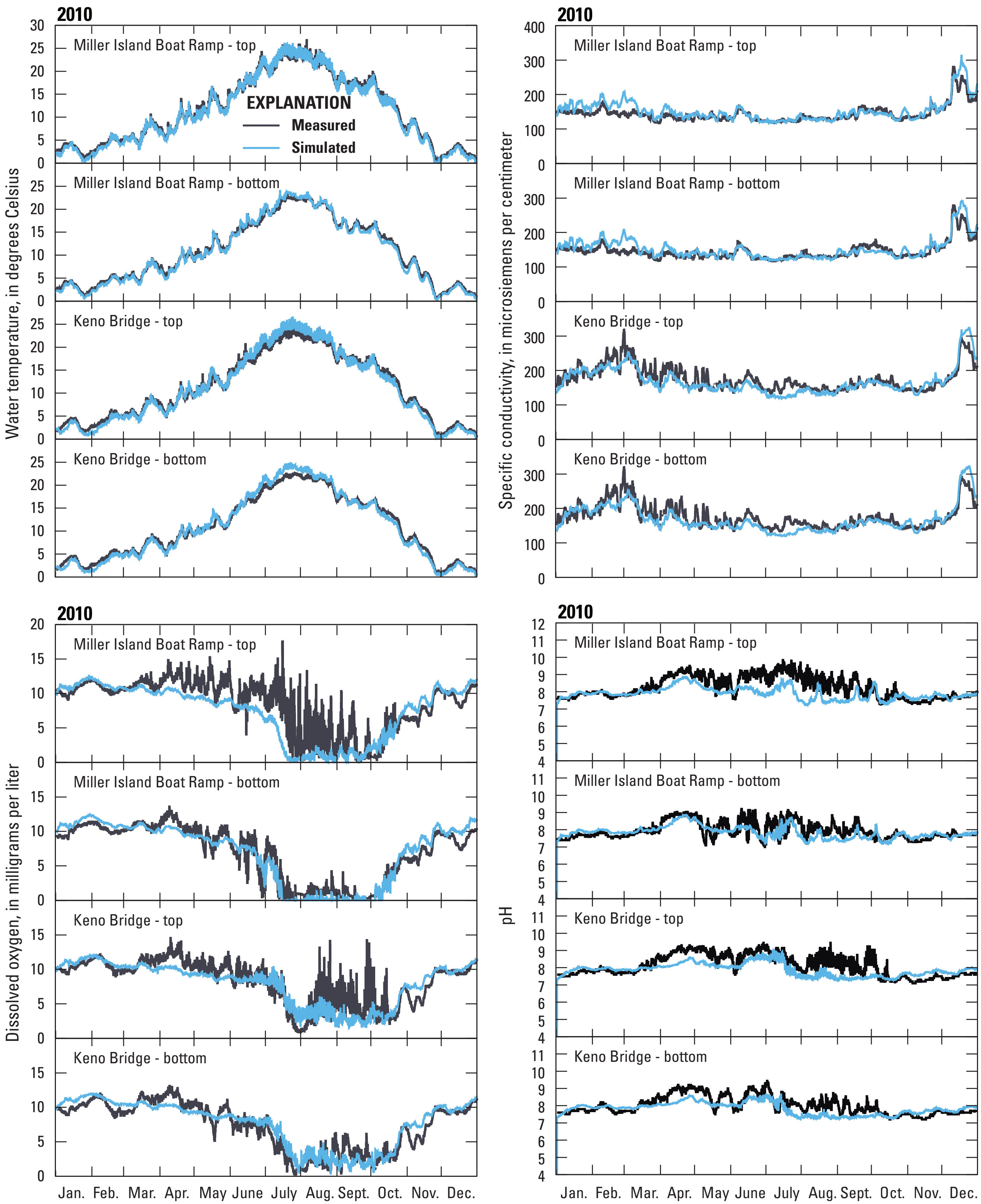

Figure 1.2. Calendar year 2010 measured and simulated hourly water temperature, specific conductance, dissolved oxygen, and pH for sites in the Klamath River upstream from Keno Dam, Oregon.

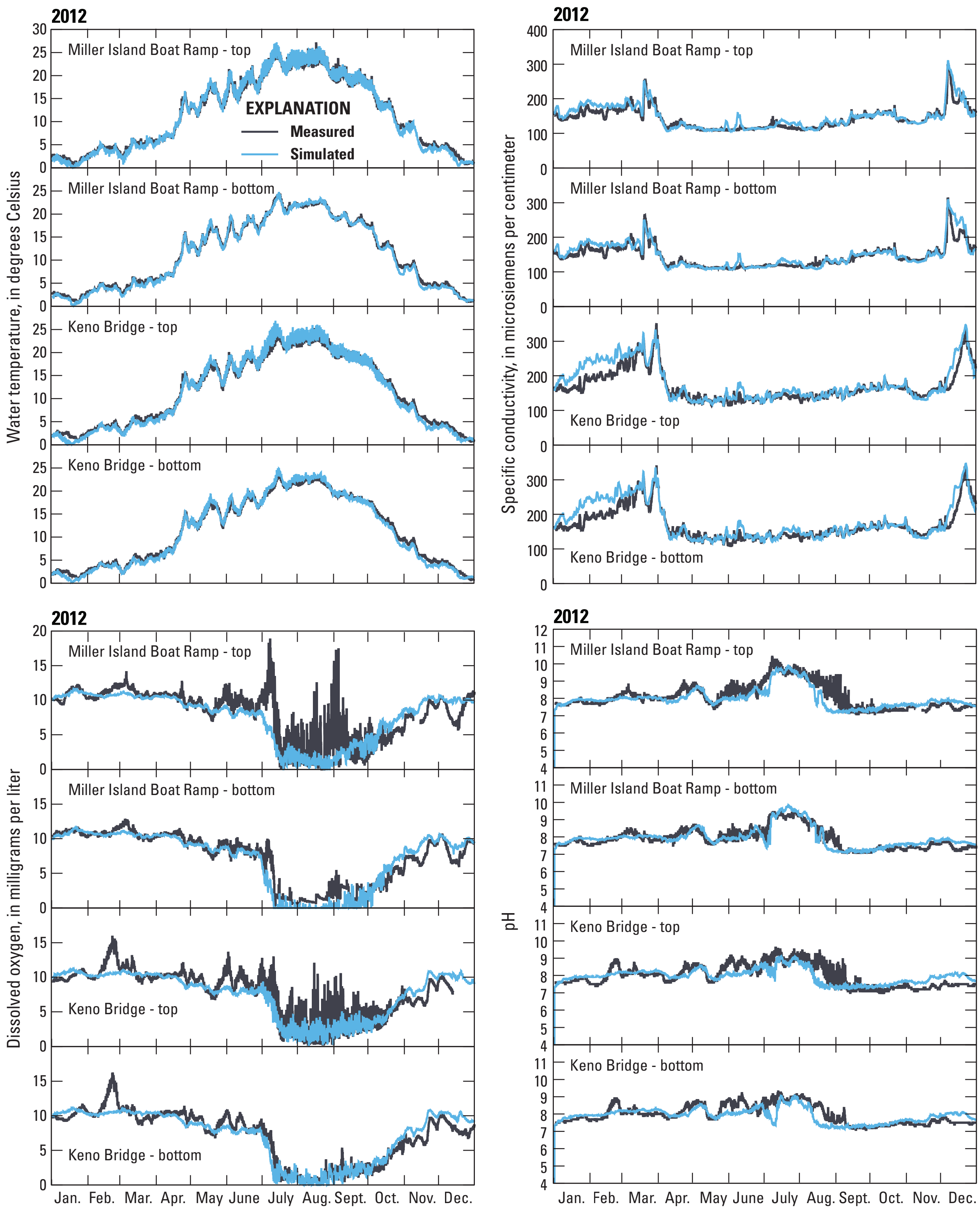

Figure 1.3. Calendar year 2012 measured and simulated hourly water temperature, specific conductance, dissolved oxygen, and pH for sites in the Klamath River upstream from Keno Dam, Oregon.

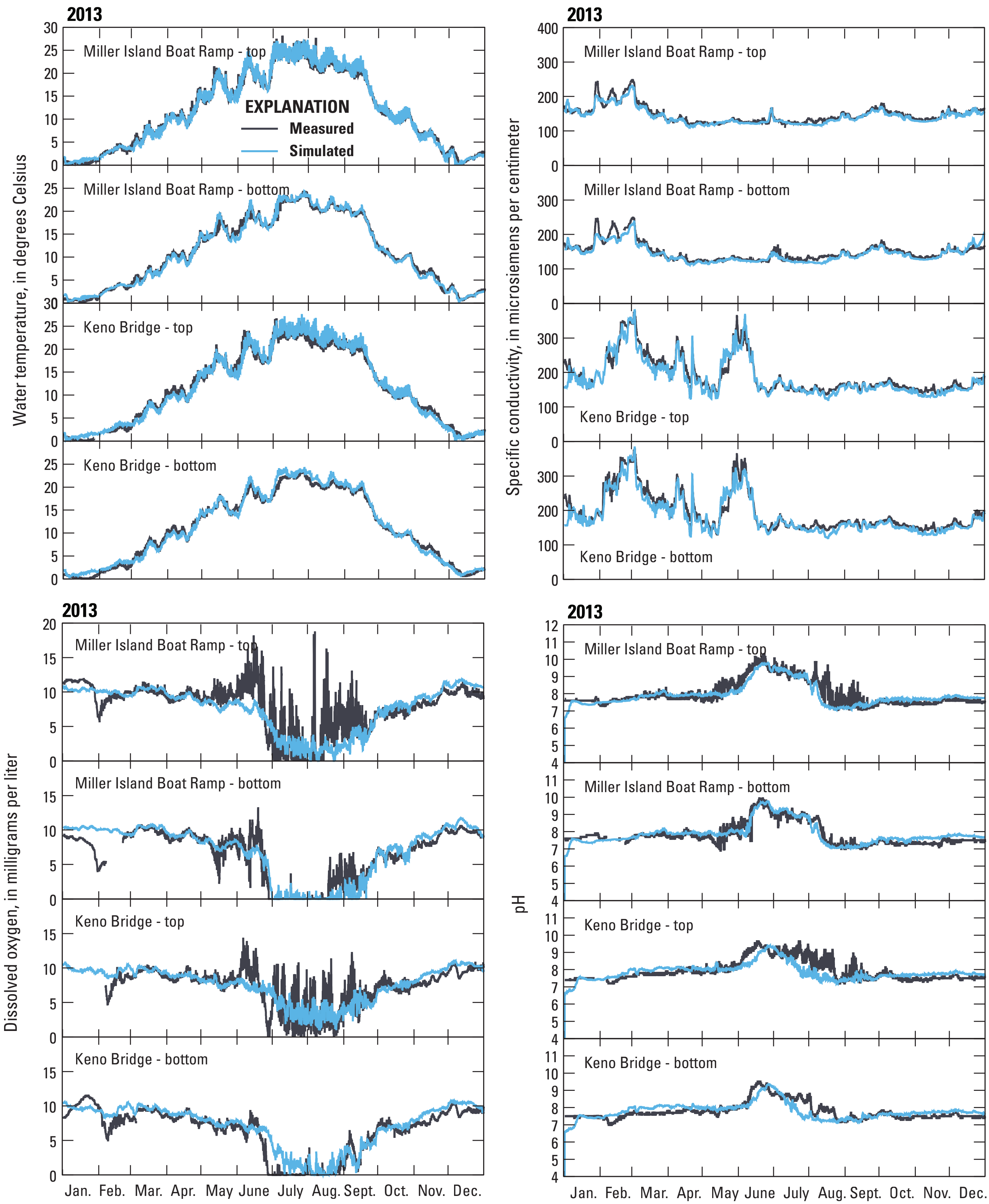

Figure 1.4. Calendar year 2013 measured and simulated hourly water temperature, specific conductance, dissolved oxygen, and pH for sites in the Klamath River upstream from Keno Dam, Oregon.

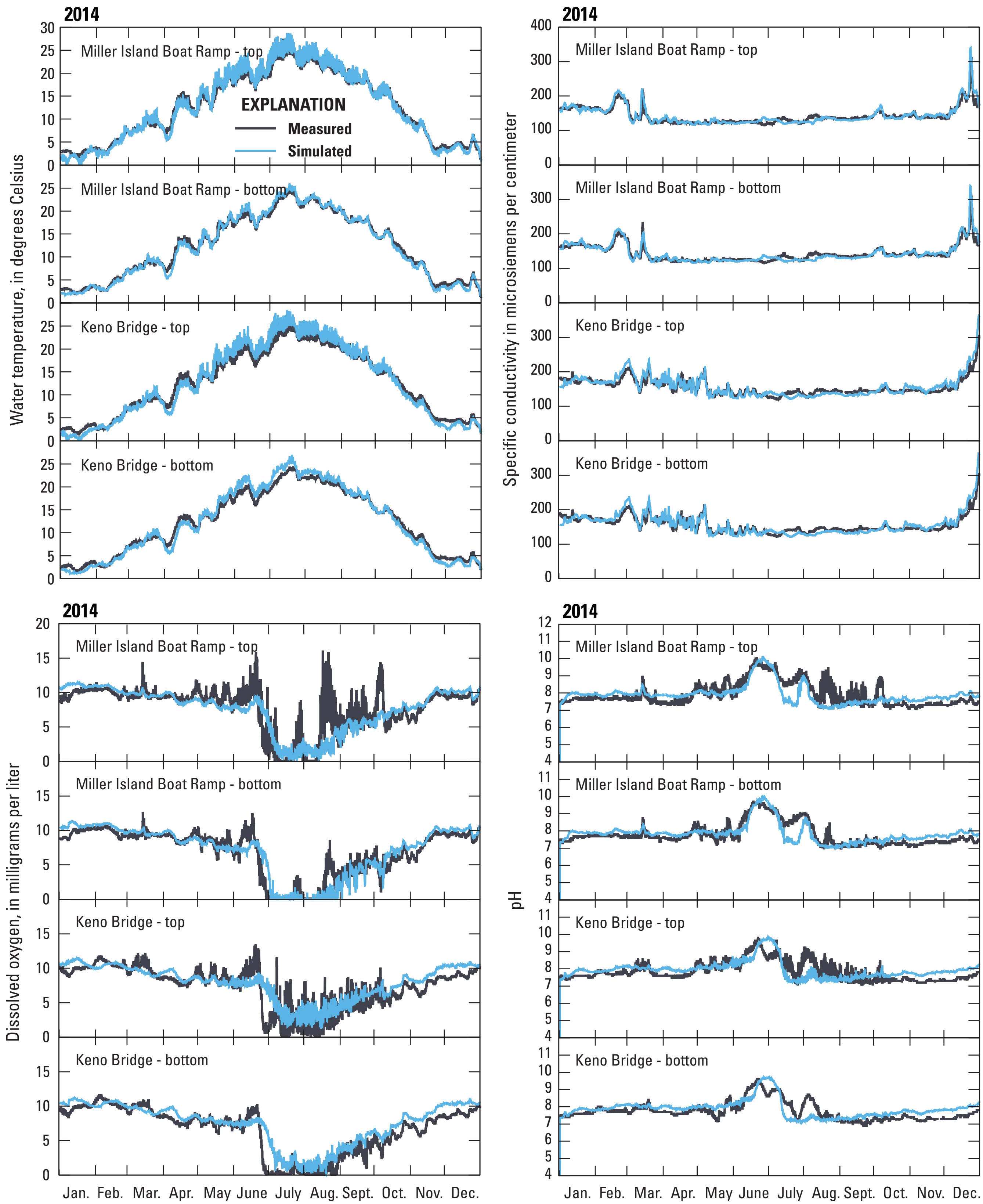

Figure 1.5. Calendar year 2014 measured and simulated hourly water temperature, specific conductance, dissolved oxygen, and pH for sites in the Klamath River upstream from Keno Dam, Oregon.

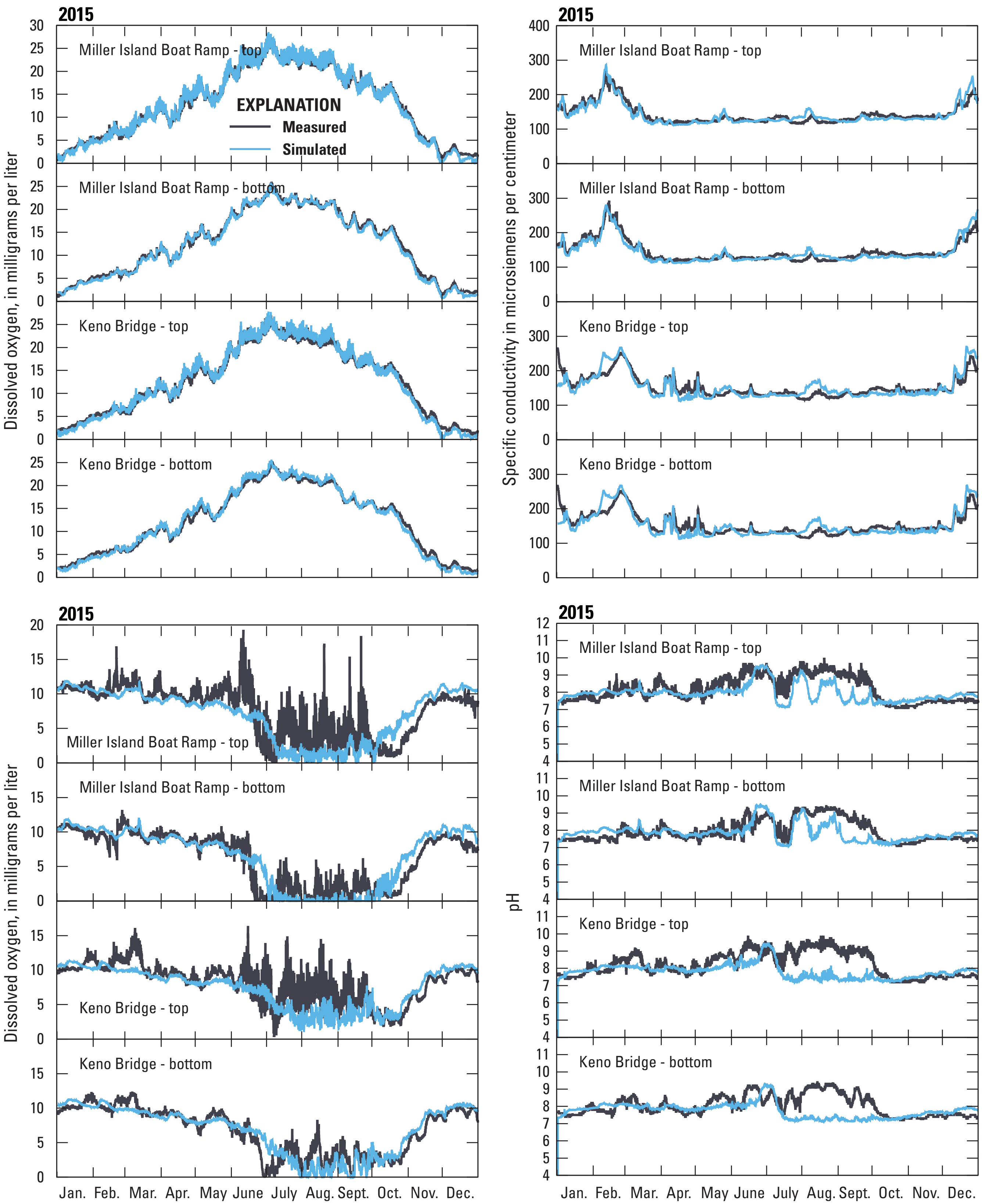

Figure 1.6. Calendar year 2015 measured and simulated hourly water temperature, specific conductance, dissolved oxygen, and pH for sites in the Klamath River upstream from Keno Dam, Oregon.

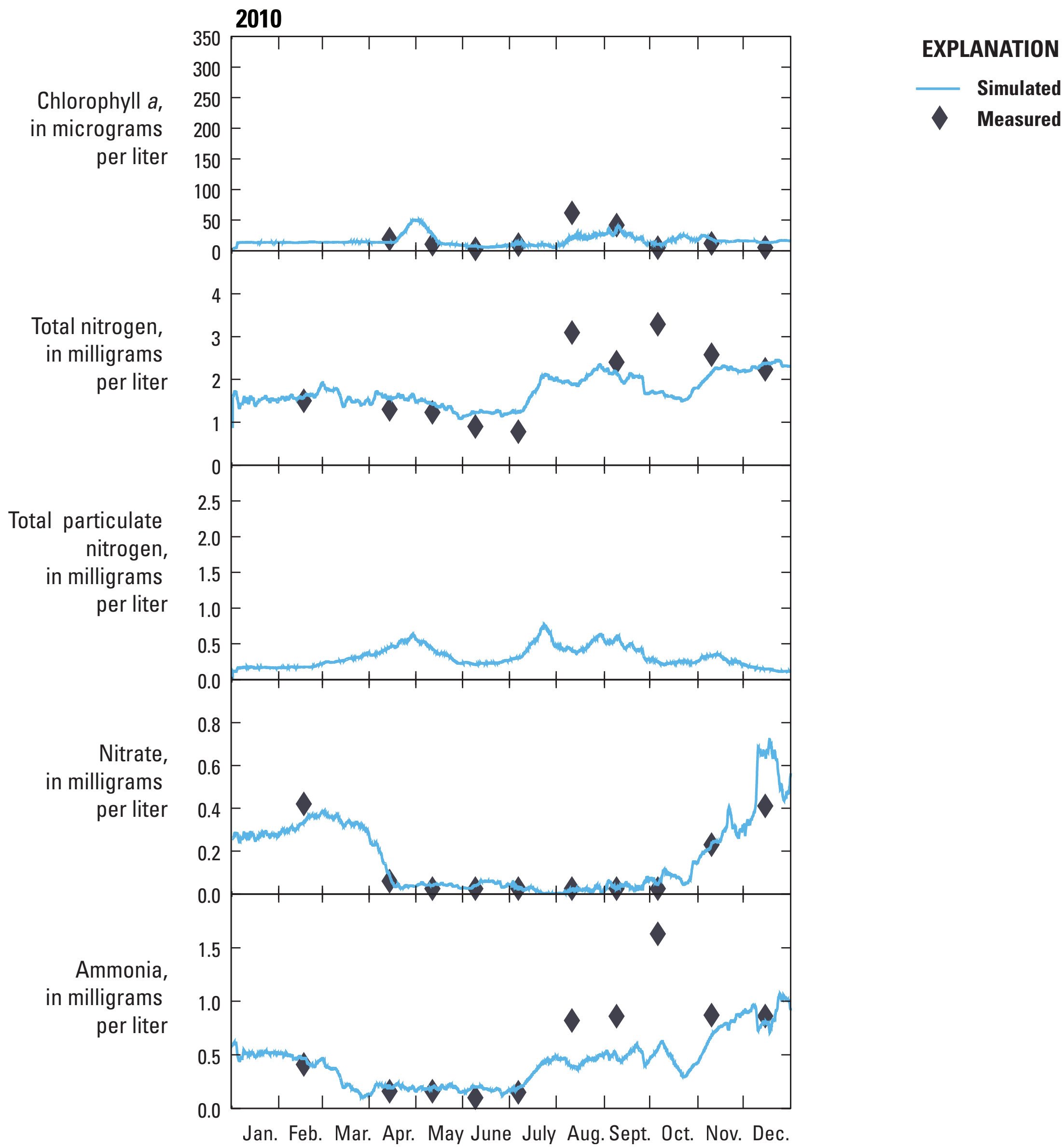

Figure 1.7. Calendar year 2010 measured and simulated nutrients, chlorophyll *a*, and organic matter at Miller Island in the upper Klamath River, Oregon.

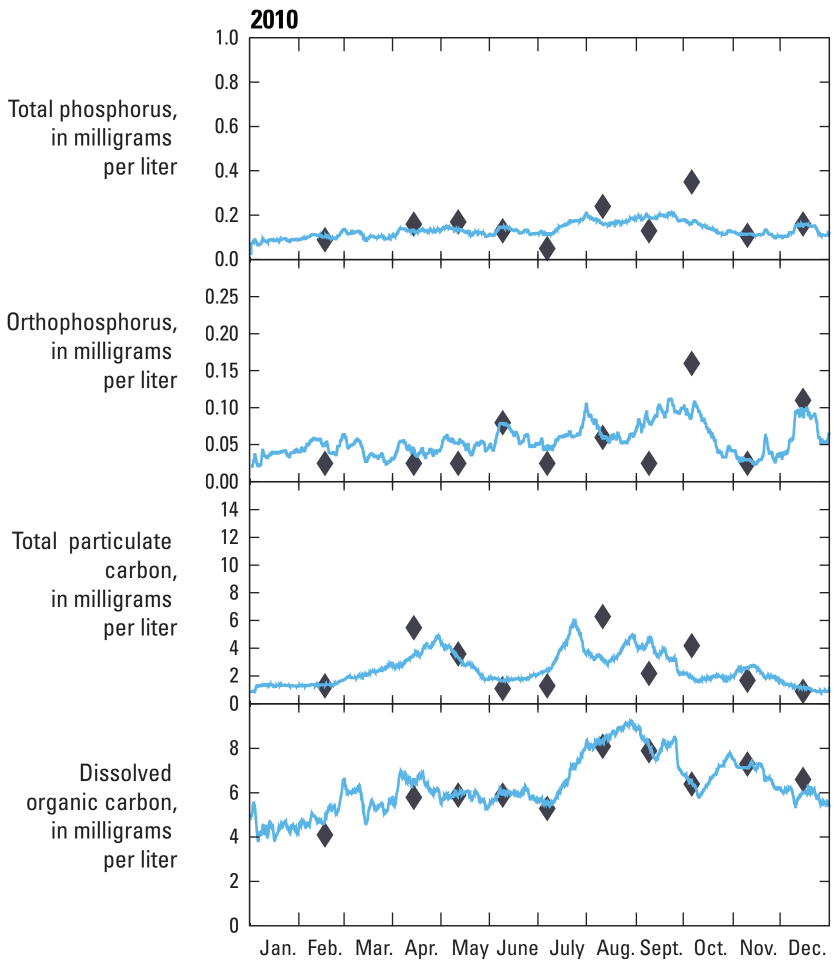

Figure 1.7.—Continued

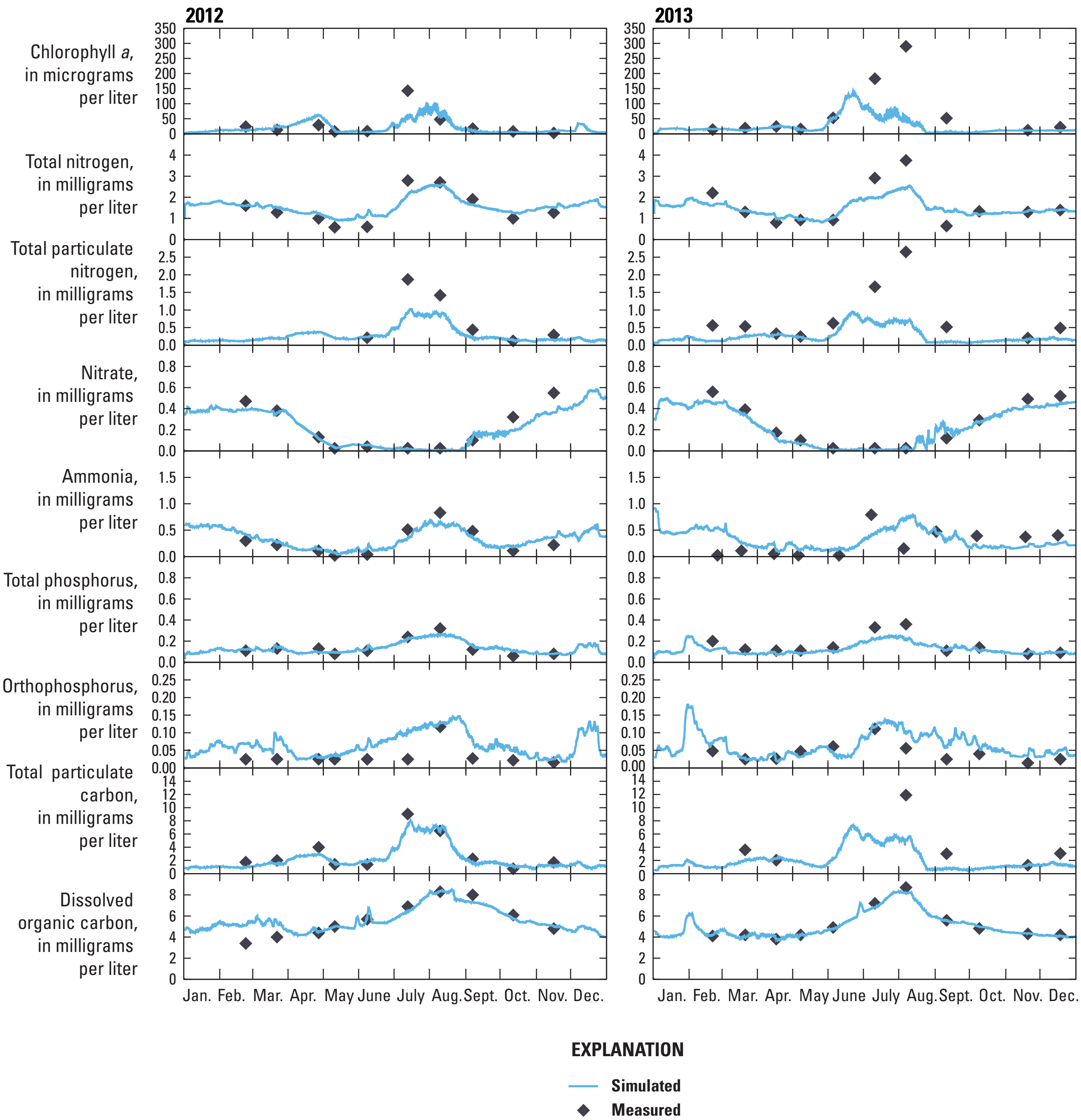

Figure 1.8. Calendar year 2012 and 2013 measured and simulated nutrients, chlorophyll *a*, and organic matter at Miller Island in the upper Klamath River, Oregon.

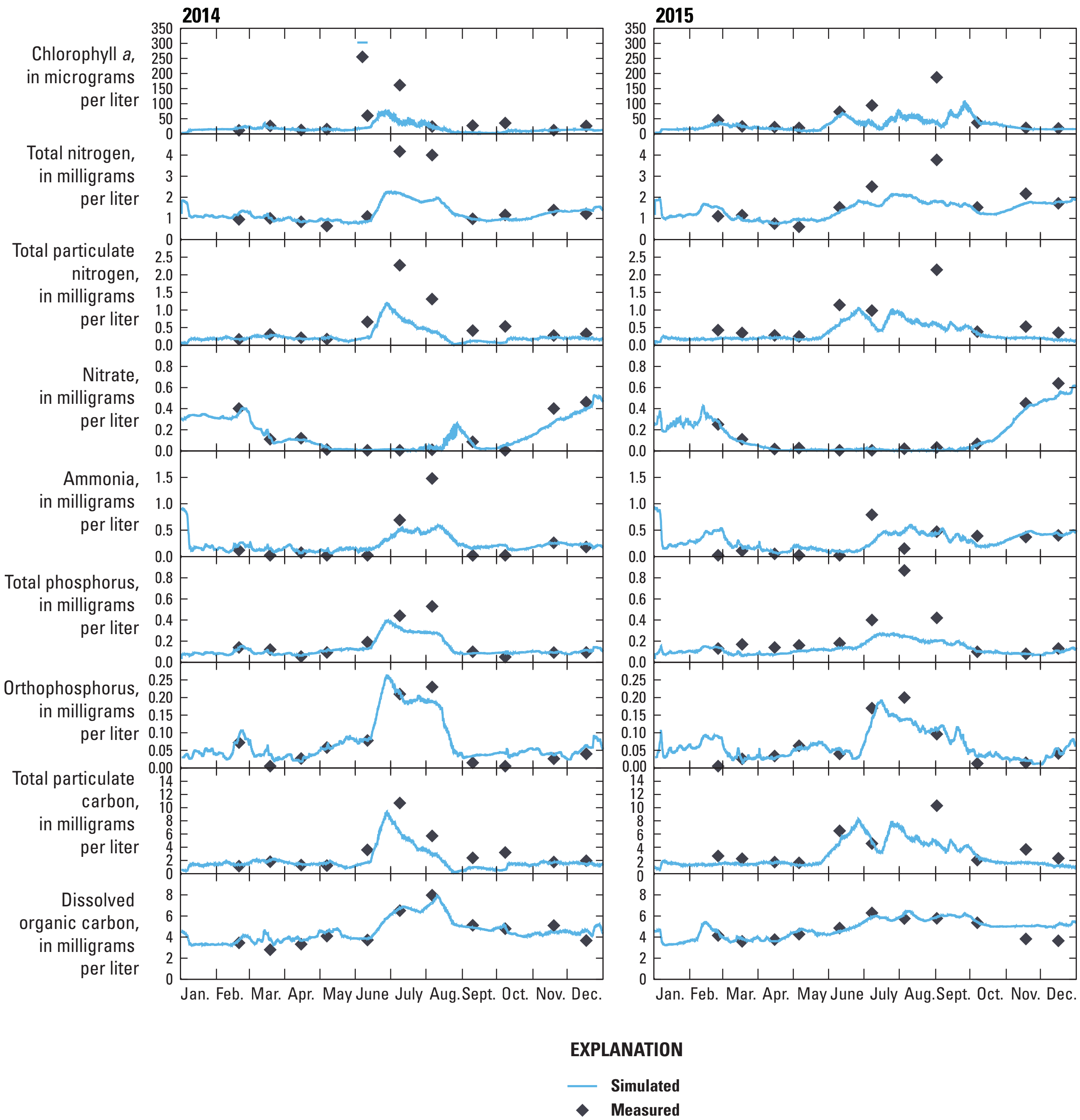

Figure 1.9. Calendar year 2014 and 2015 measured and simulated nutrients, chlorophyll *a*, and organic matter at Miller Island in the upper Klamath River, Oregon.

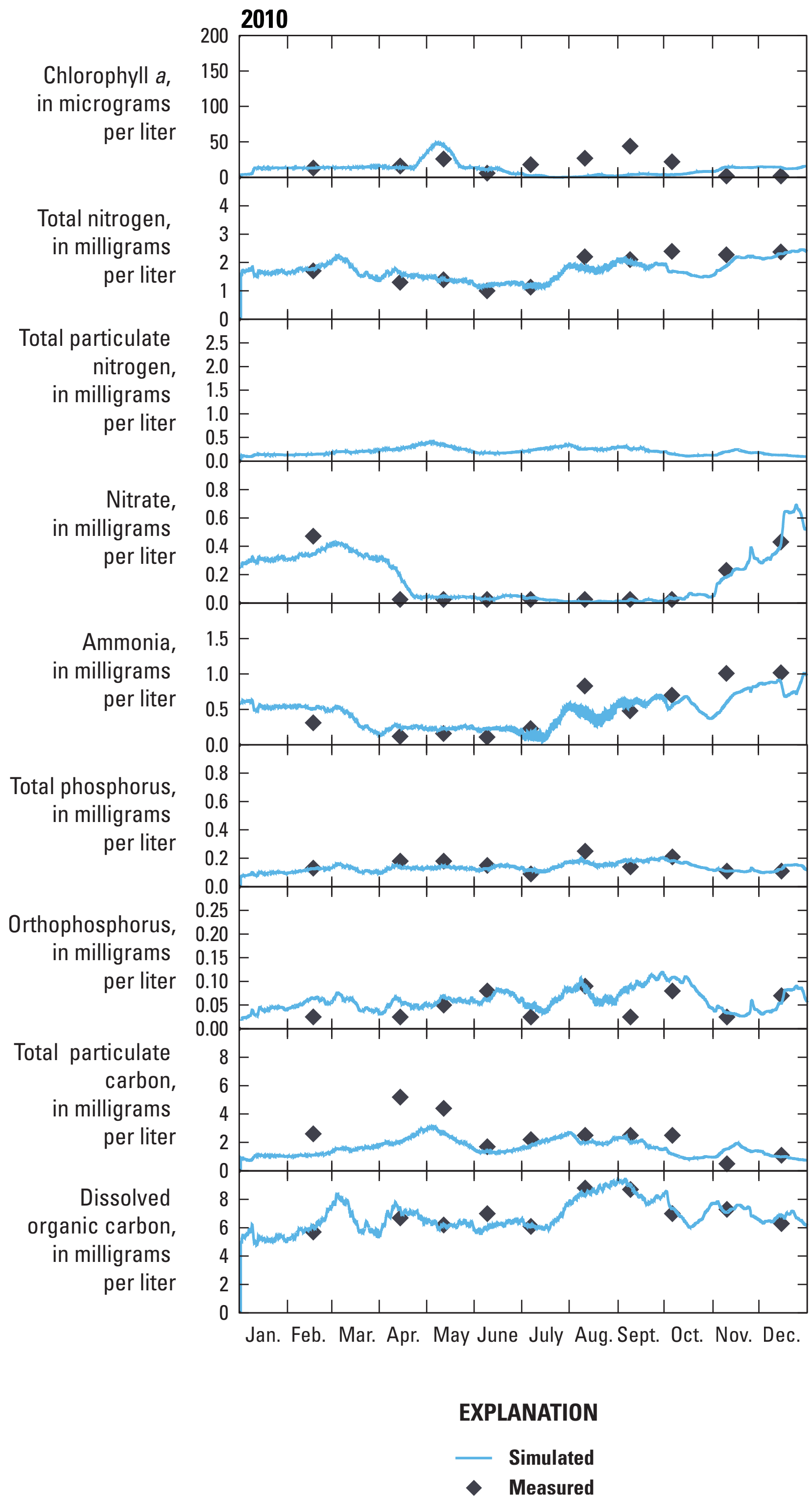

Figure 1.10. Calendar year 2010 measured and modeled simulated, chlorophyll *a*, and organic matter below the outflow of Keno Dam, Oregon.

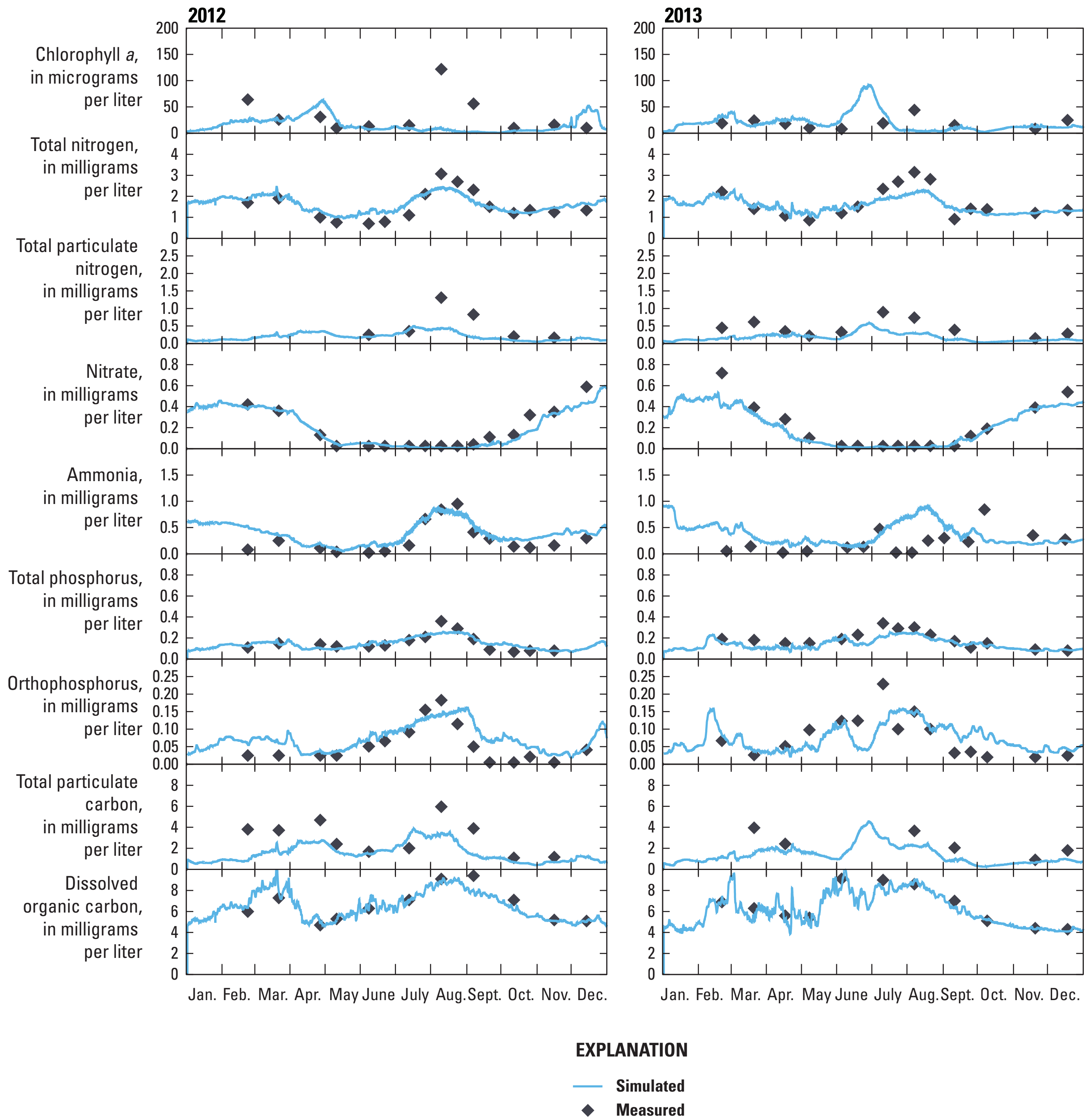

Figure 1.11. Calendar year 2012 and 2013 measured and simulated nutrients, chlorophyll *a*, and organic matter below the outflow of Keno Dam, Oregon.

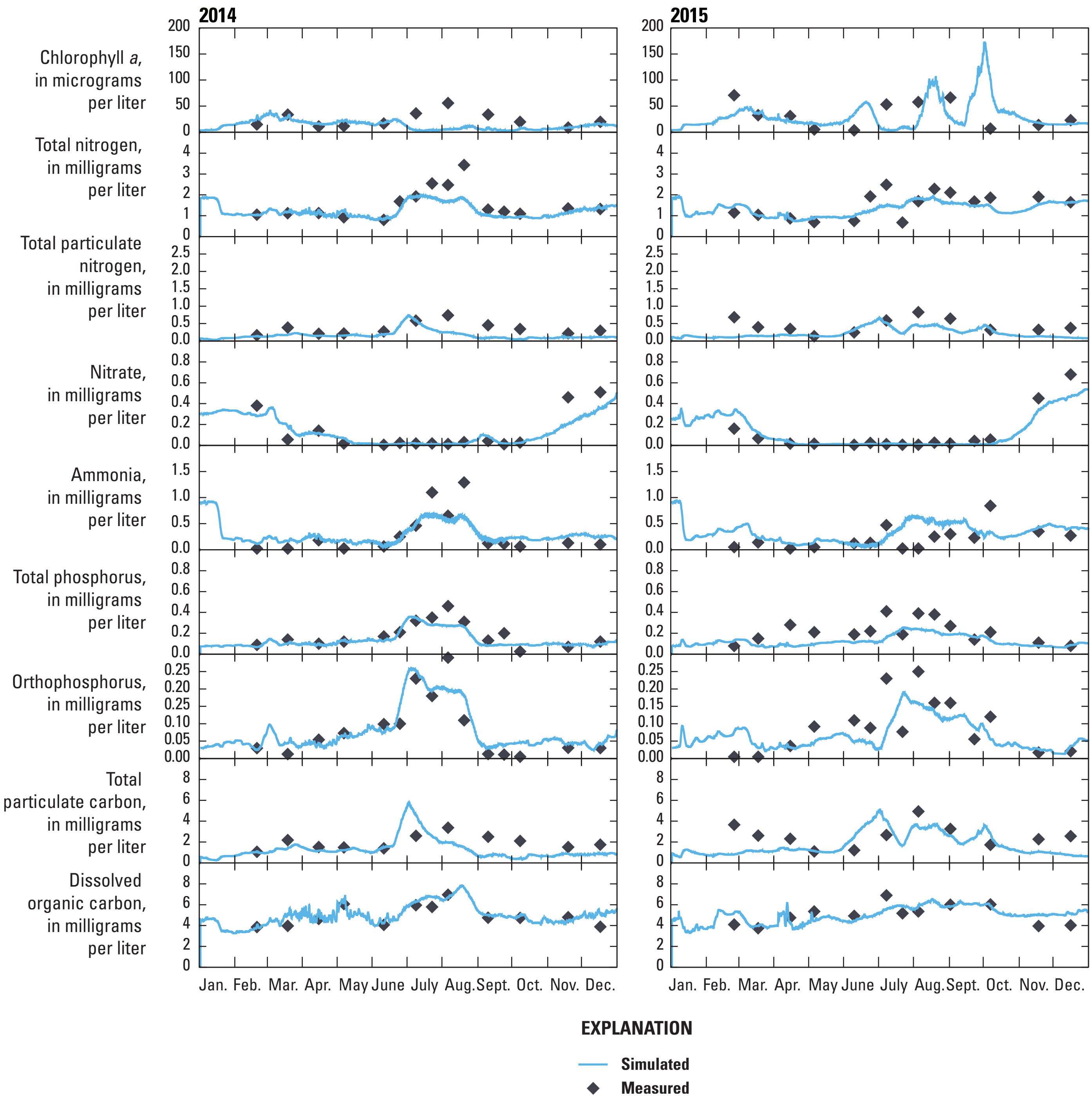

Figure 1.12. Calendar year 2014 and 2015 measured and simulated nutrients, chlorophyll *a*, and organic matter below the outflow of Keno Dam, Oregon.

Table 1.2. Goodness-of-fit statistics averaged for all calibration sites, with previous model years documented in Sullivan and others (2011) for 2006–09 and Sullivan and others (2014).

Constituent	Unit	Data type	Year	Mean error	Mean absolute error	
				This study (2010, 2012–15)	This study (2010, 2012–15)	Previous model years (2006–09, 11)
Water temperature	Degrees Celsius	hourly	2010	−0.18	0.62	0.55–0.69
			2012	−0.17	0.54	
			2013	0.09	0.61	
			2014	0.06	0.83	
			2015	−0.08	0.62	
Dissolved oxygen	milligrams per liter	hourly	2010	−0.64	1.43	0.95–1.44
			2012	−0.34	1.07	
			2013	−0.34	1.37	
			2014	−0.24	1.21	
			2015	−0.69	1.77	
pH		hourly	2010	−0.26	0.42	0.25–0.34
			2012	−0.04	0.26	
			2013	−0.03	0.31	
			2014	−0.02	0.36	
			2015	−0.27	0.49	
Ammonia	milligrams per liter	discrete sample	2010	−0.09	0.21	0.11–0.22
			2012	0.06	0.12	
			2013	0.09	0.14	
			2014	−0.04	0.19	
			2015	0.08	0.23	
Nitrate	milligrams per liter	discrete sample	2010	0.01	0.03	0.03–0.07
			2012	−0.03	0.04	
			2013	−0.04	0.05	
			2014	0.00	0.03	
			2015	−0.01	0.03	
Total nitrogen	milligrams per liter	discrete sample	2010	−0.12	0.40	0.40–0.53
			2012	0.06	0.31	
			2013	−0.19	0.42	
			2014	−0.36	0.46	
			2015	−0.45	0.66	
Orthophosphorus	milligrams per liter	discrete sample	2010	0.02	0.03	0.02–0.03
			2012	0.03	0.03	
			2013	0.00	0.03	
			2014	0.01	0.03	
			2015	−0.02	0.05	
Total phosphorus	milligrams per liter	discrete sample	2010	−0.02	0.05	0.04–0.05
			2012	0.00	0.03	
			2013	−0.06	0.06	
			2014	−0.04	0.06	
			2015	−0.12	0.13	

Table 1.2. Goodness-of-fit statistics averaged for all calibration sites, with previous model years documented in Sullivan and others (2011) for 2006–09 and Sullivan and others (2014).—Continued

Constituent	Unit	Data type	Year	Mean error	Mean absolute error	
				This study (2010, 2012–15)	This study (2010, 2012–15)	Previous model years (2006–09, 11)
Particulate carbon	milligrams per liter	discrete sample	2010	−0.80	1.33	1.09–3.55
			2012	−0.89	1.14	
			2013	−2.03	2.08	
			2014	−0.90	1.24	
			2015	−1.86	2.36	
Dissolved organic carbon	milligrams per liter	discrete sample	2010	0.18	0.36	0.37–0.72
			2012	0.00	0.52	
			2013	−0.22	0.35	
			2014	0.29	0.42	
			2015	0.00	0.44	

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Appendix 2. Monthly Averages of Klamath Straits Drain Loads to the Klamath River

Table 2.1. Monthly averages of daily total nitrogen loads from the Klamath Straits Drain to the Klamath River, as simulated in base case conditions and the three recirculation scenarios.

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Abbreviations: TMDL, Total Maximum Daily Load; lbs/day, pounds per day]

Month	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total nitrogen load, base case (lbs/day)										
January	4,840	1,410	1,530	1,270	18	343	607	993	187	252
February	6,450	2,520	2,010	3,080	21	2,090	1,250	2,750	125	0
March	7,120	5,090	5,900	4,630	0	3,510	3,530	3,400	1,370	0
April	5,330	2,610	2,900	2,230	0	1,300	3,100	2,570	1,440	867
May	5,300	2,460	2,640	2,190	9	937	1,700	2,630	760	62
June	3,160	1,920	2,580	2,220	4	1,540	1,760	2,420	605	61
July	1,210	1,380	1,270	1,330	0	1,130	1,440	1,600	128	53
August	1,430	1,190	1,140	863	0	967	1,250	1,210	21	244
September	851	837	1,110	1,010	0	788	1,150	680	104	219
October	455	388	605	367	0	225	378	178	67	133
November	283	310	471	386	0	234	158	130	86	118
December	474	544	881	676	0	207	760	270	262	342
TMDL	268	268	268	268	268	268	268	268	268	268
Total nitrogen load, scenario 1 (lbs/day)										
January	3,050	12	42	32	0	52	230	90	175	244
February	5,700	780	777	1,020	0	49	243	2,040	122	0
March	5,210	3,220	4,880	4,420	0	1,390	1,190	2,250	1,050	0
April	4,700	2,290	1,860	1,580	0	261	727	1,770	620	855
May	3,400	214	633	966	1	81	308	1,080	666	60
June	742	67	346	424	4	0	334	247	235	58
July	0	63	34	62	0	0	256	209	131	39
August	58	6	8	11	0	0	180	293	21	83
September	10	55	25	0	0	43	4	417	94	26
October	0	0	8	42	0	108	2	9	58	0
November	4	0	7	58	0	0	150	75	74	7
December	12	0	0	2	0	10	160	96	207	286
Total nitrogen load, scenario 2 (lbs/day)										
January	3,260	25	191	32	0	52	230	214	175	244
February	5,700	795	787	1,100	0	208	247	2,090	122	0
March	5,280	3,320	4,880	4,420	0	1,440	1,480	2,310	1,070	0
April	4,700	2,290	1,870	1,580	0	261	939	1,780	671	855
May	3,540	285	655	966	1	81	377	1,100	664	60
June	1,050	148	637	565	4	51	357	465	268	58
July	0	92	75	64	0	6	266	382	131	40
August	65	6	13	12	0	11	180	356	21	91
September	10	55	25	13	0	43	45	437	94	39

Table 2.1. Monthly averages of daily total nitrogen loads from the Klamath Straits Drain to the Klamath River, as simulated in base case conditions and the three recirculation scenarios.—Continued

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Abbreviations: TMDL, Total Maximum Daily Load; lbs/day, pounds per day]

Month	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total nitrogen load, scenario 2 (lbs/day)—Continued										
October	0	0	8	42	0	108	52	24	57	11
November	4	0	7	58	0	0	150	74	74	19
December	12	0	0	2	0	10	165	107	207	283
Total nitrogen load, scenario 3 (lbs/day)										
January	4,840	1,410	1,530	1,270	18	343	601	993	187	252
February	6,450	2,520	2,010	3,080	21	2,090	1,250	2,750	125	0
March	7,120	5,090	5,900	4,630	0	3,510	3,490	3,400	1,370	0
April	5,300	2,600	2,800	2,230	0	1,290	3,070	2,570	1,440	867
May	3,540	285	655	966	1	81	311	1,260	593	61
June	1,050	148	637	565	4	51	293	550	233	59
July	0	92	75	64	0	6	227	403	116	40
August	65	6	13	12	0	11	159	361	19	90
September	31	64	92	32	0	43	56	414	87	39
October	455	388	605	367	0	225	464	224	56	155
November	283	310	471	386	0	234	208	196	74	146
December	474	544	881	676	0	207	672	320	213	296

Table 2.2. Monthly averages of daily total phosphorus loads from the Klamath Straits Drain to the Klamath River, as simulated in base case conditions and the three recirculation scenarios.

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Abbreviations: TMDL, Total Maximum Daily Load; lbs/day, pounds per day]

Month	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total phosphorus load, base case (lbs/day)										
January	574	90	119	64	1	17	45	60	13	18
February	1,030	227	171	242	2	131	95	188	8	0
March	1,310	565	509	456	0	274	273	271	119	0
April	807	280	267	263	0	113	229	219	140	83
May	765	315	324	319	1	96	171	346	93	8
June	458	249	325	333	1	174	245	310	90	8
July	173	190	202	187	0	128	186	246	23	8
August	196	174	151	109	0	114	169	165	3	40
September	110	101	128	114	0	98	127	83	15	38
October	54	31	54	37	0	25	36	20	8	20
November	26	21	31	35	0	19	12	9	7	12
December	28	37	34	54	0	14	45	16	17	28
TMDL	21	21	21	21	21	21	21	21	21	21
Total phosphorus load, scenario 1 (lbs/day)										
January	365	1	3	2	0	3	17	5	12	17
February	900	75	67	84	0	3	18	130	8	0

Table 2.2. Monthly averages of daily total phosphorus loads from the Klamath Straits Drain to the Klamath River, as simulated in base case conditions and the three recirculation scenarios.—Continued

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Abbreviations: TMDL, Total Maximum Daily Load; lbs/day, pounds per day]

Month	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total phosphorus load, scenario 1 (lbs/day)—Continued										
March	957	358	421	438	0	109	91	163	91	0
April	709	244	168	186	0	23	57	145	57	82
May	491	27	80	139	0	9	25	99	68	7
June	107	9	41	63	1	0	29	28	30	8
July	0	9	6	9	0	0	25	26	18	6
August	8	1	1	2	0	0	19	38	3	13
September	1	6	2	0	0	5	0	55	14	4
October	0	0	1	4	0	13	0	1	9	0
November	0	0	0	6	0	0	16	8	11	1
December	1	0	0	0	0	1	17	11	29	41
Total phosphorus load, scenario 2 (lbs/day)										
January	389	2	15	2	0	3	17	13	12	17
February	900	76	68	90	0	13	18	134	8	0
March	971	370	421	438	0	113	114	168	93	0
April	709	244	170	186	0	23	73	147	61	82
May	510	36	83	139	0	9	30	101	68	7
June	153	19	77	85	1	6	31	52	34	8
July	0	13	12	9	0	1	27	48	18	6
August	9	1	2	2	0	1	20	47	3	14
September	1	6	2	1	0	5	5	59	14	7
October	0	0	1	4	0	13	6	3	9	2
November	0	0	0	6	0	0	16	8	11	3
December	1	0	0	0	0	1	18	12	29	40
Total phosphorus load, scenario 3 (lbs/day)										
January	574	90	119	64	1	17	44	60	13	18
February	1,030	227	171	242	2	131	95	188	8	0
March	1,310	565	509	456	0	274	271	271	119	0
April	803	280	257	263	0	111	226	219	140	83
May	510	36	83	139	0	9	29	154	68	8
June	153	19	77	85	1	6	32	79	37	8
July	0	13	12	9	0	1	29	56	18	6
August	9	1	2	2	0	1	21	51	3	14
September	4	7	9	3	0	5	7	58	15	6
October	54	31	54	37	0	25	58	31	9	26
November	26	21	31	35	0	19	25	25	12	22
December	28	37	34	54	0	14	80	38	30	38

Table 2.3. Monthly averages of daily 5-day biochemical oxygen demand loads from the Klamath Straits Drain to the Klamath River, as simulated in base case conditions and the three recirculation scenarios.

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Abbreviations: TMDL, Total Maximum Daily Load; lbs/day, pounds per day]

Month	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
5-day biochemical oxygen demand, base case (lbs/day)										
January	703	161	196	232	4	60	207	272	99	59
February	977	329	273	538	4	338	571	1,400	221	0
March	1,300	924	1,160	874	0	661	1,190	1,220	627	0
April	1,460	746	874	620	0	357	1,020	1,060	434	474
May	1,150	507	540	538	3	229	1,350	557	308	20
June	755	663	1,040	588	2	414	719	1,540	513	30
July	750	1,320	1,140	871	0	797	896	921	65	30
August	1,340	1,080	885	810	0	946	714	756	7	178
September	881	669	741	914	0	741	665	460	54	139
October	498	365	471	339	0	215	172	94	41	62
November	278	373	493	332	0	214	233	215	42	49
December	172	254	347	257	0	74	523	193	104	135
TMDL	1,329	1,329	1,329	1,329	1,329	1,329	1,329	1,329	1,329	1,329
5- biochemical oxygen demand, scenario 1 (lbs/day)										
January	443	1	5	6	0	11	55	20	86	56
February	862	106	108	177	0	8	83	753	211	0
March	945	608	982	840	0	264	397	706	505	0
April	1,290	663	557	437	0	70	169	497	168	470
May	741	49	124	235	0	20	55	259	154	19
June	171	46	84	110	2	0	69	39	64	27
July	0	54	29	44	0	0	38	29	29	26
August	54	6	6	11	0	0	19	33	4	71
September	10	40	16	0	0	41	0	40	13	13
October	0	0	6	39	0	103	0	2	7	0
November	4	0	9	56	0	0	27	31	9	1
December	5	0	0	1	0	6	31	26	27	44
5-day biochemical oxygen demand, scenario 2 (lbs/day)										
January	475	3	25	6	0	11	55	50	86	56
February	862	108	109	191	0	34	85	807	211	0
March	957	626	982	840	0	274	479	729	511	0
April	1,290	663	562	437	0	70	222	513	181	470
May	768	63	129	235	0	20	70	266	156	19
June	245	69	176	146	2	14	77	76	74	27
July	0	81	64	47	0	5	40	53	29	26
August	61	6	10	11	0	11	19	40	4	77
September	10	40	16	12	0	41	4	42	13	18
October	0	0	6	39	0	103	6	6	7	2
November	4	0	9	56	0	0	28	31	9	3
December	5	0	0	1	0	6	32	29	27	44

Table 2.3. Monthly averages of daily 5-day biochemical oxygen demand loads from the Klamath Straits Drain to the Klamath River, as simulated in base case conditions and the three recirculation scenarios.—Continued

[Loads are monthly average daily loads, calculated using all days of the month whether flow occurred. Load allocations, as specified in the Klamath River TMDL are shown. Abbreviations: TMDL, Total Maximum Daily Load; lbs/day, pounds per day]

Month	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
5-day biochemical oxygen demand, scenario 3 (lbs/day)										
January	703	161	196	232	4	60	202	272	99	59
February	977	329	273	538	4	338	571	1,400	221	0
March	1,300	924	1,160	874	0	661	1,180	1,220	627	0
April	1,450	746	842	620	0	354	1,000	1,060	434	474
May	768	63	129	235	0	20	252	274	196	20
June	245	69	176	146	2	14	127	88	126	30
July	0	81	64	47	0	5	47	136	39	24
August	61	6	10	11	0	11	26	130	4	79
September	34	46	61	29	0	41	14	149	15	17
October	498	365	471	339	0	215	83	70	8	30
November	278	373	493	332	0	214	37	83	9	23
December	172	254	347	257	0	74	135	93	33	62

Appendix 3. Components of the Nutrient and BOD5 Loads for the Recirculation Scenarios

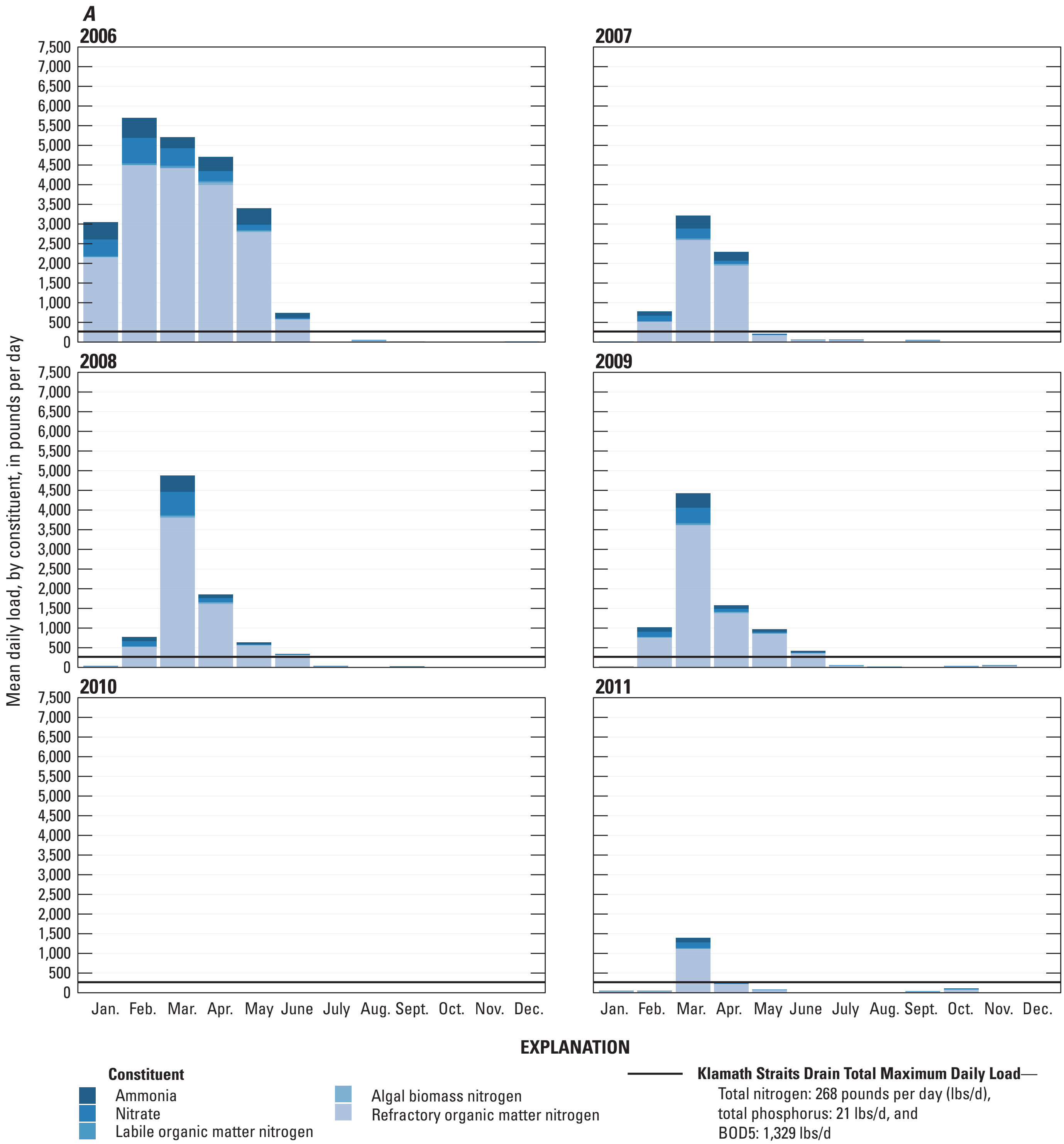


Figure 3.1. Graphs showing Klamath Straits Drain monthly average daily total nitrogen, total phosphorus, and 5-day biochemical oxygen demand (BOD5) loads for each year from 2006 through 2015 for scenario 1, broken up by the individual constituents that compose the total loads. *A*, monthly average daily total nitrogen: ammonia, nitrate, labile organic matter nitrogen, algal biomass nitrogen, and refractory organic matter nitrogen. *B*, monthly average daily total phosphorus: orthophosphorus, labile organic matter phosphorus, algal biomass phosphorus, and refractory organic matter phosphorus. *C*, monthly average daily BOD5: ammonia, labile organic matter, refractory organic matter, and algal biomass. These loads are based on simulated output for the different scenarios, calculated as instantaneous loads and then averaged to either daily, monthly, or annual loads.

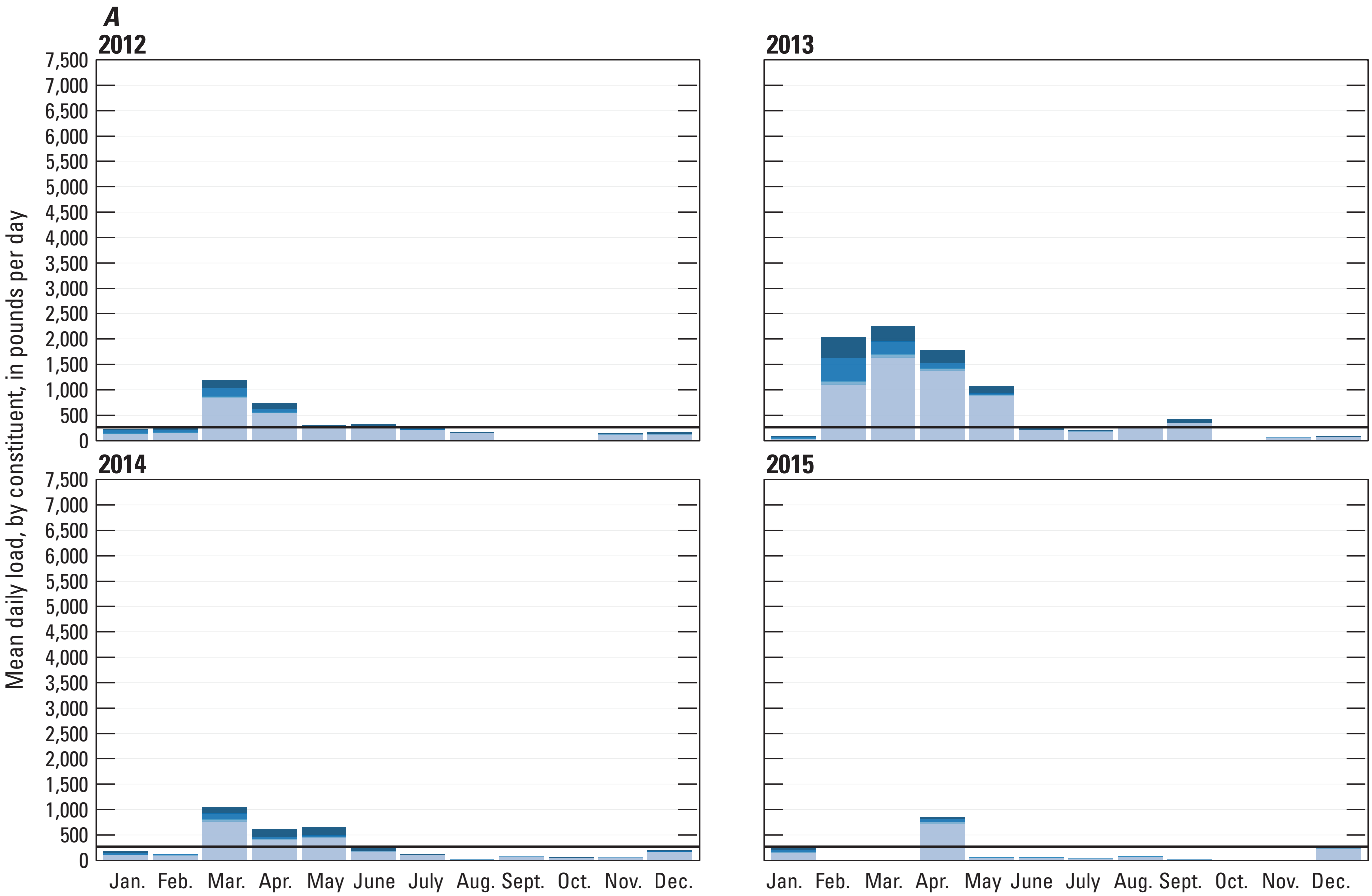


Figure 3.1.—Continued

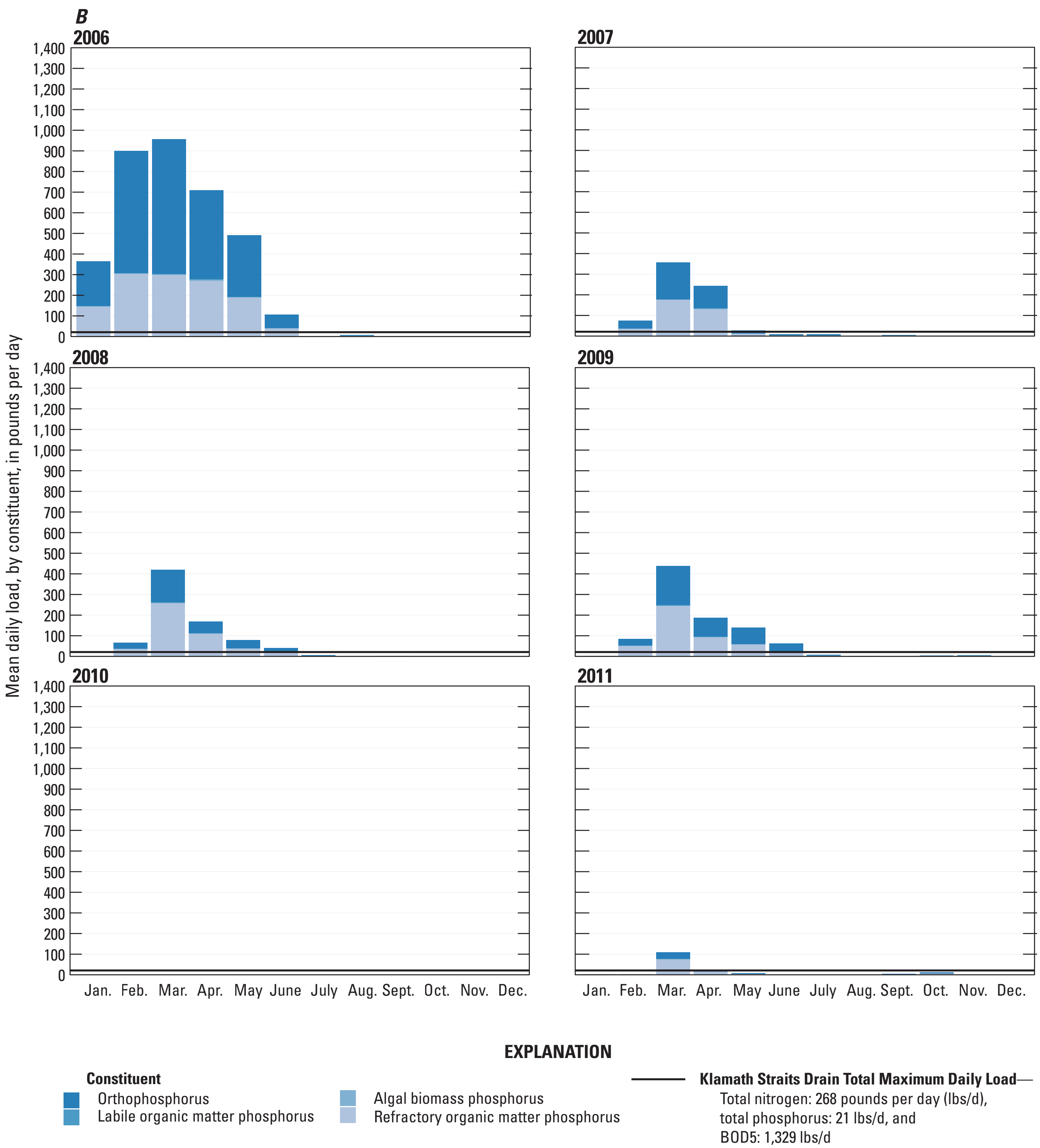


Figure 3.1.—Continued

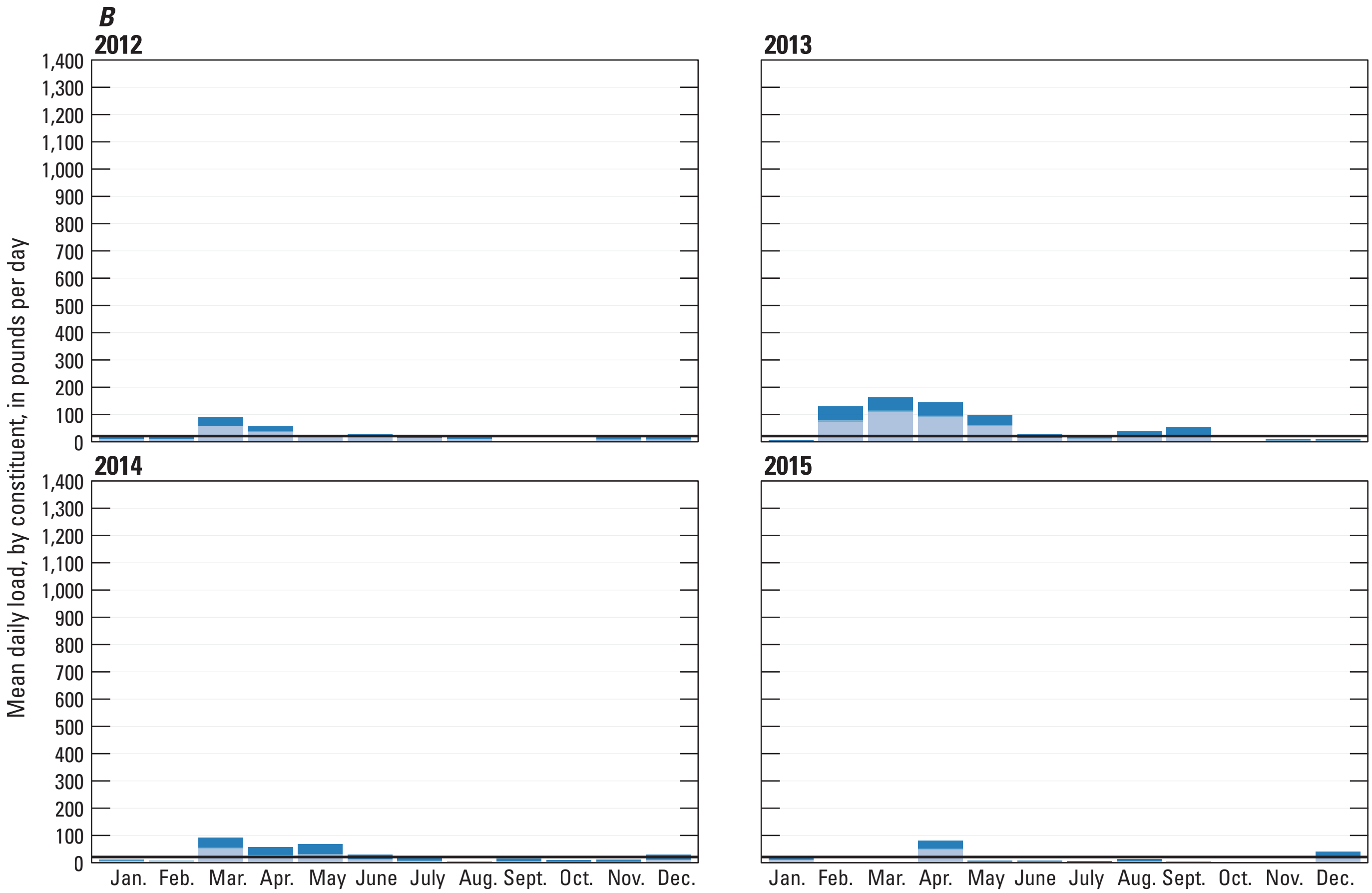


Figure 3.1.—Continued

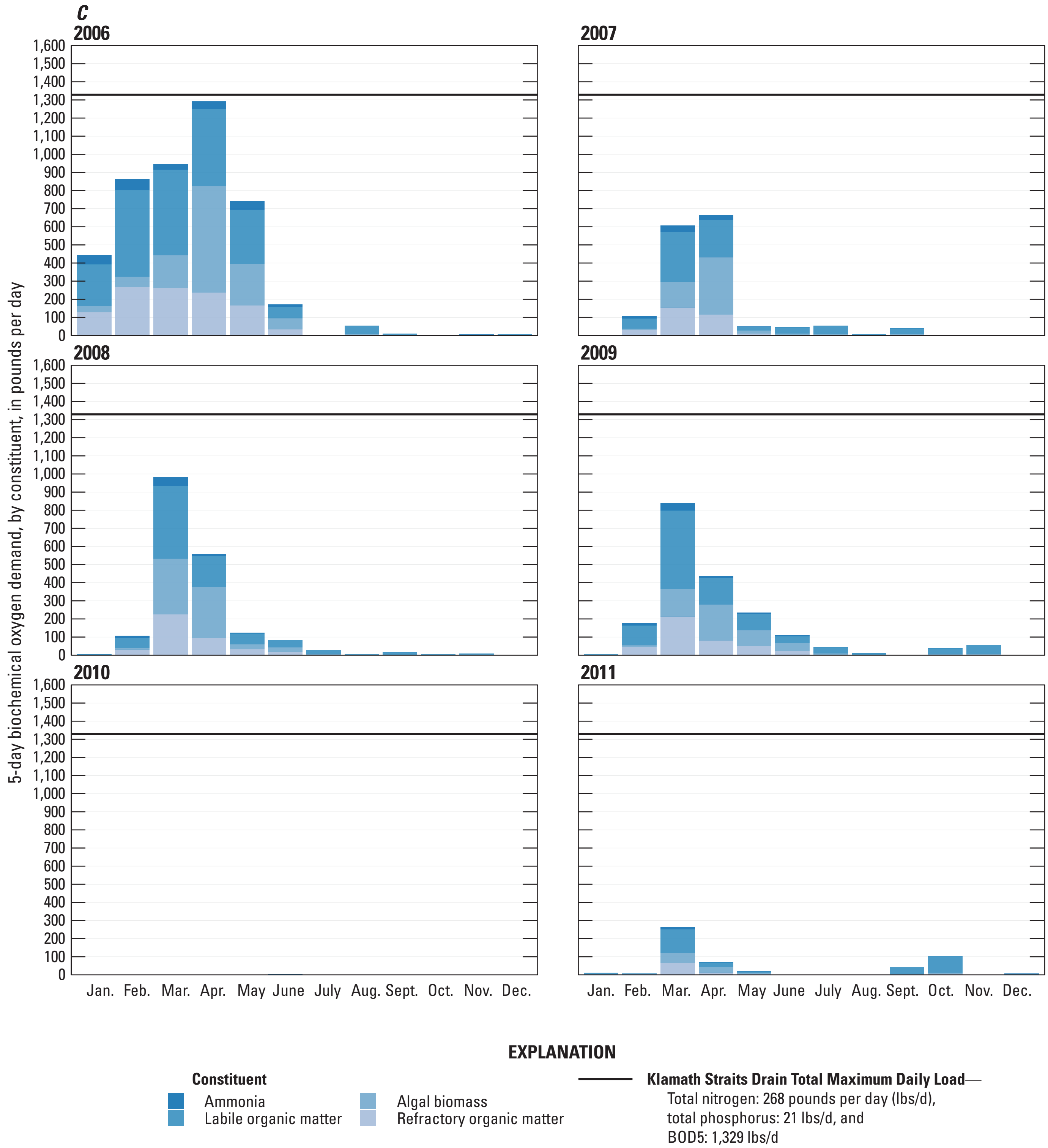


Figure 3.1.—Continued

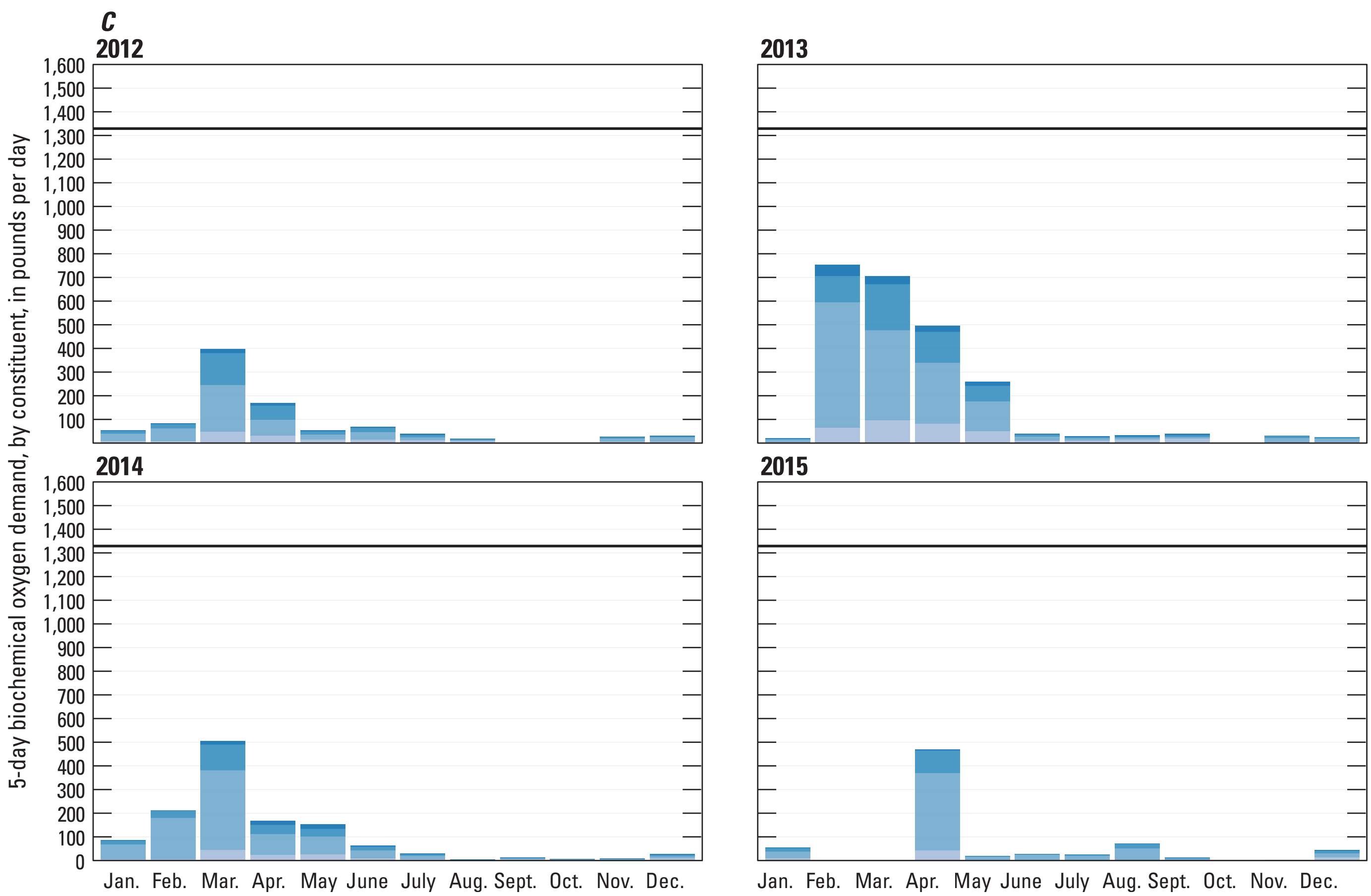


Figure 3.1.—Continued

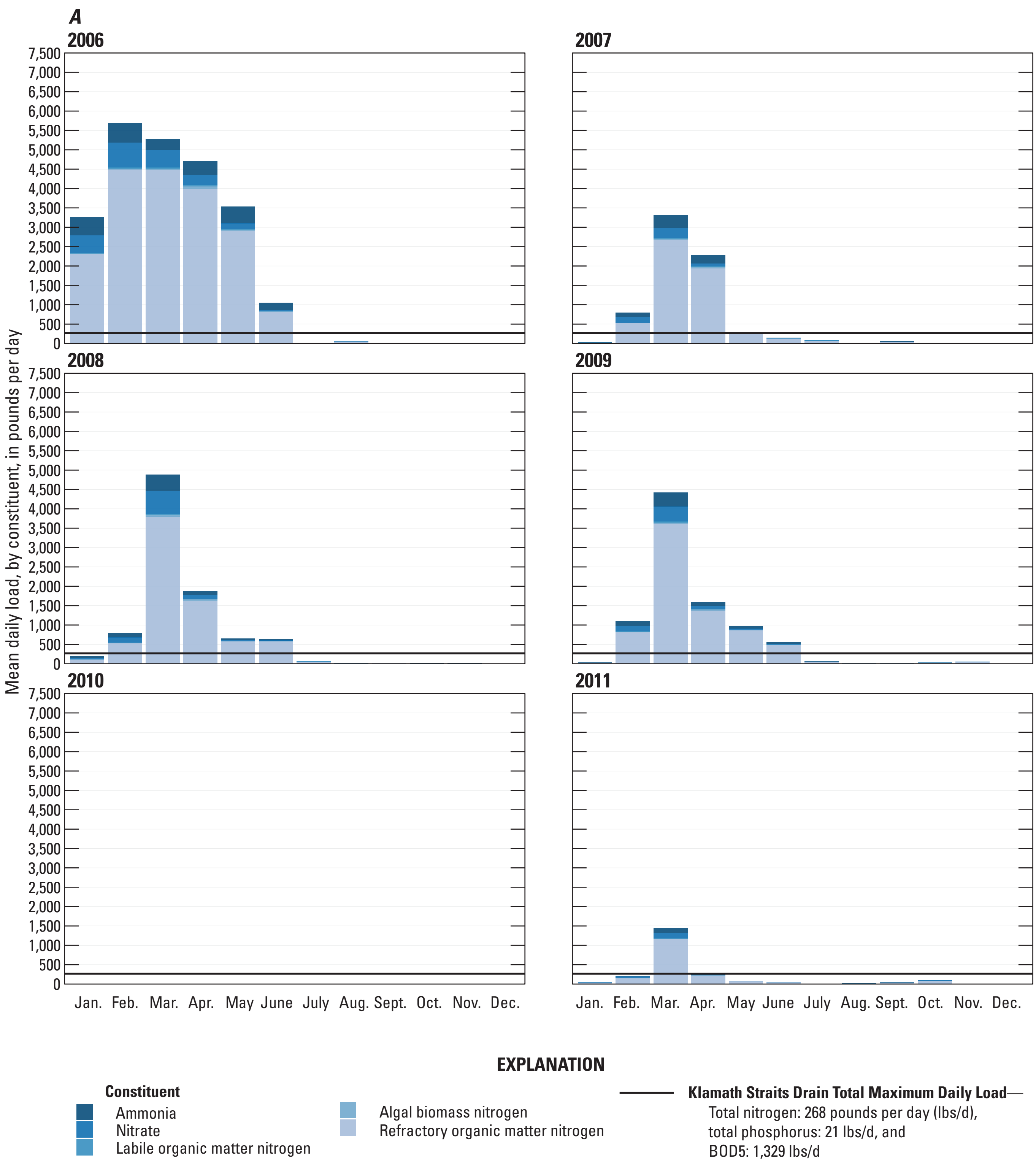


Figure 3.2. Graphs showing Klamath Straits Drain monthly average daily total nitrogen, total phosphorus, and 5-day biochemical oxygen demand (BOD5) loads for each year from 2006 through 2015 for scenario 2, broken up by the individual constituents that compose the total loads. *A*, monthly average daily total nitrogen: ammonia, nitrate, labile organic matter nitrogen, algal biomass nitrogen, and refractory organic matter nitrogen. *B*, monthly average daily total phosphorus: orthophosphorus, labile organic matter phosphorus, algal biomass phosphorus, and refractory organic matter phosphorus. *C*, monthly average daily BOD5: ammonia, labile organic matter, refractory organic matter, and algal biomass. These loads are based on simulated output for the different scenarios, calculated as instantaneous loads and then averaged to either daily, monthly, or annual loads.

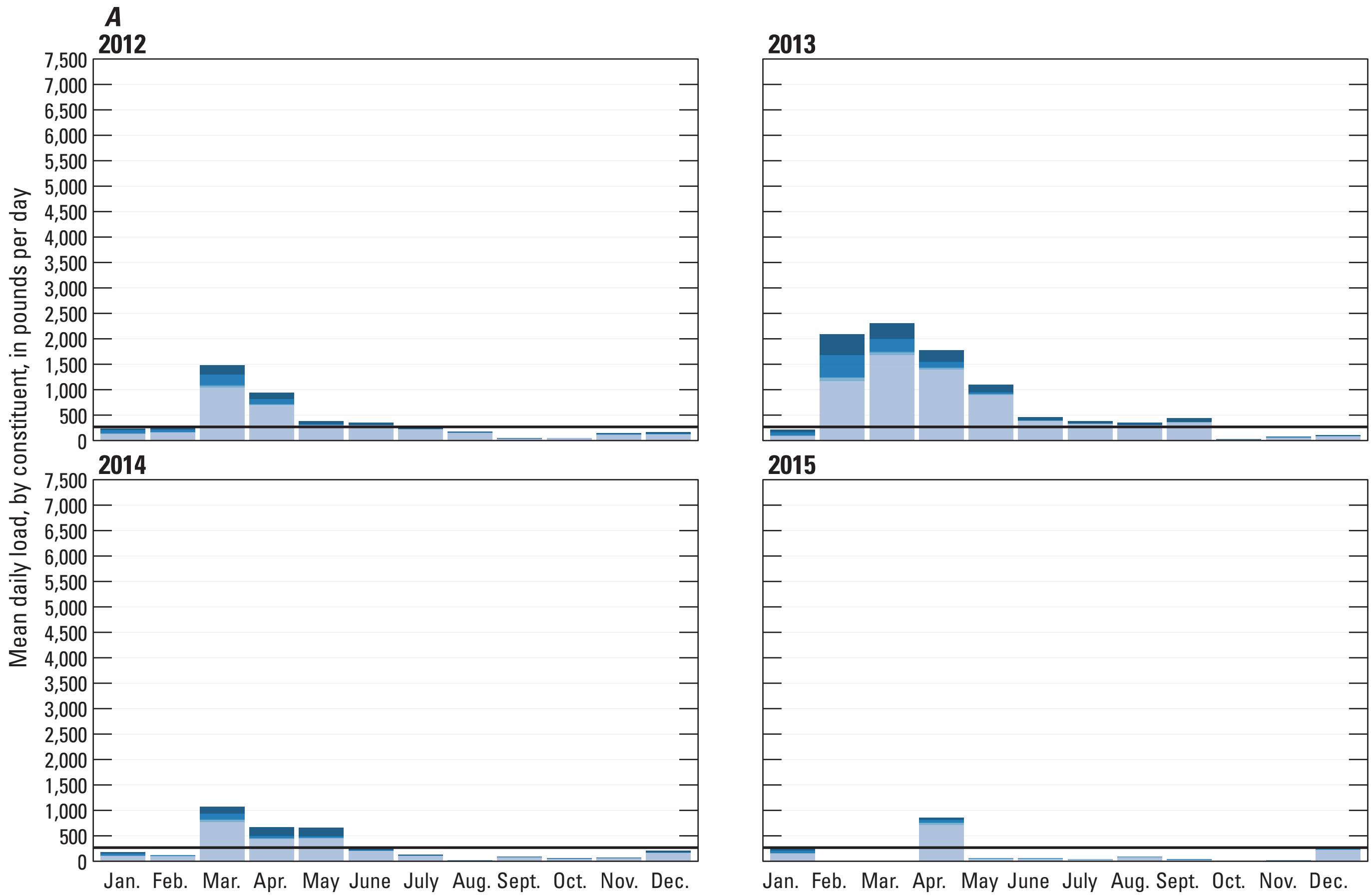
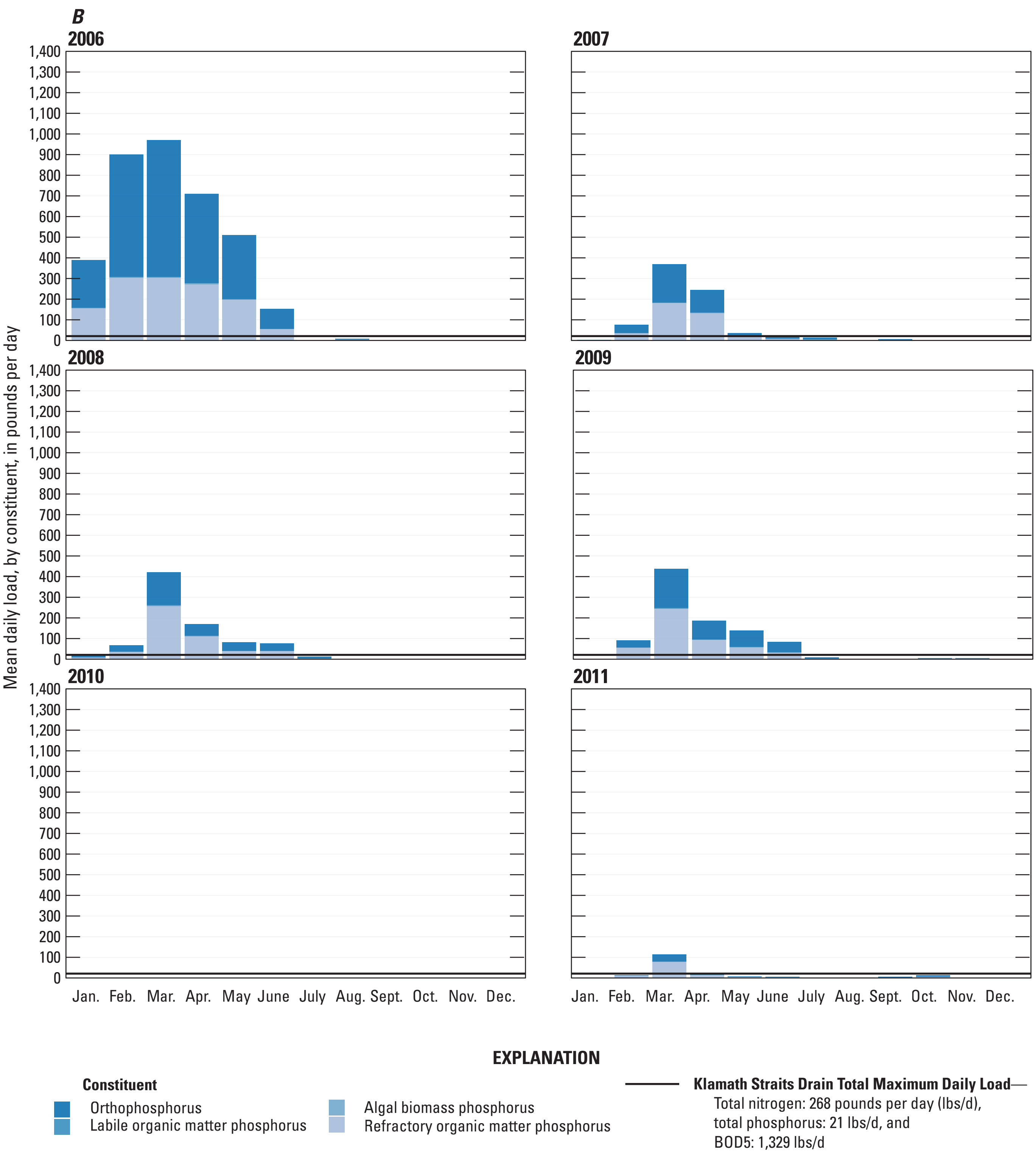


Figure 3.2.—Continued



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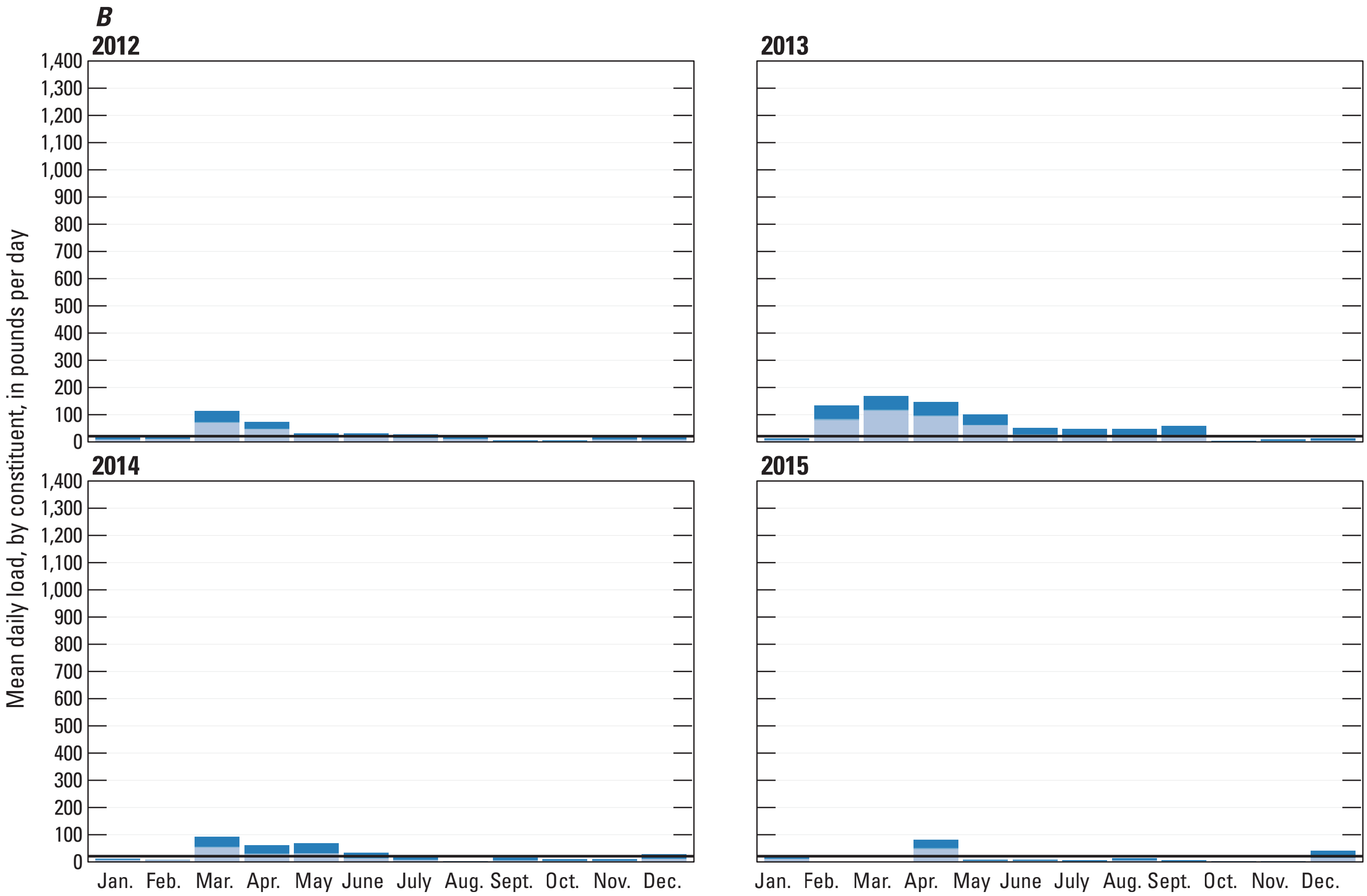

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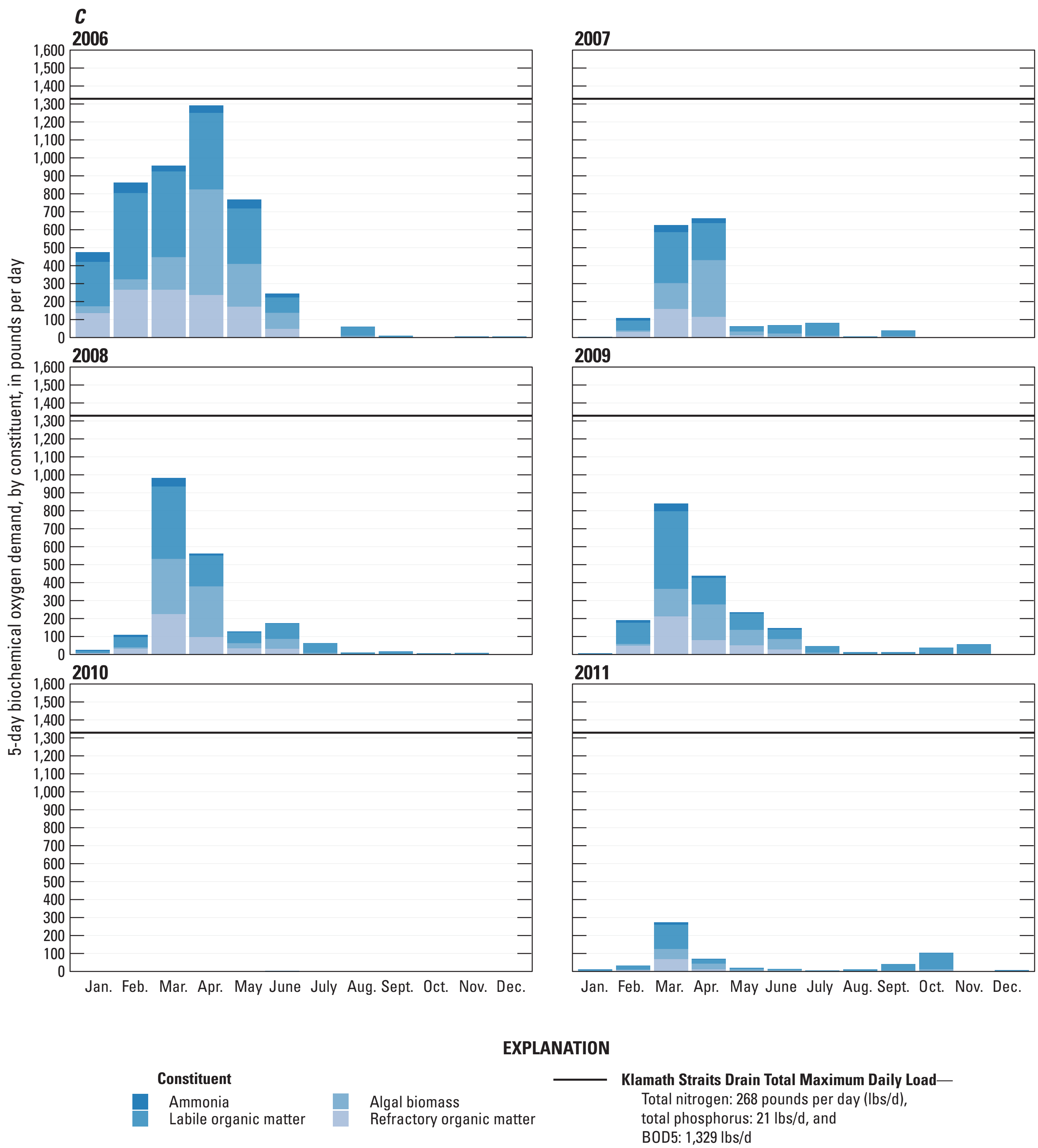

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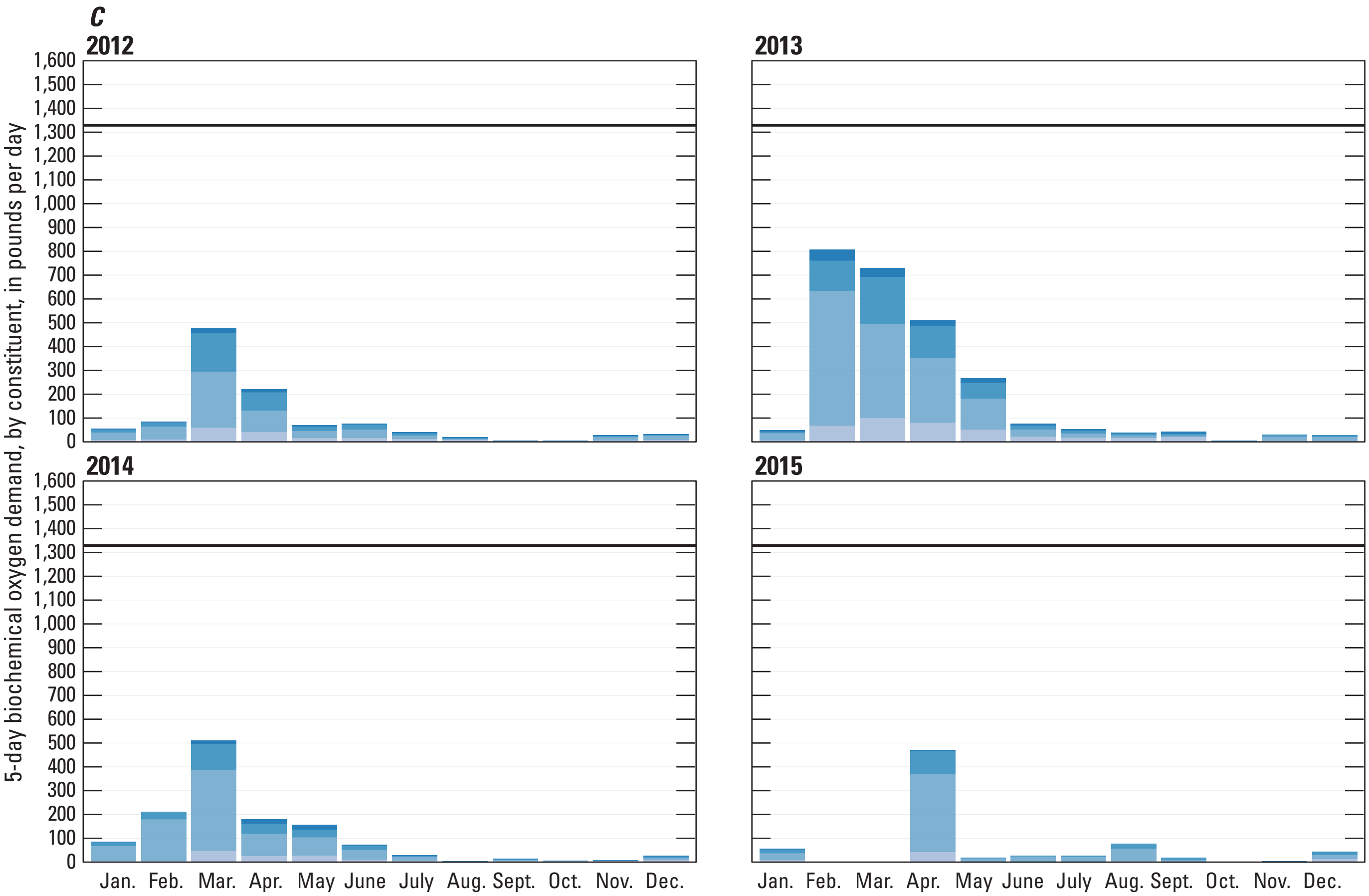

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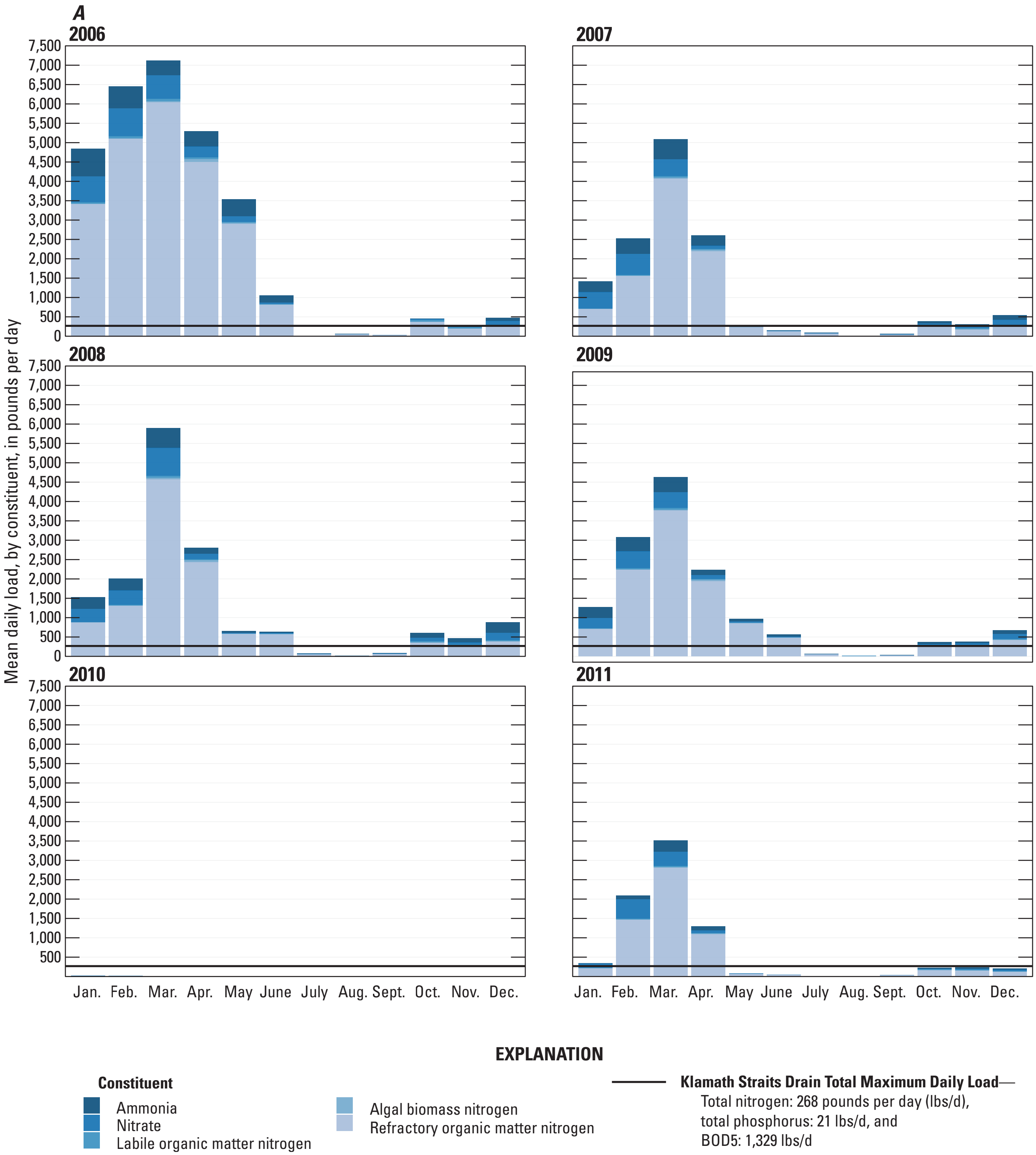
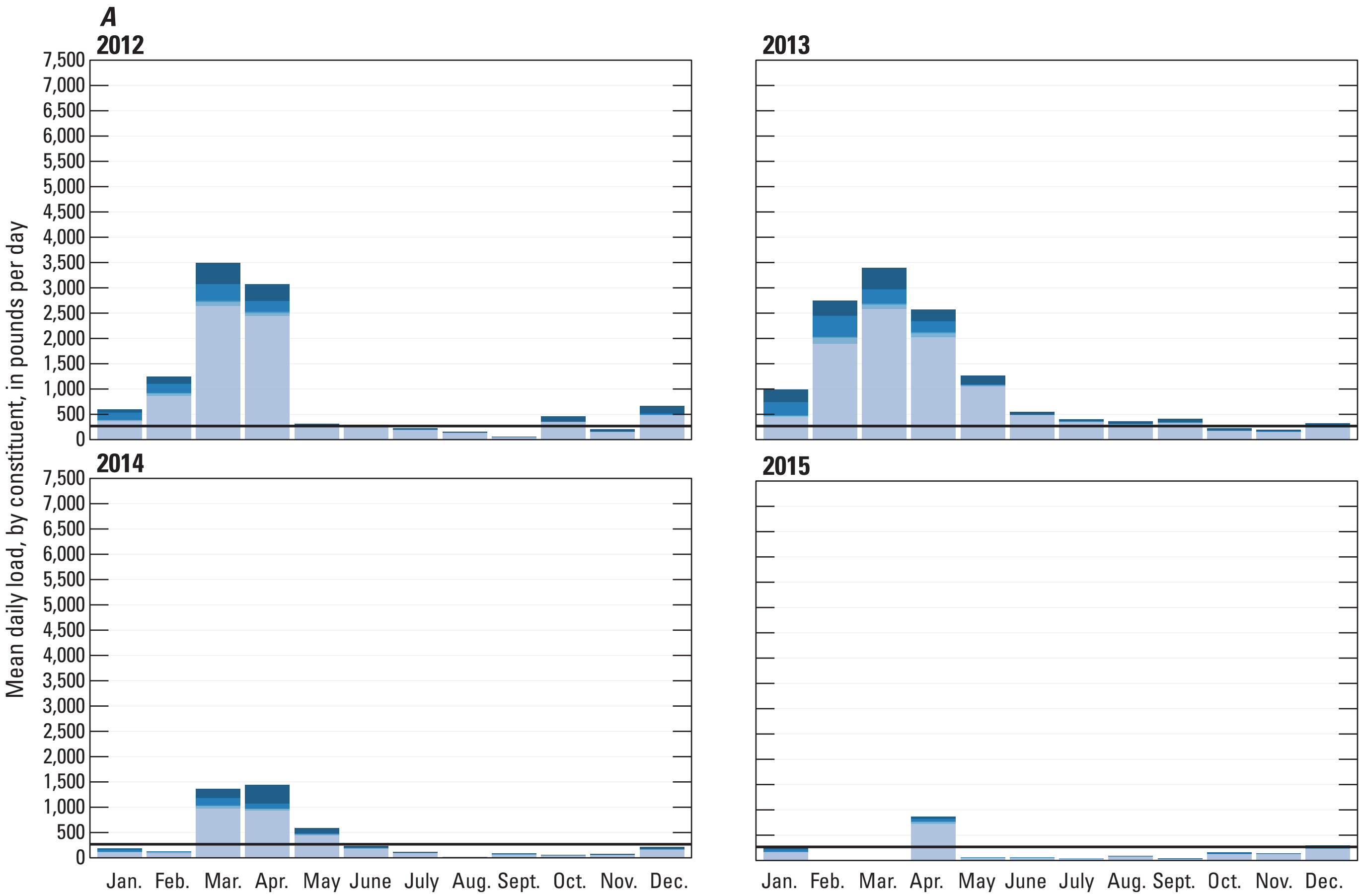


Figure 3.3. Graphs showing Klamath Straits Drain monthly average daily total nitrogen, total phosphorus, and 5-day biochemical oxygen demand (BOD5) loads for each year from 2006 through 2015 for scenario 3, broken up by the individual constituents that compose the total loads. *A*, monthly average daily total nitrogen: ammonia, nitrate, labile organic matter nitrogen, algal biomass nitrogen, and refractory organic matter nitrogen. *B*, monthly average daily total phosphorus: orthophosphorus, labile organic matter phosphorus, algal biomass phosphorus, and refractory organic matter phosphorus. *C*, monthly average daily BOD5: ammonia, labile organic matter, refractory organic matter, and algal biomass. These loads are based on simulated output for the different scenarios, calculated as instantaneous loads and then averaged to either daily, monthly, or annual loads.



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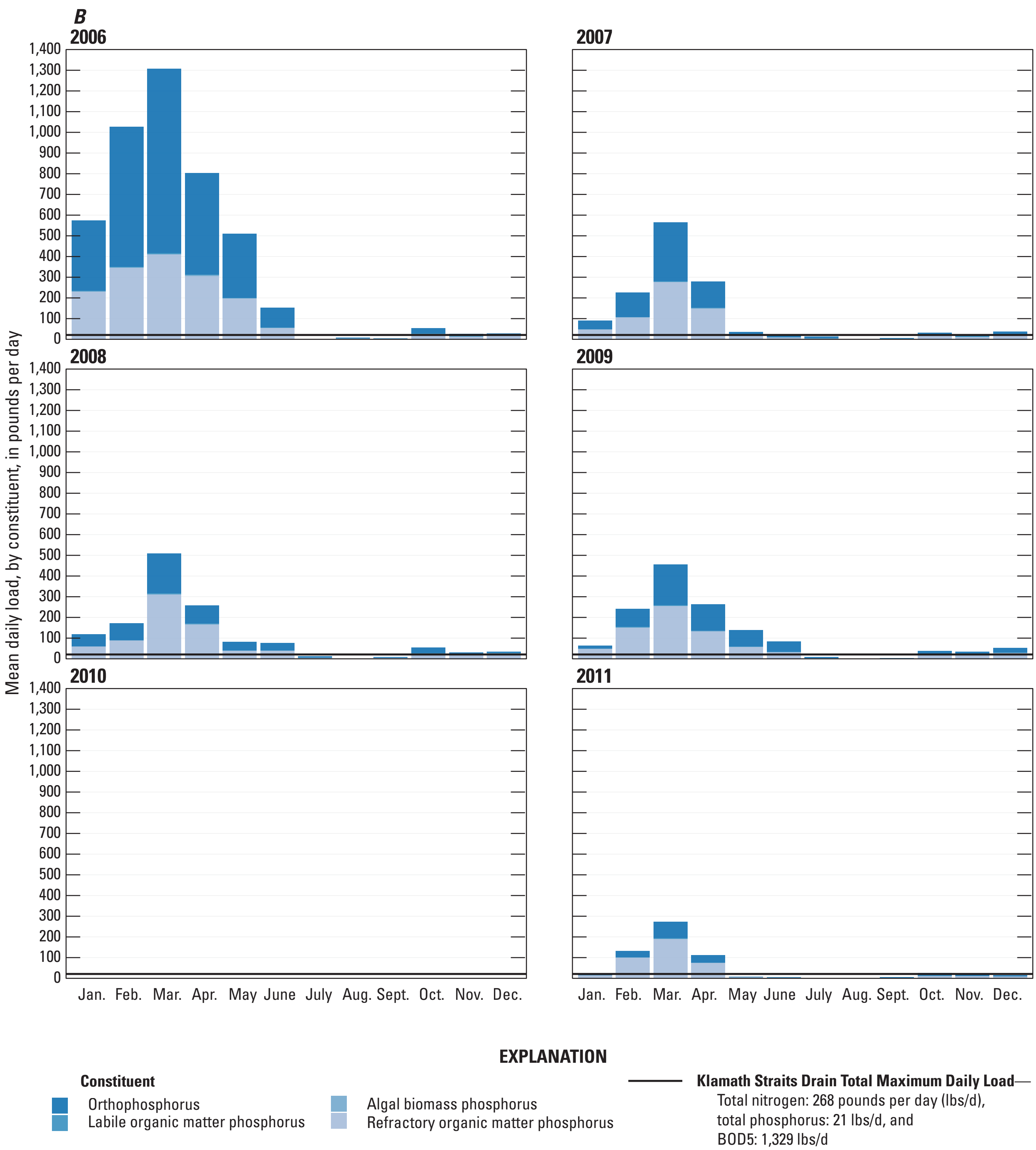

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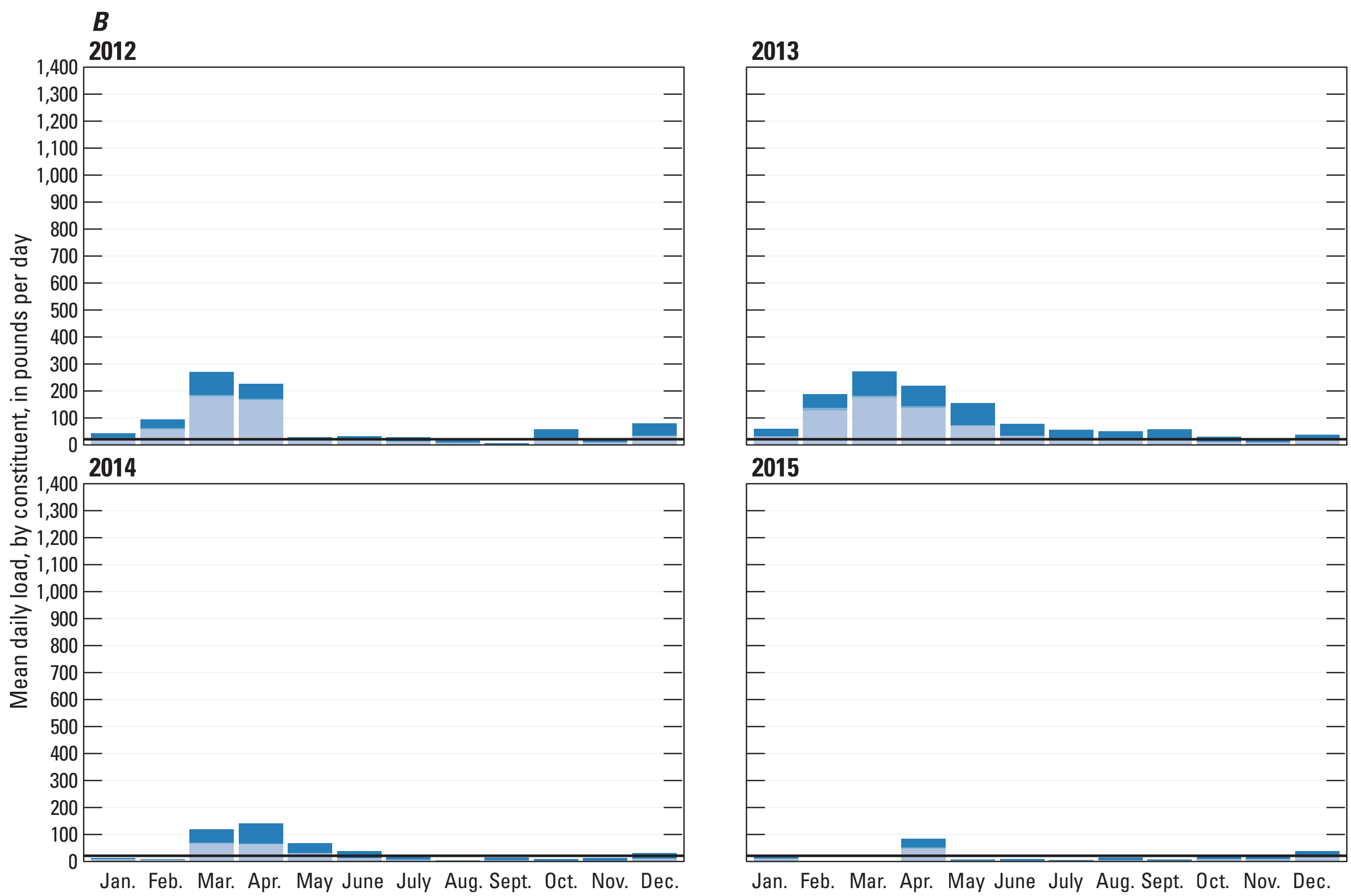

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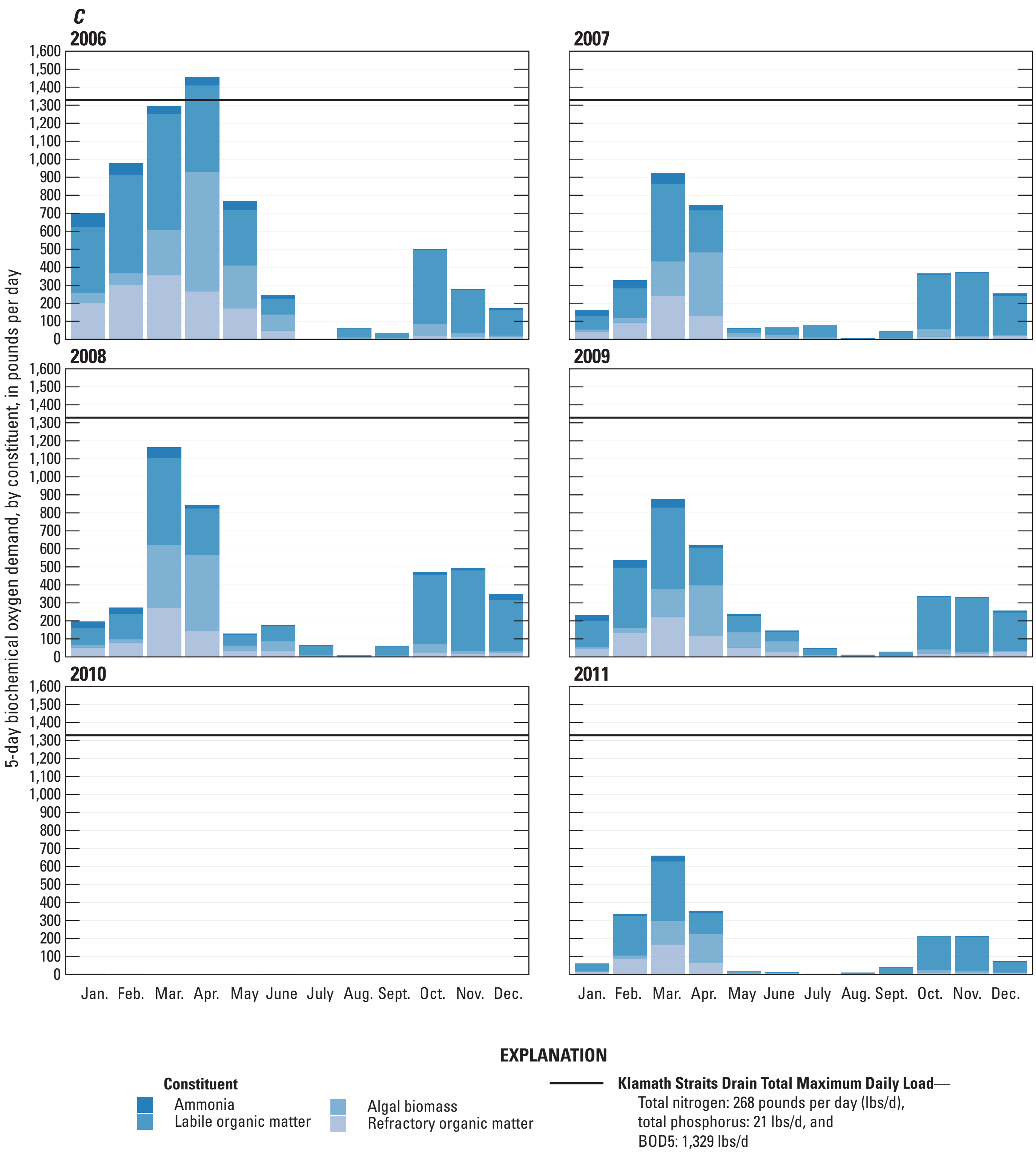

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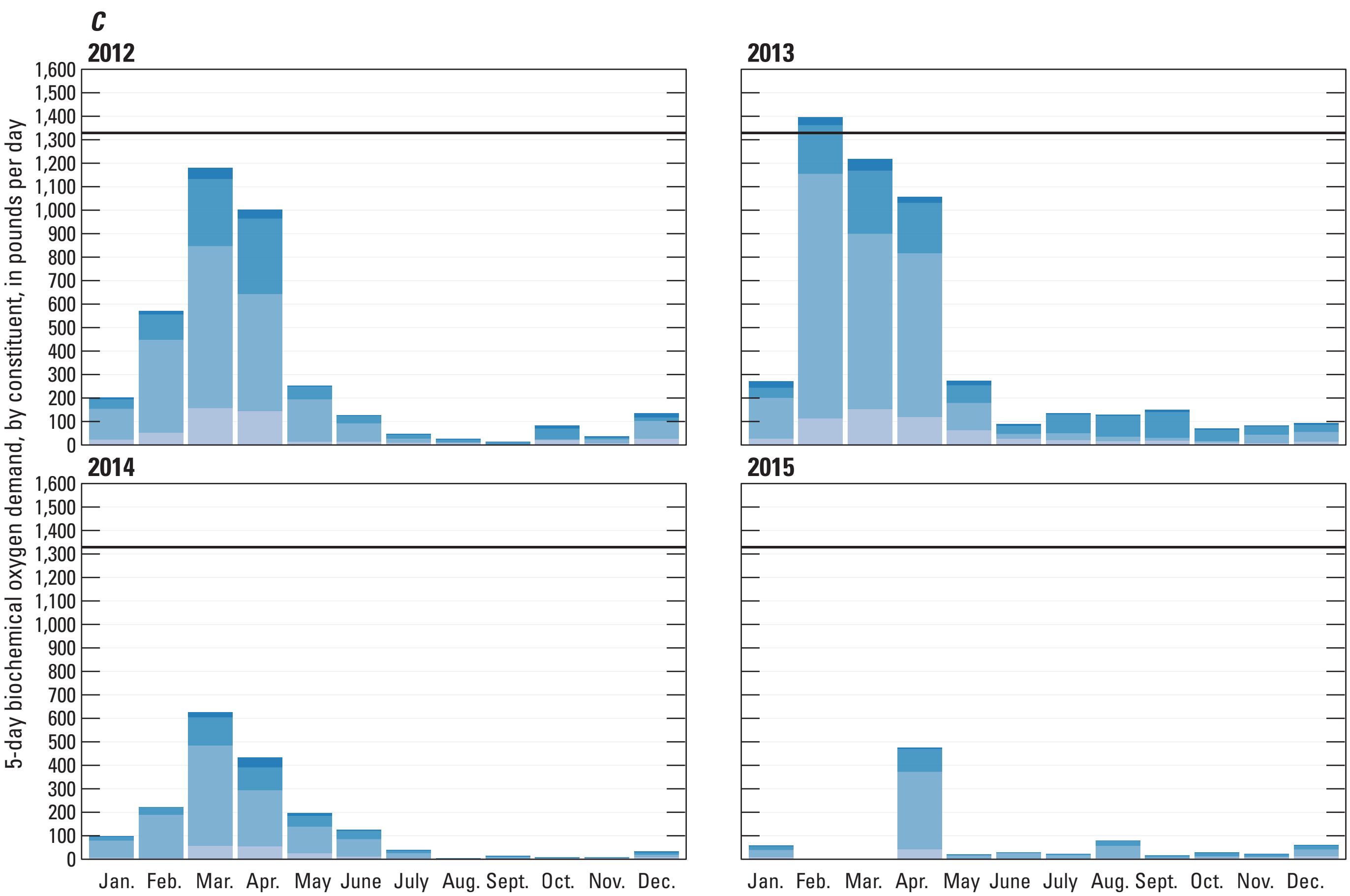

Figure 3.3.—Continued

For more information about the research in this report, contact
Director, Oregon Water Science Center
U.S. Geological Survey
601 SW 2nd Avenue, Suite 1950
Portland, OR 97204
https://www.usgs.gov/centers/oregon-water-science-center

Manuscript approved on May 11, 2023

Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Tacoma Publishing Service Center

Smith and Sullivan—**Modeling Water-Quality Effects to Klamath River from Recirculation in Drains and Canals, Oregon and California, 2006–15**—SIR 2023–5059

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20235059