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Water Quality of a Drained Wetland, Caledonia Marsh on Upper Klamath Lake, Oregon, after Flooding in 2006

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By Mary K. Lindenberg and Tamara M. Wood

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Conversion Factors

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
milliliter (mL)	0.03381	fluid ounce (oz)
liter (L)	1.057	quart (qt)
milligram per liter (mg/L)	1	part per million (ppm)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
microgram per liter (µg/L)	1	part per billion (ppb)
micrometer (µm)	3.937×10^{-5}	inch (in.)

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

$$°F=(1.8×°C)+32.$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to 1 milligram per liter. Milligrams per liter is equivalent to parts per million. Micrograms per liter is equivalent to parts per billion.

Datums

In this report, the term "elevation" refers to distance above the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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Abstract

The unexpected inundation of Caledonia Marsh, a previously drained wetland adjacent to Upper Klamath Lake, Oregon, provided an opportunity to observe nutrient release from sediments into the water column of the flooded area and the resulting algal growth. Three sites, with differing proximity to the levee breach that reconnected the area to Upper Klamath Lake, were selected for water sample collection in the marsh. Chlorophyll *a* concentrations (an indicator of algal biomass) were lowest and dissolved nutrient concentrations were highest at the site farthest from the breach. At the site where chlorophyll *a* concentrations were lowest, dissolved organic carbon concentrations were highest, and the presence of tannic compounds was indicated by the dark brown color of the water. Both DOC and specific conductance was higher at the site farthest from the breach, which indicated less mixing with Upper Klamath Lake water at that site. Dissolved oxygen concentrations and pH were lowest at the beginning of the sampling period at the site farthest from the levee breach, coincident with the lowest algal growth. Phosphorus concentrations measured in the flooded Caledonia Marsh were greater than median concentrations in Upper Klamath Lake, indicating that phosphorus likely was released from the previously drained wetland soils of the marsh when they were flooded. However, a proportional increase in algal biomass was not measured either in the marsh or in the adjacent bay of the lake. Nitrogen to phosphorus ratios indicated that phosphorus was not limiting to algal growth at the marsh sites, and possibly was not limiting in the adjacent bay either. In terms of nutrient dynamics, wetlands normally function as nutrient sinks. In contrast, the drained wetlands around Upper Klamath Lake cannot be expected to provide that function in the short term after being flooded and may, in fact, be a source of nutrients to the lake instead. The consequences for algal growth in the lake, however, seem to be small.

Introduction

On June 7, 2006, Caledonia Marsh, a previously drained wetland, was flooded unintentionally due to a break in the levee on its western border with Upper Klamath Lake, Oregon (fig. 1). Caledonia Marsh was separated from Upper Klamath Lake in 1916 by the construction of a levee around the northern and western boundary of the marsh. Until June 7, Caledonia Marsh was used primarily for agriculture (Snyder and Morace, 1997). In the southeastern corner of Caledonia Marsh, two parcels of land were restored to wetlands in 1997 and 2000 as mitigation for impacts to wetlands from resort development. The name Caledonia Marsh will be referred to as "flooded Caledonia Marsh" for the remainder of this report, where appropriate.

Aerial photographs taken 2 days after the breach reveal the extent of flooding in the marsh (fig. 2). A sediment plume extending out of the marsh and into the lake indicates sediment disturbance at or near the site of the breach (fig. 3). Waters near the inside of the external levee were turbid, indicating sediment disturbance and suspension into the water column. Field crews measured a depth of 8 m at the site of the breach, which indicates deep scouring when floodwaters flowed into the marsh.

Hydrologic Description of Upper Klamath and Agency Lakes

Upper Klamath and Agency Lakes are located in south-central Oregon, in a graben structural valley; the lake basin has a drainage area of 9,842 km². The climate in this valley is semiarid due to the rain-shadow effect of the flanking mountains, which reach an elevation of 2,743 m, and the warm easterly currents moving off the Pacific Ocean from the west (Johnson, 1985). Upper Klamath Lake is a large, shallow lake with a surface area of 232 km². The average and

Bathymetry: Produced by Glen Canyon Environmental Studies
in cooperation with U.S. Bureau of Reclamation, Mid-Pacific
Region, Klamath Basin Area Office, and the Klamath Tribes.
Digital Raster Graphics and Elevation: Produced by U.S.
Geological Survey, various scales. Projection: UTM, Zone 10
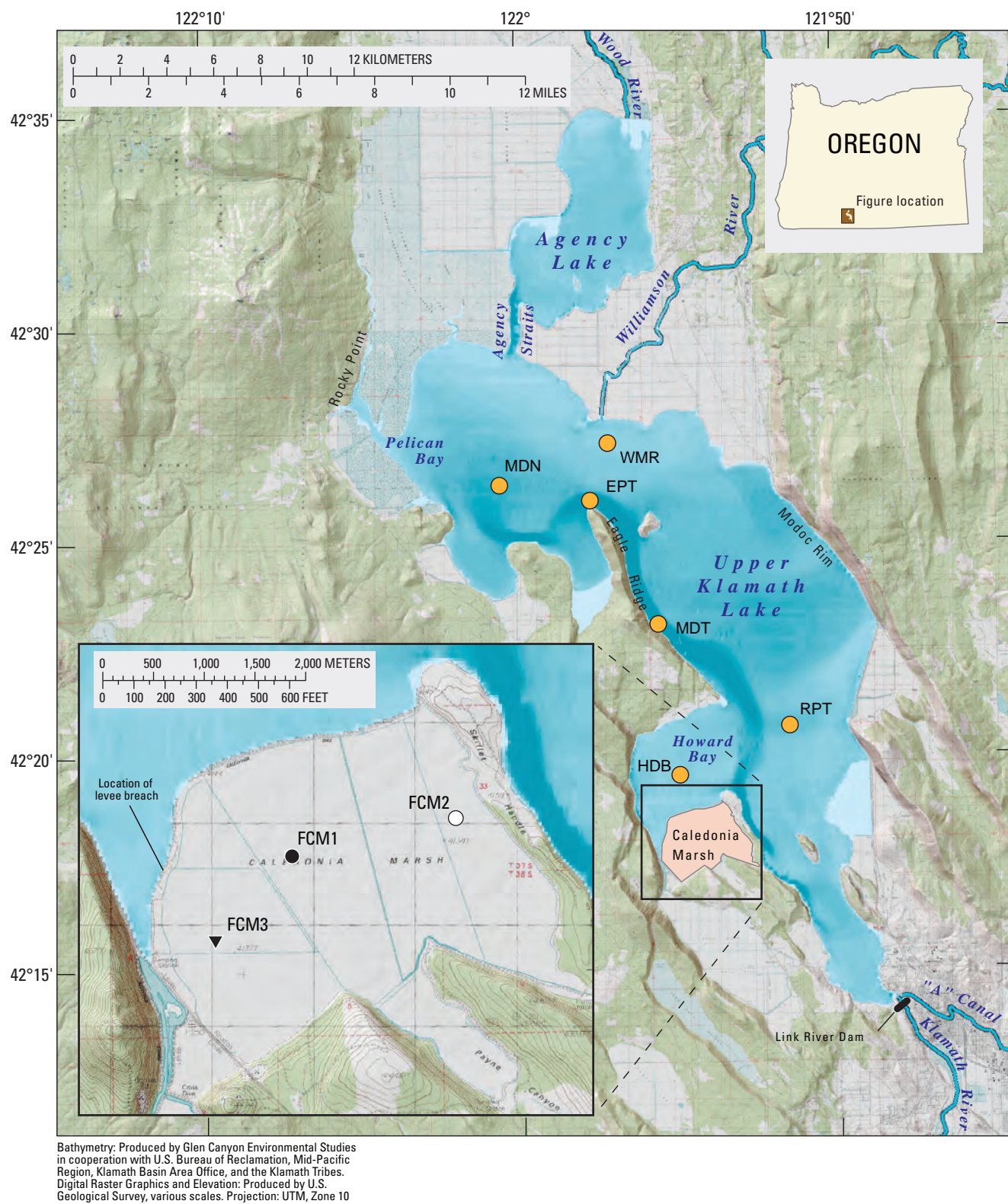
Figure 1.   Map showing location of flooded Caledonia Marsh and water quality sampling sites, Upper Klamath Lake, Oregon, 2006

Figure 2.   Photograph showing flooding in Caledonia Marsh, Upper Klamath Lake, Oregon, June 9, 2006

maximum lake depths are 2.8 and 15 m, respectively. Agency Lake, which has a surface area of 38 km², is connected to the northern part of Upper Klamath Lake through Agency Straits. Inflows to the lakes include the Wood River to Agency Lake, the Williamson River to Upper Klamath Lake, and spring sources at various locations, specifically from Pelican Bay and from the eastern shore near Modoc Rim (fig. 1). Upper Klamath Lake outflows to the Link River, which was dammed in 1921. The Link River Diversion Dam controls the lake to a maximum elevation of 1,263.4 m and provides water for the Bureau of Reclamation's Klamath irrigation project by diverting flow from the Link River into the "A" canal.

Upper Klamath Lake is home to two species of endangered fish, the Lost River sucker (*Deltistes luxatus)* and the shortnose sucker (*Chasmistes brevirostris*). Historically, Upper Klamath Lake was eutrophic, but an increase in monocultural blooms of *Aphanizomenon flos-aquae*, a blue-green alga (Phinney and Peek, 1960; Kann, 1998), has been linked to changes in the basin. Human activities, such as the severance and drainage of wetlands adjacent to the lake and water-control and diversion practices (Bradbury and others, 2004; Eilers and others, 2004), resulted in hypereutrophic conditions that contributed directly and indirectly to the decline of endangered suckers (Perkins and others, 2000; Banish and others, 2007).
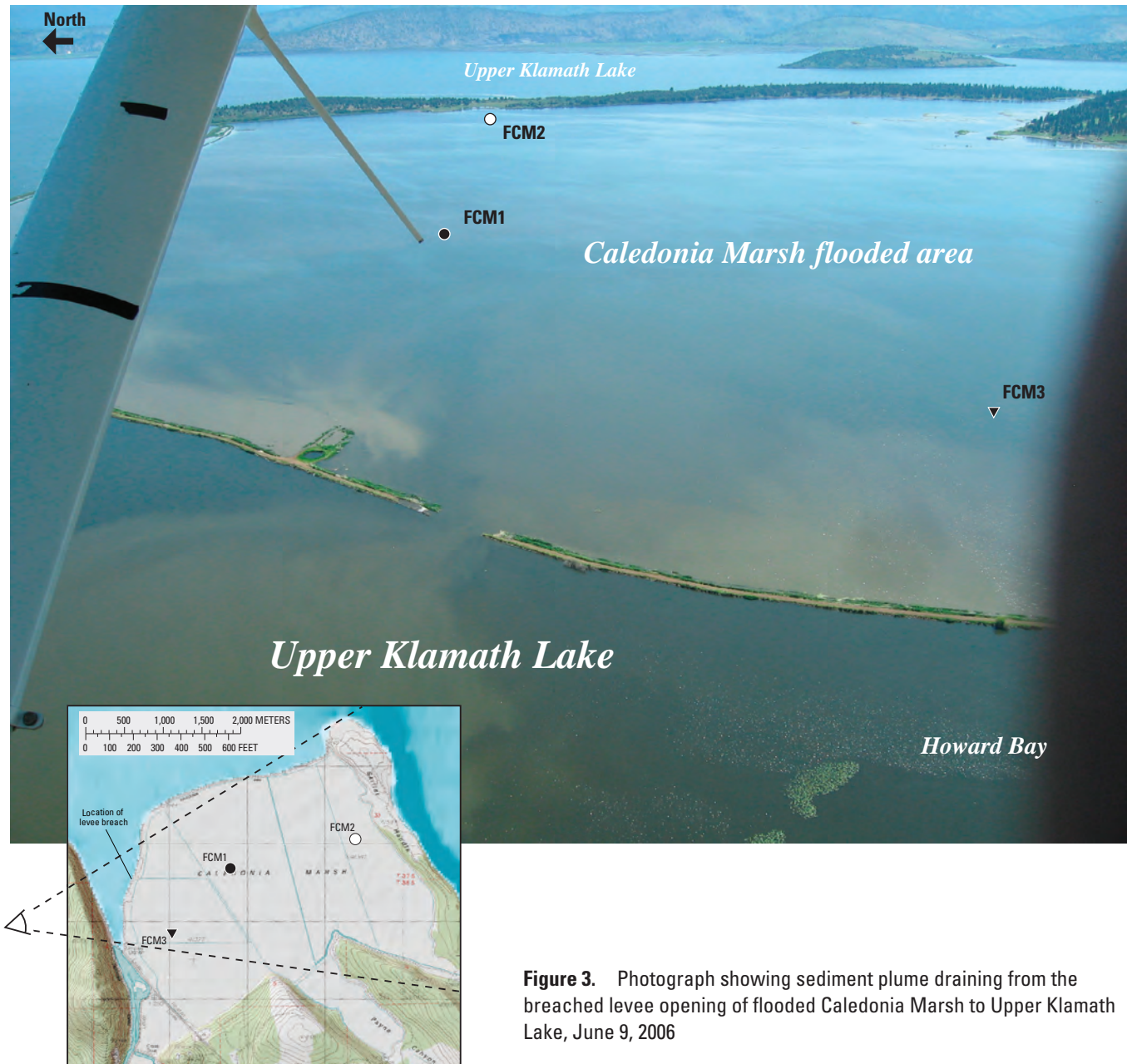
Figure 3. Photograph showing sediment plume draining from the breached levee opening of flooded Caledonia Marsh to Upper Klamath Lake, June 9, 2006

Wetlands Around Upper Klamath and Agency Lakes

Wetlands have been identified as key to nutrient cycling dynamics, in addition to providing food and habitat for birds and fish. They can act as nutrient sinks before water is released downstream to rivers, lakes, and oceans (Carter, 1996; Novitzki and others, 1996). Constructing wetlands, in particular swamps and marshes, may be a viable way to reduce nitrogen and phosphorus loads to a hydrologic system

(Reuter and others, 1992; Guardo and others, 1995), although the efficiency of nutrient reduction is debatable depending on the hydrodynamics of the system and wetland type (Bullock and Acreman, 2003; Fisher and Acreman, 2004; McCormick and Campbell, 2007). Wetlands that are drained tend to undergo accelerated decomposition and land subsidence (Kentula, 1996). The exposed soils are subject to aerobic microbial activity accelerating the decomposition of organic matter and mobilizing nutrients previously held by peat soils.

This decomposition is greater at higher temperatures and in agricultural lands that undergo tillage, which breaks the soil surface and increases air and oxygenated water penetration into the soils (Maciak, 1972). Subsidence occurs as pore water leaves the pore spaces and allows air to replace water in the pores. Because the compressibility of air is greater than the compressibility of water, sediments become compacted by the overlying weight and subsidence occurs. Decompositional processes that oxidize organic materials in these soils also result in subsidence (Stephens, 1956; Mulqueen, 1986).

The draining of wetlands around Upper Klamath Lake likely had an affect on nutrient dynamics in the system (Miller and Tash, 1967; Bortleson and Fretwell, 1993; Snyder and Morace, 1997; Rykbost and Charlton, 2001). Historically, 162 km^2 of wetland habitat surrounded Upper Klamath and Agency Lakes (fig. 4). Between 1889 and 1971, 57 percent of those wetlands were drained for cattle grazing or crop cultivation (Snyder and Morace, 1997). One approach being implemented to restore the functional ecology of the lake is to breach the levees separating these drained wetlands from the lake. By 2001, the 12 km^2 Wood River property was restored to wetland habitat, thereby increasing the area of undrained wetland to 49 percent of the historical total. In 1998, 29 km^2 at Agency Lake Ranch was converted from a previously drained wetland for cattle grazing to a water-storage area, where water is impounded between October and July and pumped to low water levels from July to October depending on the climate in a particular year (Damien Ciotti, Bureau of Reclamation, oral commun., 2007). Agency Lake Ranch was expanded in 2005 to include an additional 11 km^2 at Barnes Ranch. Although Agency Lake Ranch and Barnes Ranch were not restored to a typical vegetated wetland habitat, the area that was flooded is more likely to attract wetland plants and animals as water storage than as a cattle ranch.

The Williamson River Delta area, which is owned by The Nature Conservancy, is another large wetland restoration project (fig. 4). On October 30, 2007, about 19 km^2 of previously reclaimed wetland west of Williamson River was reconnected to Upper Klamath and Agency Lakes by breaching several levees at the northern end of Upper Klamath Lake and the eastern shore of Agency Lake. In the future, about 11 km^2 on the eastern side of the Williamson River will be flooded to complete the restoration of the Williamson River Delta to historical conditions. In the long term, the reconnection of these wetlands is expected to provide benefit in terms of restored habitat for larval and juvenile suckers, as well as the eventual restored function of nutrient sequestration. Reflooding previously drained wetland areas also should slow the process of nutrient release that occurs when the peat

soils exposed to the air by draining are oxidized (Snyder and Morace, 1997). In the short term, however, reflooding these reclaimed wetlands that have been in agricultural use may act as a source of nutrients to the lake (Aldous and others, 2005).

The unexpected flooding of Caledonia Marsh provided an opportunity to collect data that will help to quantify the load of nutrients that might be expected when other reclaimed wetlands are flooded. The nutrient loads from Caledonia Marsh are particularly relevant to the reflooding of previously drained wetlands on which the land use was similar to that on the flooded Caledonia Marsh—largely grain and vegetable crop cultivation. Other reclaimed wetlands surrounding UKL that were used for grain and vegetable crops include the recently reflooded Williamson River Delta. The reflooded wetlands of the Wood River, Barnes Ranch, and Agency Lake Ranch were historically used for cattle grazing, and the nutrient loads from Caledonia Marsh may be less comparable to the nutrients loads from those wetlands.

Purpose and Scope

The purpose of this report is to characterize and compare nutrient and chlorophyll *a* concentrations, and water quality parameters in the flooded Caledonia Marsh for several months immediately after flooding. Results of the water quality sampling among the three sites in the marsh and between the marsh and the lake are compared. The results of this study will help to understand the water quality dynamics of flooded, previously drained wetlands and to facilitate the restoration of wetlands.

Flooded Caledonia Marsh and Upper Klamath Lake Water Quality Sampling Sites

Sampling at three sites in flooded Caledonia Marsh (fig. 1) started on June 21, 2006, 2 weeks after the breach, and continued until September 11, 2006, when water levels dropped too low to allow boat access to sites. Water column depths were 2.5, 2.1, and 2.7 m at sites FCM1, FCM2, and FCM3, respectively at the start of sampling, and were lower by approximately 1 m by September 11, 2006. Site locations were chosen to cover an even spatial distribution of the flooded Caledonia Marsh area, and to provide samples from within each of the submerged internal levees. Site FCM2, farthest to the east, was near an internal levee covered by apparent noncultivated vegetation on the periphery of cropland, while sites FCM1 and FCM3 were on cropland with no apparent vegetation growth at that time. All three sites
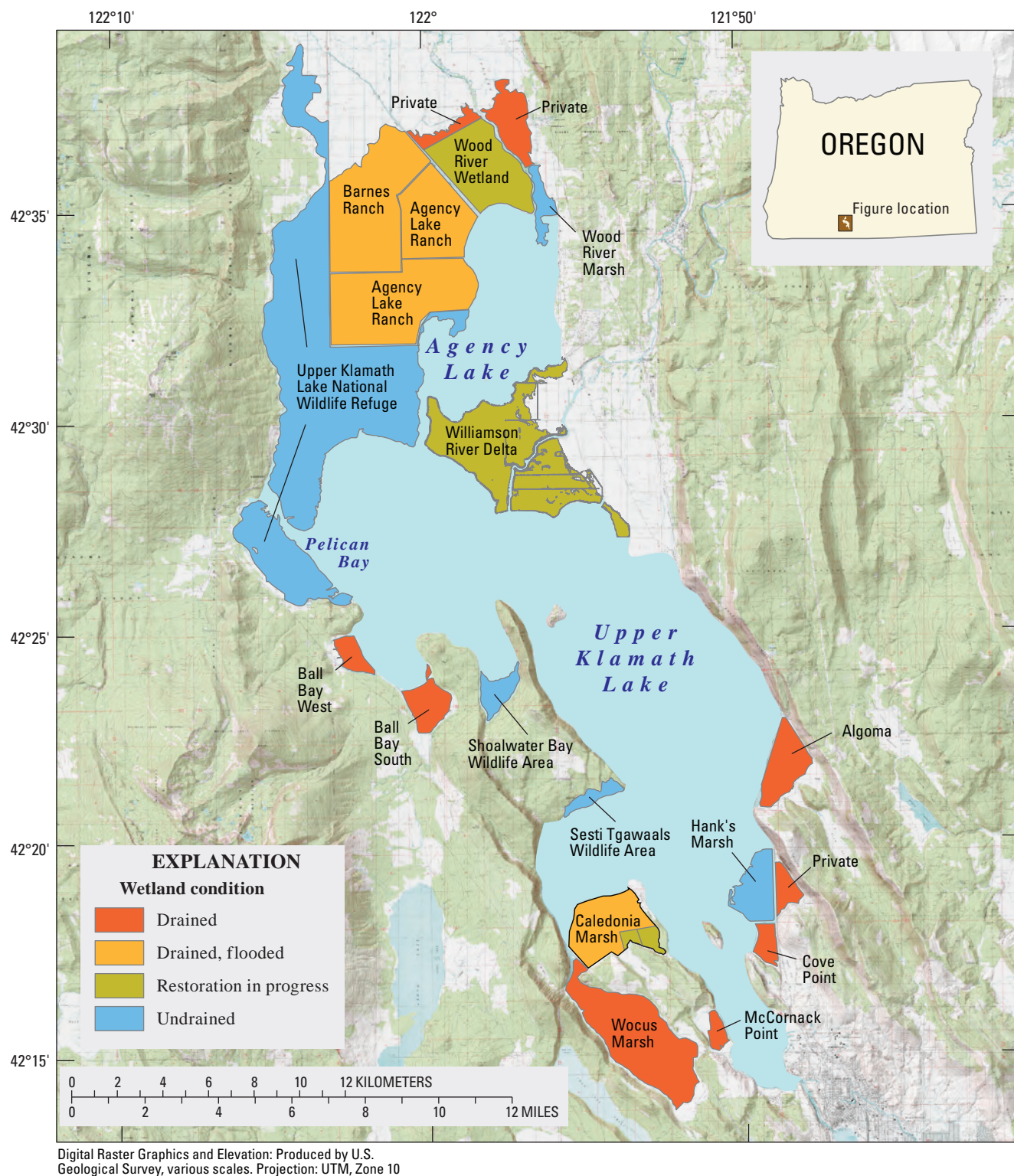
Figure 4.   Map showing wetlands surrounding Upper Klamath and Agency Lakes, Oregon, 2006

were on or near areas farmed for grain (Jon Barkee and Jeff Woolworth, Running Y Ranch., Klamath Falls, oral commun., 2007), although it is not likely that there was much growth at the time of the levee breach. Sites FCM1 and FCM3 were closest to the breach, at a distance of about 1.3 and 0.9 km, respectively. Site FCM1 was separated from the breach by one submerged internal levee. Site FCM2 was farthest from the breach, at a distance of about 2.9 km, and was separated from

the breach by three submerged internal levees (fig. 5). Site FCM2 also was closest to an area of restored wetlands in the southeastern corner of the marsh.

Through a long-term monitoring program, water samples were collected concurrently at six sites (MDN, WMR, RPT, HDB, MDT, and EPT) in Upper Klamath Lake (fig. 1). Although these sites are referred to herein, the data from the lakewide sites are discussed in Lindenberg and others (2009).
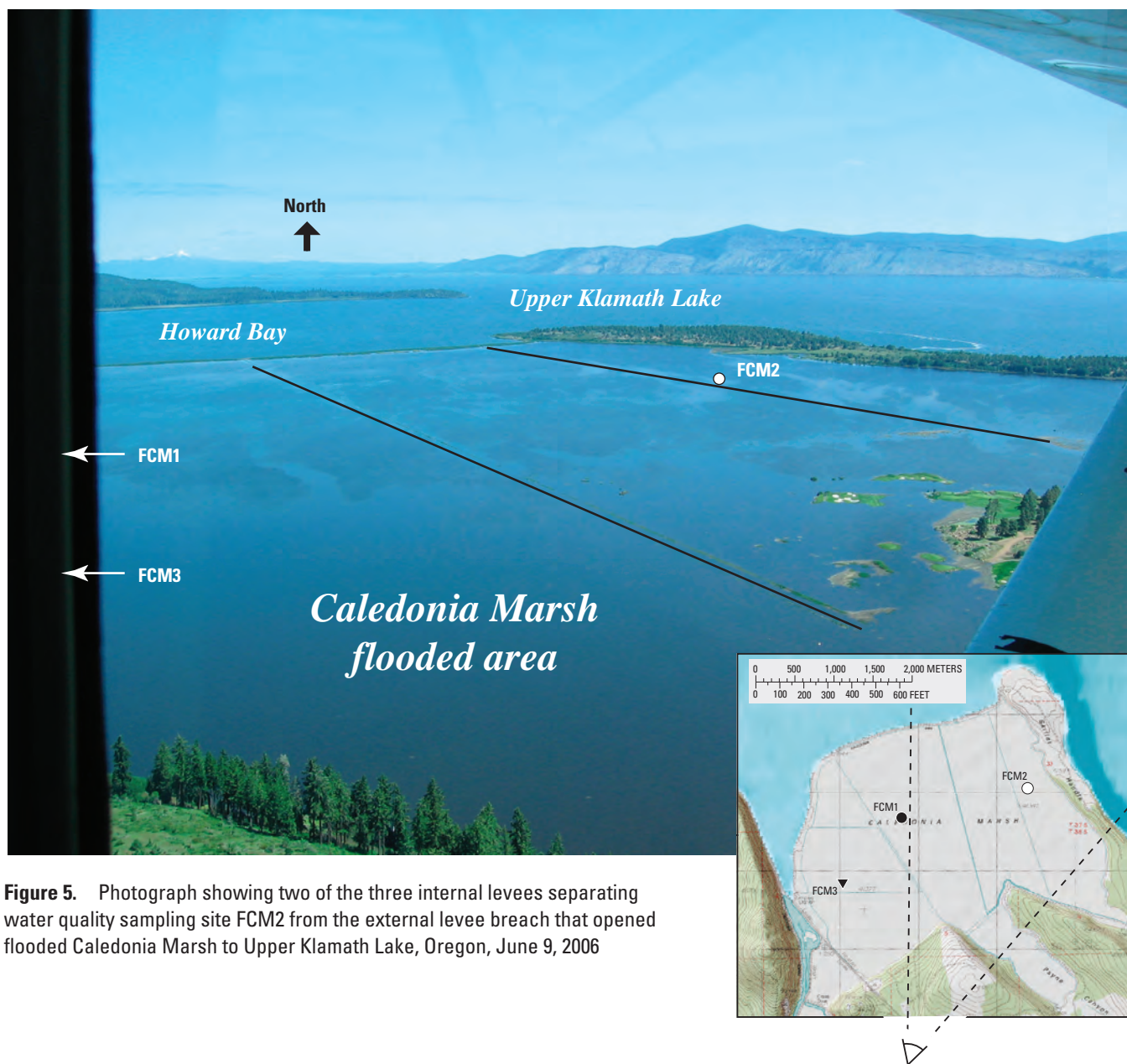
Figure 5.   Photograph showing two of the three internal levees separating water quality sampling site FCM2 from the external levee breach that opened flooded Caledonia Marsh to Upper Klamath Lake, Oregon, June 9, 2006

Methods

Water Quality Data Collection

Water samples were collected weekly according to established collection and quality control protocols (U.S. Geological Survey, 1997 to present). The results of the quality-assurance data associated with these samples are discussed in the appendix A. Water quality monitors were used at the time of sample collection to measure instantaneous water temperature, dissolved oxygen, pH, and specific conductance. Calibrations and data handling were performed according to techniques described by Wagner and others (2006). Finalized data are stored in the USGS National Water Information System database and can be accessed at http://waterdata.usgs.gov/nwis.

Samples were collected in two ways: (1) as a depth-integrated sample (to reduce bias of constituents that are variable with depth) for the analysis of constituents in unfiltered water, or (2) as a point sample for the analysis of constituents in filtered water. The depth-integrated samples were collected with a weighted cage that was lowered at a constant rate into the water to 0.5 m from the bottom. For the collection of samples analyzed for total phosphorus, total nitrogen, and chlorophyll *a*, the weighted cage was outfitted with two 1-L bottles. Each bottle had two small ports, one for water to flow in and one for the escape of displaced air. The contents of the bottles from multiple descents of the cage sampler were combined in a churn splitter. Total phosphorus and total nitrogen samples were preserved with 1 mL of 4.5 normal sulfuric acid and chilled until they were sent to the National Water Quality Laboratory (NWQL) for analysis. Chlorophyll *a* samples were filtered onto glass fiber filters, frozen, and sent on dry ice to NWQL. For the collection of samples analyzed for total particulate carbon, total particulate nitrogen, total inorganic carbon, and total organic carbon, the weighted cage was outfitted with a 1-L amber glass bottle. After filling, the amber bottle was capped and chilled on ice until processing. Samples were filtered using the vacuum-filtration method described by U.S. Geological Survey (1997 to present) before they were sent to NWQL for analyses.

The point samples were collected by lowering one end of a hose to mid-depth in the water column and then pumping the water through a 0.45 μm capsule filter. This filtered water was collected into a 125-mL brown polyethylene bottle that was chilled and sent to NWQL for the analysis of ammonia, orthophosphate, and nitrite-plus-nitrate. The sample for the analysis of dissolved organic carbon (DOC) was collected into a 125-mL baked amber glass bottle, preserved with 1 mL of 4.5 normal sulfuric acid, and chilled until it was sent to NWQL.

Statistical Methods

All statistical analyses were run using nonparametric methods, like the Spearman rank correlation, which was applied using Sigmaplot for Windows, version 10.0 (Systat Software, Inc., San Jose, Calif.). Analysis of variance (ANOVA) tests were applied using the Tukey studentized range test for differences in the means on rank-transformed data, and were run using SAS System for Windows™, release 9.1.3 (SAS Institute, Inc., Cary, N.C.).

Water Sample and Instantaneous Water Quality Monitor Data Results

Water sample collection started on June 21 at site FCM1 and on June 28 at sites FCM2 and FCM3, and continued on a weekly basis until the final sample collection on September 11, 2006. Samples were collected on 11 dates at site FCM1 and 10 dates at sites FCM2 and FCM3. Concentrations of chlorophyll *a* and total nutrients trended upward through the summer from the lowest value on the first sampling date in June to the highest value on variable dates in August at each site (fig. 6). With the exception of total phosphorus, the concentrations of total nutrients and chlorophyll *a* were consistently lower at site FCM2 than at sites FCM1 and FCM3. Chlorophyll *a* ranged from a low of 3 μg/L at site FCM2 on June 28 to a high of 189 μg/L at site FCM3 on August 23 (table 1); total particulate nitrogen ranged from a low of 90 μg/L at site FCM1 on June 21 to a high of 2,890 μg/L at site FCM3 on August 9; total nitrogen ranged from a low of 1,000 μg/L at site FCM1 on June 21 to a high of 4,940 at site FCM3 on September 11; total particulate carbon ranged from a low of 500 μg/L at site FCM1 on June 21 to a high of 15,487 μg/L at site FCM3 on September 11; total phosphorus ranged from a low of 89 μg/L at site FCM1 on June 21 to a high of 530 μg/L at sites FCM2 and FCM3 on August 23 and August 9, respectively.

Dissolved nutrient concentrations were more variable in the timing and location of maximum and minimum values than chlorophyll *a* and total nutrient concentrations. Orthophosphate concentrations increased slightly over the course of the summer until early August and then decreased (fig. 7); during most of the summer the concentrations at site FCM2 were greater than at sites FCM1 and FCM3. Ammonia and nitrite-plus-nitrate concentrations were greater at site FCM2 than at sites FCM1 and FCM3 until early August for ammonia and late August for nitrite-plus-nitrate. DOC concentrations increased steadily at all sites from June 28

Table 1.   Minimum, maximum, and median values of chlorophyll *a*, total particulate nitrogen, total nitrogen, total particulate carbon, total phosphorus, orthophosphate, ammonia, dissolved organic carbon, nitrite-plus-nitrate, dissolved oxygen, pH, and specific conductance at sites FCM1, FCM2, and FCM3, flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006.

[**Abbreviations:** μg/L, microgram per liter; μS/cm, microsiemen per centimeter; mg/L, milligram per liter]

Analyte	Site								
	FCM1			FCM2			FCM3		
	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median
Chlorophyll *a* (μg/L)	169	4	71	78	3	18	189	27	91
Total particulate nitrogen (μg/L)	2,270	90	1,080	1,410	230	400	2,890	200	1,925
Total nitrogen (μg/L)	3,950	1,000	2,840	2,970	1,590	2,305	4,940	1,230	3285
Total particulate carbon (μg/L)	12,800	500	5,500	8,400	1,200	2,100	15,487	1,100	11,700
Total phosphorus (μg/L)	480	89	380	530	280	380	530	154	400
Orthophosphate (μg/L)	216	59	177	354	126	272	222	72	179
Ammonia (μg/L)	158	6	20	369	13	118	191	15	23
Nitrite-plus-nitrate (μg/L)	74	8	16	126	16	27	29	8	16
Dissolved organic carbon (μg/L)	20,800	9,500	16,700	22,900	13,500	21,100	21,600	10,900	18,266
Dissolved oxygen (mg/L)	11.73	6.50	8.10	10.12	2.90	5.10	13.21	4.40	7.83
pH	9.34	7.60	8.50	8.85	7.07	7.55	9.24	7.50	8.50
Specific conductance (μS/cm)	214	131	193	273	180	253	223	141	209

through September 11—when sample collection ended—and concentrations at site FCM2 were greater than sites FCM1 and FCM3 (table 1). Orthophosphate ranged from a low of 59 μg/L at site FCM1 on June 21 to a high of 354 μg/L at site FCM2 on August 9; ammonia ranged from a low of 6 μg/L at site FCM1 on July 12 to a high of 369 μg/L at site FCM2 on June 28; nitrite-plus-nitrate ranged from a low of 8 μg/L at sites FCM1 and FCM3 on August 16 to a high of 126 μg/L at site FCM2 on August 9; DOC ranged from a low of 9,500 μg/L at site FCM1 on June 21 to a high of 22,900 μg/L at site FCM2 on September 6.

For most sampling dates, dissolved oxygen concentrations and pH were lower and specific conductance concentrations were greater at site FCM2 than at sites FCM1 or FCM3 (fig. 8, table 1), and the overall trend in these three variables was increasing through the summer at all three sites. Dissolved oxygen conentrations ranged from a low of 2.90 mg/L at site FCM2 on June 28 and July 12 to a high of 13.21 mg/L at site FCM3 on September 6; pH ranged from a low of 7.07 at site FCM2 on July 17 to a high of 9.34 at site FCM1 on September 11; specific conductance values ranged from a low of 131 μS/cm at site FCM1 on June 21 to a high of 273 μS/cm at site FCM2 on September 6.
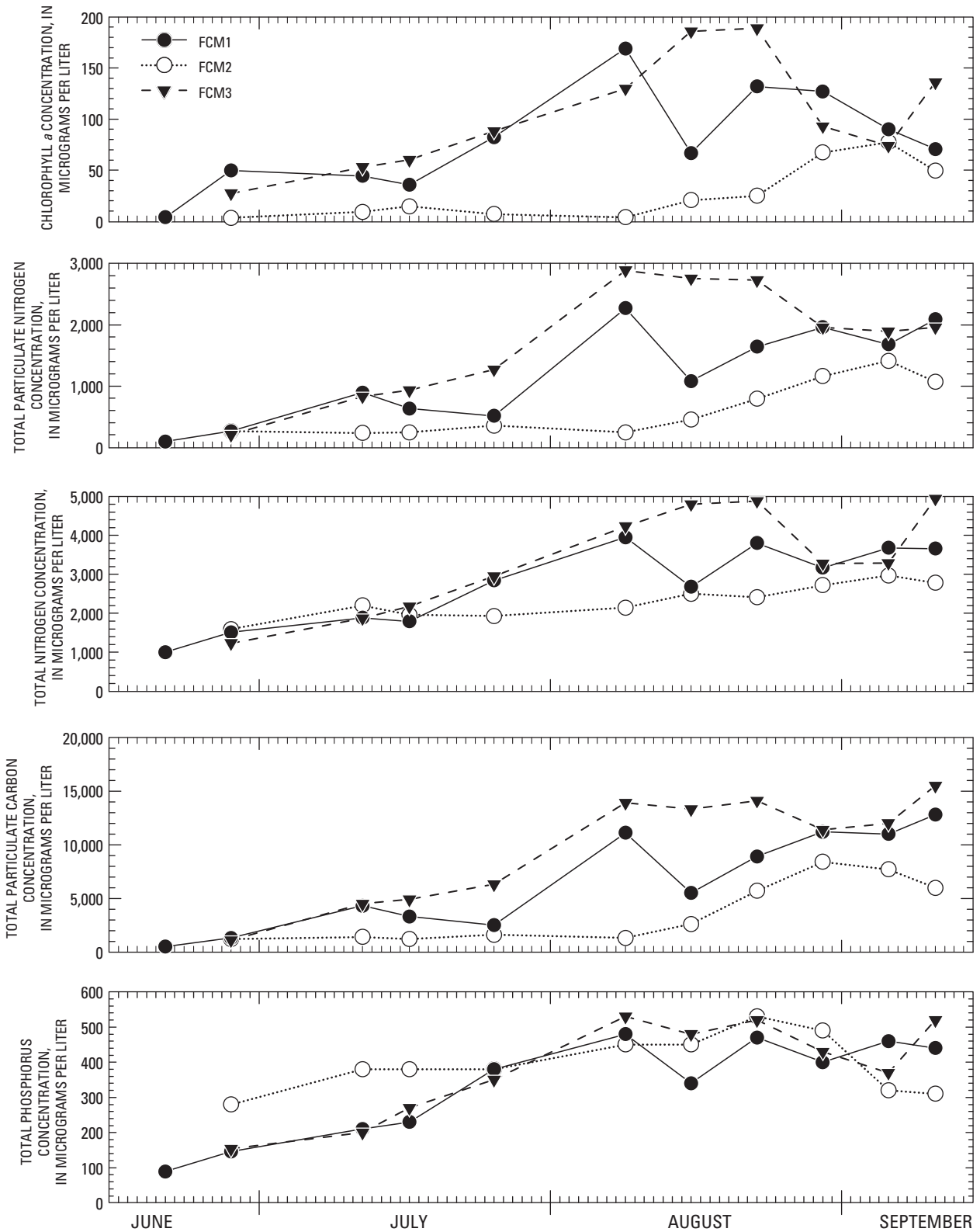
Figure 6. Graphs showing concentrations of chlorophyll *a*, total particulate nitrogen, total nitrogen, total particulate carbon, and total phosphorus at sites FCM1, FCM2, and FCM3 in flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006
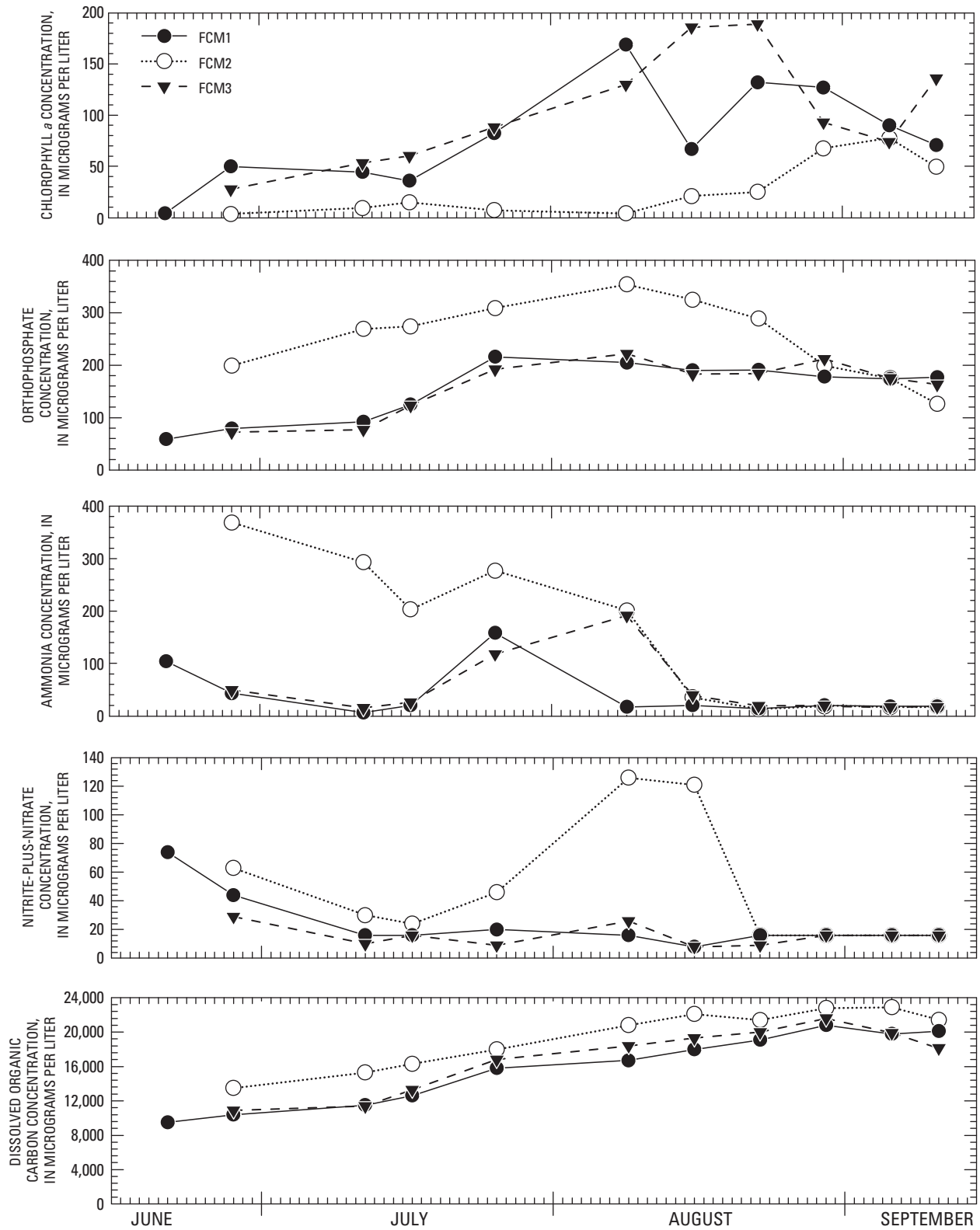
Figure 7.   Graphs showing concentrations of chlorophyll *a*, orthophosphate, ammonia, nitrite-plus-nitrate, and dissolved organic carbon at sites FCM1, FCM2, and FCM3 in flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006.
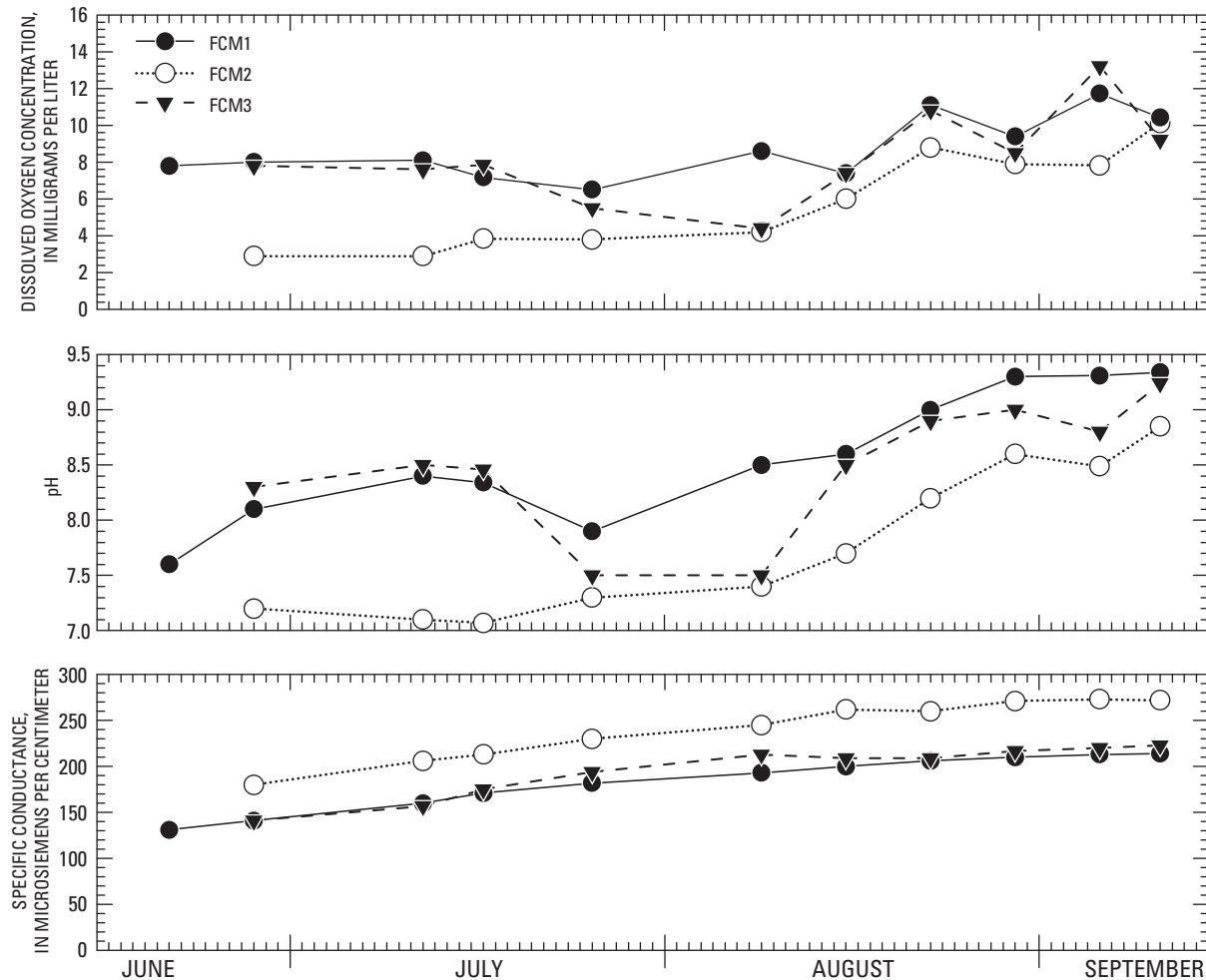
Figure 8.   Graphs showing dissolved oxygen concentration, pH, and specific conductance values at sites FCM1, FCM2, and FCM3 in flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006

Comparison of Water Quality Data Among Sites in Flooded Caledonia Marsh

Comparison of Water Sample Data

Water sample results generally were more similar between the two sites closest to the breach, sites FCM1 and FCM3 than site FCM2. The site farthest from the breach, site FCM2, was more influenced by the restored marshes in the southeastern corner of the flooded Caledonia Marsh. Total particulate nitrogen, total nitrogen, total particulate carbon, and total phosphorus tended to follow the week-to-week trends

in chlorophyll *a* concentrations at sites FCM1 and FCM3 (fig. 6). At these two sites, total nutrient concentrations slowly increased over June, July, and the first week in August, after which there was more fluctuation in the concentrations, but no indication of a decrease before the end of the sampling period on September 11. The similarity between total particulate nitrogen, total nitrogen, and chlorophyll *a* indicates that most of the nitrogen is incorporated in algal biomass, for which chlorophyll *a* is a surrogate measurement. The same can be said of carbon and phosphorus, as indicated by the similar trends in total particulate carbon, total phosphorus, and chlorophyll *a*.

Consistent with the lower chlorophyll *a* concentrations at site FCM2, total particulate nitrogen and total particulate carbon concentrations also were lower at site FCM2

than at sites FCM1 and FCM3 (fig. 6). Total phosphorus concentrations at site FCM2, in contrast, were similar in magnitude to concentrations at sites FCM1 and FCM3. Total nitrogen concentrations at site FCM2 also were similar to those at sites FCM1 and FCM3 at least during the beginning of the sampling period. An ANOVA confirmed that the distributions of total phosphorus and nitrogen were not distinguishable statistically ($p > 0.05$) among all three sites (table 2), whereas chlorophyll *a* concentrations were significantly less at site FCM2 than at sites FCM1 or FCM3.

Orthophosphate concentrations were significantly different at site FCM2 relative to those at sites FCM1 and FCM3, as detected by the ANOVA test (table 2), and consistent with the fact that orthophosphate concentrations at site FCM2 were greater than at sites FCM1 and FCM3 until the last three sampling dates (fig. 7). Ammonia concentrations were not different significantly among the sites, although concentrations at site FCM2 were greater than at sites FCM1 and FCM3 until August 8. Similar to orthophosphate concentrations at site FCM2, ammonia concentrations decreased toward the end of the sampling period, when chlorophyll *a* concentrations increased at site FCM2, which indicates the uptake of bioavailable nutrients by algae. Nitrite-plus-nitrate concentrations decreased from June 21 to July 16, then peaked at site FCM2 in early to mid-August, whereas concentrations at sites FCM1 and FCM3 varied minimally. The peak in nitrite-plus-nitrate concentrations at site FCM2 might have been the result of a nitrification process converting a small fraction of ammonia to nitrite.

DOC concentrations were slightly greater at site FCM2 than at sites FCM1 and FCM3 (fig. 7), although there was no significant difference among the sites (table 2). Among all sites, DOC ranged from 9,500 to 22,900 µg/L, with median

values of 16,700 µg/L at site FCM1, 21,100 µg/L at site FCM2, and 18,266 µg/L at site FCM3. These median DOC concentrations measured in the flooded Caledonia Marsh are at the high end of the range of values in wetlands and eutrophic lakes, typically 10,000–15,000 µg/L (Thurman, 1985). These values also are higher than concentrations measured in Upper Klamath Lake, which ranged from 4,800 to 8,900 µg/L (Kuwabara and others, 2007). Over the course of the summer, a steady increase in DOC was measured at all three flooded sites and in the lake.

Decomposition of plants and woody debris creates tannic compounds that color the water in shades of brown. Field crews reported that the color of the water column at site FCM2 was darker than at the other sites, perhaps indicating more tannic compounds in the water column. The location of site FCM2, however, was very close to an internal levee where weedy vegetation exists during the growing season. The DOC concentrations at site FCM2 might have resulted from plant decomposition at the site or in the restored wetlands in the southeast corner of flooded Caledonia Marsh, which were hydraulically connected to the marsh near site FCM2.

Comparison of Instantaneous Water Quality Monitor Data

Dissolved oxygen concentrations and pH increased over the sampling period at all three sites, but both remained lower at site FCM2 than at the other two sites during the entire sampling period (fig. 8). These differences in dissolved oxygen concentration and pH among the three sites were similar to the differences in algal growth as indicated by chlorophyll *a*, in that dissolved oxygen concentrations, pH, and chlorophyll *a* were lower at site FCM2 than at sites FCM1 and FCM3 (figs. 6 and 8). Because the byproduct of photosynthesis is the production of dissolved oxygen and consumption of carbon dioxide, algal growth is often accompanied by an increase in dissolved oxygen and pH during the photosynthetic period. Dissolved oxygen concentrations and pH were lower at site FCM2 because algal growth (as measured by chlorophyll *a* concentrations) was lower at site FCM2 than sites FCM1 and FCM3.

Specific conductance ranged from 131 to 273 µS/cm among all flooded Caledonia Marsh sites (fig. 8), and increased steadily throughout the sampling period at all three sites. As observed in the DOC concentrations, measured values were greater at site FCM2 than at sites FCM1 and FCM 3 (fig. 9). The similarity between the patterns of DOC and specific conductance among the three sites suggests that the same factors influenced the concentrations, whether different soils and land use at FCM2, or less mixing with water from Upper Klamath Lake. Specific conductance values measured in Upper Klamath Lake (100–140 µS/cm; Hoilman

Table 2.   Results of analysis of variance of total phosphorus, total nitrogen, chlorophyll *a*, orthophosphate, ammonia, and dissolved organic carbon for sites FCM1, FCM2, and FCM3 in flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006.

[All concentrations are in micrograms per liter. Means were calculated from weekly water samples. Sites that share a letter are not statistically distinguishable ($p > 0.05$) from each other. Sites that do not share a letter are statistically distinguishable ($p < 0.05$). **Abbreviations:** µg/L, microgram per liter]

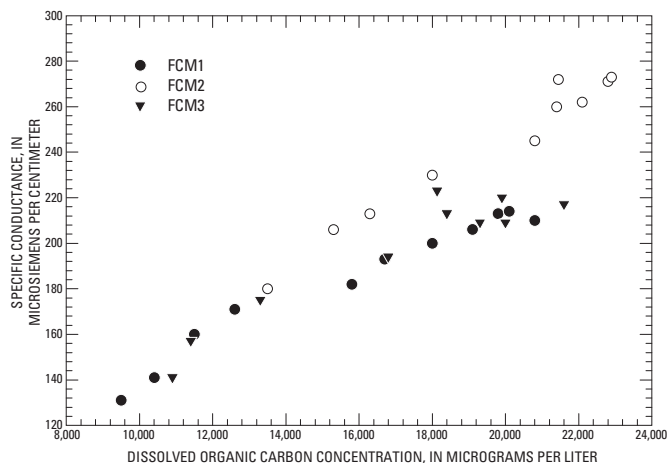| Analyte	Site		
	FCM1	FCM2	FCM3
Total phosphorus	A	A	A
Total nitrogen	A	A	A
Chlorophyll *a*	A	B	A
Orthophosphate	A	B	A
Ammonia	A	A	A
Dissoved organic carbon	A	A	A

Figure 9.   Graph showing relation of specific conductance concentrations to dissolved organic carbon concentrations at sites FCM1, FCM2, and FCM3 in flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006

and others, 2008) were less than those measured in the flooded Caledonia Marsh and other wetlands around the lake. Concentrations in the Wood River Wetland, for example, were similar to those in flooded Caledonia Marsh (Kurt Carpenter, U.S. Geological Survey, oral commun., 2007). Specific conductance values in Wood River Wetland were correlated positively with chloride concentrations (Kurt Carpenter, U.S. Geological Survey, oral commun., 2007), but chloride was not measured in this study.

Comparison of Water Quality in the Flooded Caledonia Marsh and Upper Klamath Lake

During the months when water samples were collected at sites FCM1, FCM2, and FCM3 in flooded Caledonia Marsh, water samples also were collected from Howard Bay (HDB) and from five sites around Upper Klamath Lake (sites MDN, WMR, RPT, MDT, and EPT; fig. 1). Hereafter, the five sites around Upper Klamath Lake are referred to as "lakewide" sites. A median concentration for the lakewide sites was determined for each of the following constituents—chlorophyll *a*, total phosphorus, and total nitrogen (fig. 10). Howard Bay is adjacent to flooded Caledonia Marsh and was the source of the water that flooded Caledonia Marsh when the levee breached. Chlorophyll *a* concentrations were much higher at site HDB, but were similar among sites FCM1 and

FCM3 and the median lakewide concentrations. In contrast, total phosphorus concentrations at site HDB were more similar to those at the flooded Caledonia Marsh sites, and the median lakewide concentrations were lower by comparison. Total nitrogen concentrations were higher at site HDB and more variable at all locations, except for the distribution observed in the median lakewide sites concentrations, which was more consistent.

The difference in total phosphorus concentrations between the flooded Caledonia Marsh sites and the median lakewide sites was indicative of the release of orthophosphate from peat soils in the marsh. Between June 5 and July 3, the median orthophosphate concentration at site HDB was 11 µg/L, as compared to the median orthophosphate concentration between June 21 and June 28 at sites FCM1, FCM2, and FCM3, which was 79 µg/L. The flux of orthophosphate from drained wetland soils that are subsequently flooded is expected to be greater than the flux from wetlands that were never drained. This difference is because the total phosphorus pool is greater, largely due to the greater bulk density of the drained soils, which results from compaction caused by the long-term drainage (Graham and others, 2005), and because more of the phosphorus is in labile form after long-term degradation of peat soils (Snyder and Morace, 1997). Although sampling did not start at all sites until June 28 (16 days after the levee breach) and orthophosphate flux may have been greater before sampling inception—especially within the first 48 hours (Aldous and others, 2007)—the daily orthophosphate flux from FCM sites was comparable with that in other studies. From June 28 to July 26, orthophosphate fluxes calculated from water samples collected at sites FCM1, FCM2, and FCM3 were 11.13, 7.51, and 10.71 (mg/m^2)/d, respectively. These estimates of orthophosphate flux were calculated by dividing the difference in orthophosphate concentrations from June 28 to July 26 by the number of days and multiplying by the average depth at each site. Because some of the orthophosphate is taken up by algae for growth, the actual flux is greater and these values should be considered a lower bound. These values are at the lower end of the range in orthophosphate flux measured from cores collected from previously drained wetlands around Upper Klamath Lake and analyzed in a laboratory (between 8.56 and 55.52 (mg/m^2)/d; Aldous and others, 2005).

As lake water levels lowered by approximately 1 m over the summer, water from the flooded Caledonia Marsh drained into Howard Bay, possibly transporting higher orthophosphate concentrations into the lake. Total phosphorus concentrations at site HDB and the lakewide sites were significantly higher in 2006 than in 2005, but a corresponding increase in chlorophyll *a* between the 2 years was not observed (fig. 11, table 3).
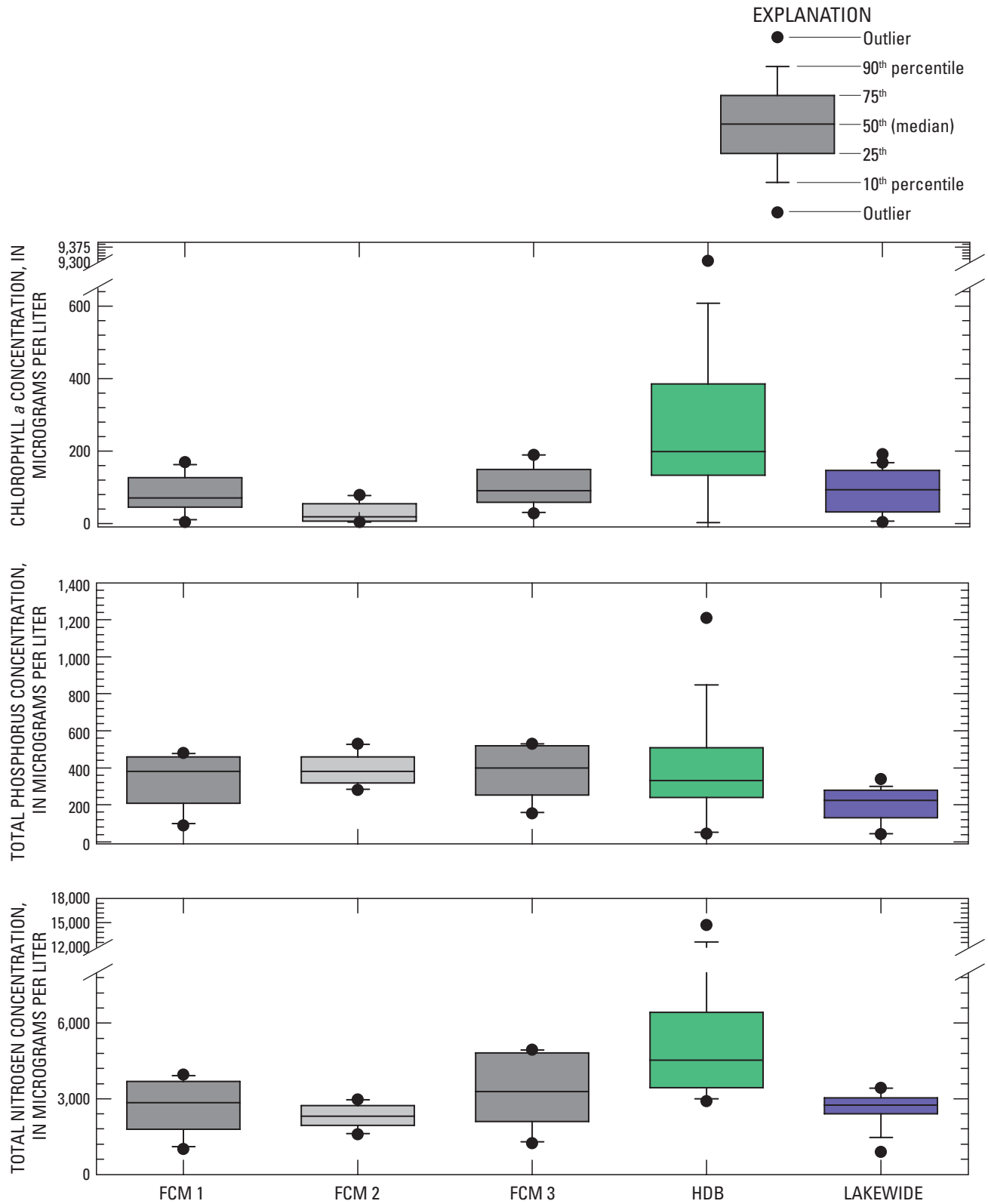
Figure 10.   Boxplots showing statistical distribution of chlorophyll *a*, total phosphorus, and total nitrogen concentrations measured at flooded Caledonia Marsh sites (FCM1, FCM2, and FCM3), the Howard Bay site (HDB), and the median lakewide sites, Upper Klamath Lake, Oregon, 2006
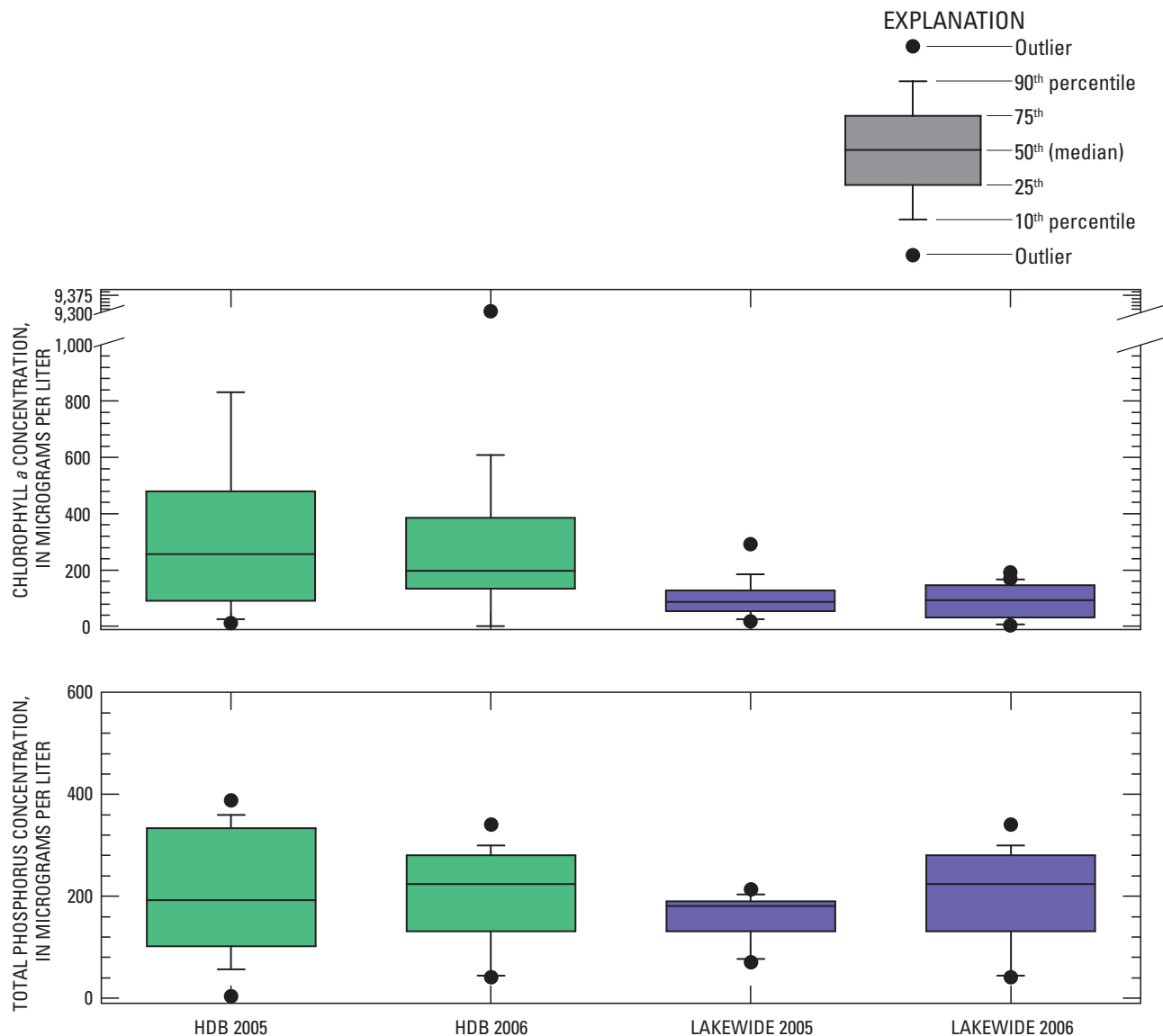
Figure 11. Boxplots showing statistical distribution of chlorophyll *a* and total phosphorus concentrations measured at Howard Bay (HDB) and of the median concentrations of lakewide sites, Upper Klamath Lake, Oregon, 2005 and 2006

Table 3. Results of analysis of variance of chlorophyll *a* and total phosphorus for site HDB in Upper Klamath Lake, Oregon, 2005–06.

[All concentrations are in micrograms per liter. Means were calculated from weekly water samples. Sites that share a letter are not statistically distinguishable ($p>0.05$) from each other. Sites that do not share a letter are statistically distinguishable ($p<0.05$)]

Analyte	Site and year	
	HDB 2005	**HDB 2006**
Chlorophyll *a*	A	A
Total phosphorus	A	B

Algal Growth

Chlorophyll *a* is used commonly as a surrogate for phytoplankton biomass. Other studies have shown that during the summer, *Aphanizomenon flos-aquae* is the predominant phytoplankton species in Upper Klamath Lake (Kann, 1998; Wood and others, 2006; Hoilman and others, 2008;). The algal biomass in flooded Caledonia Marsh is assumed to have been composed primarily of *Aphanizomenon flos-aquae*, because the waters that flooded Caledonia Marsh were from Upper Klamath Lake. This assumption is supported by field observations, although at the time of the Caledonia Marsh levee breach, chlorophyll *a* concentrations in Howard Bay were the lowest of the growing season (fig. 12), indicating that any algal growth in the flooded area occurred after the flooding event.

Chlorophyll *a* concentrations at sites FCM1 and FCM3 increased steadily from June 28 until the middle of the sampling period, becoming more variable by the end of the sampling period (fig. 6). In contrast, chlorophyll *a* concentrations measured at site FCM2 were significantly lower than those measured at the other FCM sites (table 2).

The difference between sites indicates that one or more factors (such as growth inhibition or nutrient limitation) affected algal growth at site FCM2.

One factor that may have contributed to lower algal growth at site FCM2 was the presence of humic substances, which are products of the degradation of plant material and a major component of DOC. The difference in chlorophyll *a* concentrations at the FCM sites could be indicative of algal inhibition or reduction in availability of inorganic micronutrients by humic substances (Saunders, 1957; Wetzel, 1968; Kim and Wetzel, 1993; Klug, 2002). This hypothesis is supported by observations of the brownish color of the water at FCM2 in comparison to FCM1 and FCM3. Humic substances constitute a major portion of chromophoric (colored) dissolved organic matter, which often correlates with the concentration of DOC (Wetzel, 2001), and has been shown to impart color to the water in proportion to its concentration (Ishikawa and others, 2006). This hypothesis remains speculative, however, because the concentration of humic material was not measured directly, and while higher DOC concentrations were measured at FCM2 than at the other two sites, the differences were not statistically significant (table 2).
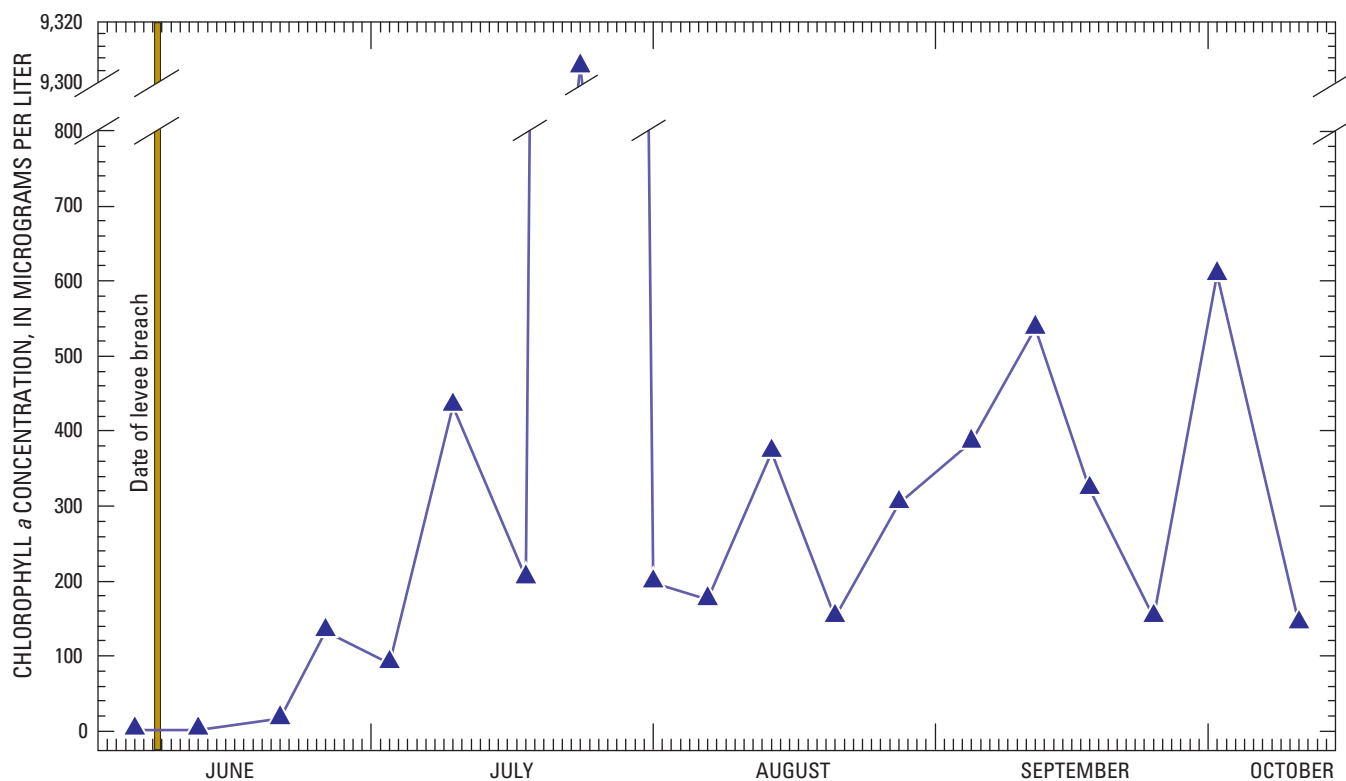
Figure 12.   Graph showing chlorophyll *a* concentrations in Howard Bay, Upper Klamath Lake, Oregon, 2006

Another possible cause for differences in chlorophyll *a* concentrations among FCM sites is nutrient limitation. Total nitrogen to total phosphorus ratios are indicative of the potential for a nutrient to be limiting in a system. Ratios of total nitrogen to total phosphorus generally were less than 10 for all the FCM sites (fig. 13), which indicates a nitrogen limiting system (Forsberg and Ryding, 1980). Most of the

ratios of lakewide sites lie in the range of nitrogen and phosphorus limitation (>10 and <17, respectively). The lower ratios at FCM sites than at the lakewide sites, particularly at site FCM2, reflect differing nutrient dynamics and might explain why chlorophyll *a* concentrations measured at site FCM2 were lower than those at the median lakewide sites (fig. 10) even though there was a surplus of bioavailable phosphorus at site FCM2.

Figure 13.   Graph showing relation of chlorophyll *a* concentrations to the ratio of total nitrogen and total phosphorus concentrations in flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006

Summary

The drained and natural wetlands surrounding Upper Klamath Lake may influence nutrient cycling in the lake. Natural wetlands, such as swamps and marshes, can seques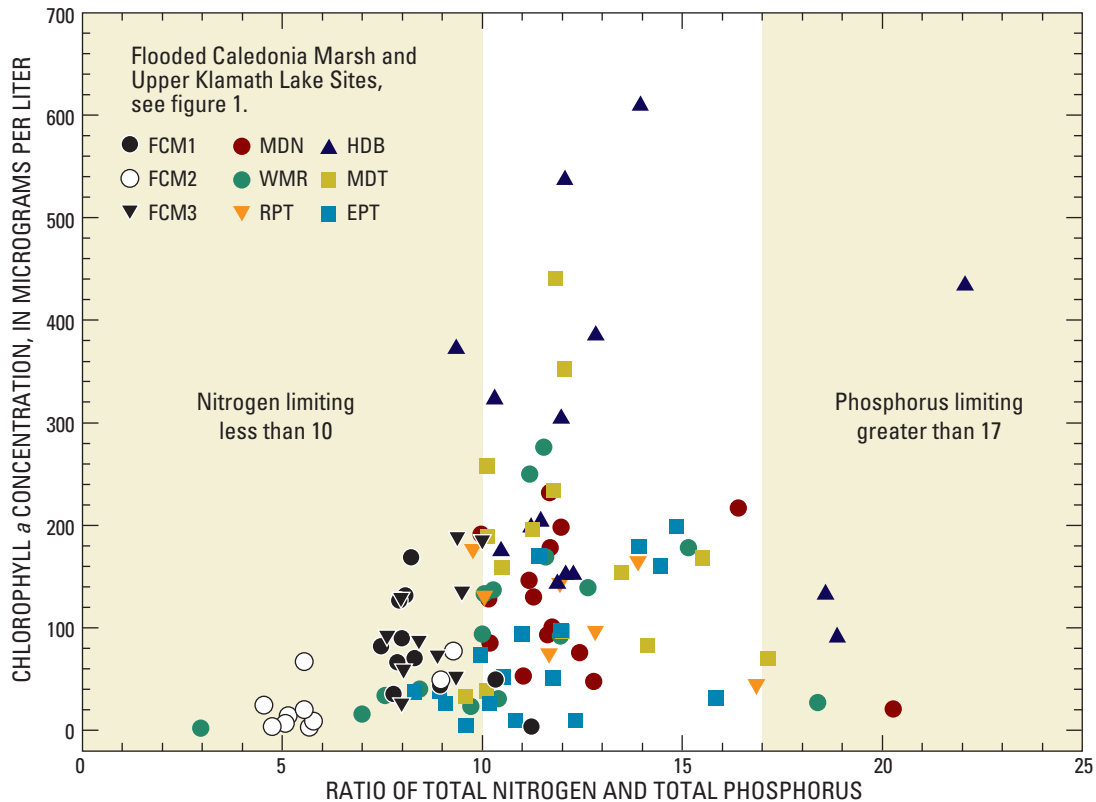ter nutrients from tributary inflows; whereas, nutrients are released when oxidized peat soils that formed in previously drained wetlands are flooded. After a previously drained wetland is flooded, many years can pass before natural wetland functions are restored. In the short term, nutrients left over from agricultural practices or from the oxidation of peat soils may be transferred to the overlying water column. Flooded Caledonia Marsh, a drained wetland used for agriculture for many years, became of interest when the marsh was flooded accidentally due to a levee breach in early June 2006. The study focuses on what affect a newly flooded drained wetland has on nutrient concentrations in the lake.

Water quality characteristics at one marsh site, FCM2, were somewhat different relative to the other two marsh sites (FCM1 and FCM3), for reasons that might include a greater distance from the levee breach, proximity to a restored wetland, and possibly the presence of vegetation. A brown color in the water column at FCM2 was consistent with higher dissolved organic carbon (DOC) concentrations at that site, where the water column likely was colored by humic acids, a major component of DOC. Both DOC concentrations and specific conductance values, were higher at FCM2 than at the other two sites. The same factors were likely responsible for the higher values of both constituents. A difference in soil type and land use cannot be ruled out, but it seems likely that there was less mixing at FCM2 with water from Upper Klamath Lake, which was characterized by lower DOC concentrations and lower specific conductance values than any of the flooded marsh sites. Chlorophyll *a* concentrations, a surrogate for algal biomass (primarily the blue-green alga *Aphanizomenon flos-aquae*), were lower at site FCM2 than at the other two sites, which indicates that algal growth was limited by some mechanism at site FCM2. Some studies have shown algal growth inhibition in the presence of humic compounds, as measured by DOC.

Site FCM2 also differed with regard to trends in total nutrient species relative to chlorophyll *a* concentration. Concentrations of bioavailable nutrients—orthophosphate, ammonia, nitrite-plus-nitrate—were greater at site FCM2 than at the other marsh sites, indicating that nutrient limitation was not responsible for the lack of algal growth at site FCM2. Ratios of total nitrogen to total phosphorus were indicative of a nitrogen limitation at all sites, but to a greater extent at site FCM2. Ratios at the marsh sites were different from those at lakewide sites and indicate different nutrient dynamics in the lake relative to the flooded marsh.

Total phosphorus and orthophosphate concentrations were greater in the marsh than in the open waters of the lake. The difference in phosphorus concentrations between the marsh and the lake could have been due to the release of phosphorus from the inundated soils after flooding. Although total phosphorus concentrations in the hydraulically connected Howard Bay increased from 2005 to 2006, no significant increase in algal growth occurred during the same period. Therefore, short-term increases in bioavailable phosphorus that can be expected when the previously drained wetlands around the lake are reflooded will not necessarily lead to a proportional increase in algal growth in the lake. This also underscores that it should not be assumed that phosphorus is the primary factor limiting algal growth in the lake at all times and all areas of the lake.

Acknowledgments

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Appendix A. Quality Control and Quality-Assurance of Water Samples

Eighteen percent of the chlorophyll *a* samples, 33 percent of the total phosphorus samples, 32 percent of the total nitrogen samples, 36 percent of the dissolved nutrient samples (orthophosphate, ammonia, and nitrite-plus-nitrate), 38 percent of the particulate samples (total particulate nitrogen, total particulate carbon, particulate inorganic carbon, and particulate organic carbon), and 37 percent of the dissolved organic carbon samples collected were used for quality-assurance purposes, which included field blanks (the first sample collected every week) and either a split sample or a method replicate (each type every other week). Field blanks are samples of reagent-grade inorganic blank water processed onsite through clean sampling equipment, before an environmental sample is collected. Analysis of blank samples determines whether the processes of collection, handling, transport, and analysis cause measurable contamination. Split samples are environmental water samples collected once and divided with the use of a churn splitter into two or more samples that are used to determine the variability in the analytical methods. Replicate samples are environmental samples collected twice in rapid succession from the same location and analyzed to determine the variability of the system, the sampling method, and the analytical methods.

The results of the quality-assurance sampling indicated that precision and accuracy were acceptable and the variability in sampling and processing was smaller than the week-to-week variability (table A1). Most of field-blank concentrations of total phosphorus and orthophosphate were less than the laboratory's minimum reporting level. The median values of the blank samples greater than the minimum reporting level were 0.006 and 0.013 mg/L for total phosphorus and orthophosphate, respectively. The field-blank samples of total nitrogen and ammonia revealed some contamination, where almost one-half of the samples were greater than laboratory minimum reporting level, although it was minimal compared to the concentrations of the environmental samples collected the same week. The number of nitrite-plus-nitrate blank sample values greater than the laboratory minimum reporting level was less than for total nitrogen and ammonia, indicating that the contamination in total nitrogen samples was dominated by the ammonia-nitrogen species. Only one blank sample collected for total particulate nitrogen was greater than the minimum reporting level. Contamination of ammonia blanks in a 2003–04 study was attributed to atmospheric deposition (Wood and others, 2006). The use of capsule filters since then has diminished but did not eliminate the problem completely. Total particulate carbon blank samples were all below minimum reporting level. The median concentration of DOC blank samples was twice the minimum reporting level, indicating an increased chance for contamination.

Variability of analytical methods as measured by split samples generally was low. The median relative percentage difference of chlorophyll *a*, ammonia, total particulate nitrogen, total particulate carbon, and particulate organic carbon was greater than 10 percent, but less than 13 percent in split samples. Relative percentage difference of the other analytes was less than 10 percent in split samples. Variability of the environmental system and analytical methods as measured by replicate samples generally was low. The median relative percentage difference of replicate samples generally is slightly higher than split samples. This is expected because the variability of the environmental samples is added to the variability of the sampling and analytical methods. The median relative percentage difference of chlorophyll *a*, total particulate nitrogen, total particulate carbon, and particulate organic carbon was greater than 10 percent and less than 16 percent in replicate samples. Relative percentage difference of the other analytes was less than 10 percent in replicate samples. The large relative percentage difference in ammonia split samples was high due to a large difference (40 percent) in a set of low concentration samples (6 and 10 µg/L). The relative percentage difference of chlorophyll *a*, total particulate nitrogen, total particulate carbon, and particulate organic carbon split and replicate samples was slightly greater than 10 percent due to the variability of the filtration process. Overall, variability of quality-assurance samples was minimal relative to the variability of the environmental samples.

Table A1.   Quality-assurance results of blank, split, and replicate samples for the water quality sample collection program in flooded Caledonia Marsh, Upper Klamath Lake, Oregon, 2006.

[**Abbreviations:** mg/L, milligram per liter; MRL, minimum reporting level; >, greater than; –, not applicable]

	Blank samples						
Analyte	Number of samples		Percentage of blank samples	MRL (mg/L)	Number of blank samples > MRL	Value of blank samples > MRL (mg/L)	
	Blank	Total				Maximum	Median
Chlorophyll *a*	11	148	7	0.001	7	0.007	0.005
Total phosphorus	52	207	25	.004	17	.011	.006
Total nitrogen	44	190	23	.06	18	.30	.12
Orthophosphate	61	211	29	.006	1	–	.013
Ammonia	61	211	29	.01	23	.04	.02
Nitrite-plus-nitrate	61	211	29	.016	7	.052	.031
Total particulate nitrogen	12	59	20	.022	1	–	.030
Total particulate carbon	12	59	20	.12	0	–	–
Particulate inorganic carbon	12	59	20	.12	0	–	–
Particulate organic carbon	12	59	20	.12	0	–	–
Dissolved organic carbon	11	58	19	.4	7	7	.8

	Split samples				
Analyte	Number of samples		Percentage of split samples	Difference between split samples	
	Split	Total		Median (mg/L)	Median (percent)
Chlorophyll *a*	8	148	5	0.006	11.38
Total phosphorus	9	207	4	.010	4.26
Total nitrogen	7	190	4	.160	6.64
Orthophosphate	8	211	4	.001	2.22
Ammonia	8	211	4	.003	12.44
Nitrite-plus-nitrate	8	211	4	.001	.45
Total particulate nitrogen	5	59	8	.070	11.76
Total particulate carbon	5	59	8	.400	12.90
Particulate inorganic carbon	5	59	8	.000	.00
Particulate organic carbon	5	59	8	.400	12.90
Dissolved organic carbon	5	58	9	.400	3.13

	Replicate samples				
Analyte	Number of samples		Percentage of replicate samples	Difference between replicate samples	
	Replicate	Total		Median (mg/L)	Median (percent)
Chlorophyll *a*	9	148	6	0.021	15.38
Total phosphorus	8	207	4	.016	5.41
Total nitrogen	9	190	5	.200	4.73
Orthophosphate	6	211	3	.001	.51
Ammonia	6	211	3	.002	5.13
Nitrite-plus-nitrate	6	211	3	.001	1.05
Total particulate nitrogen	6	59	10	.270	13.50
Total particulate carbon	6	59	10	1.450	13.53
Particulate inorganic carbon	6	59	10	.000	.00
Particulate organic carbon	6	59	10	1.350	12.64
Dissolved organic carbon	5	58	9	.000	.00