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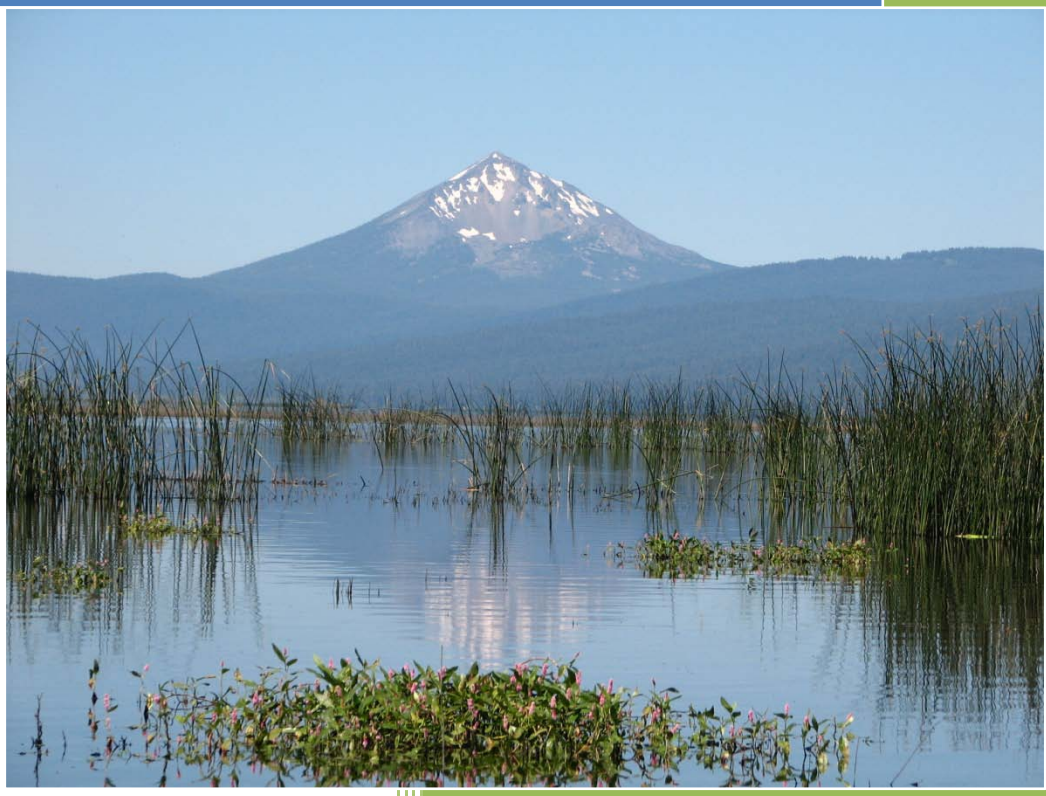
2007-2009

Post-Restoration Water Quality Conditions at the Williamson River Delta, Upper Klamath Basin, Oregon



Siana Wong, Heather Hendrixson, and Carolyn Doehring

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Cover: Williamson River Delta, Oregon, looking west toward Mt. McLoughlin (Photograph taken by Carolyn Doehring, 2008)

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Prepared By:

The Nature Conservancy
Siana Wong, Heather Hendrixson, and Carolyn Doehring*
226 Pine St.
Klamath Falls, OR 97601

Prepared For:

Oregon Watershed Enhancement Board
775 Summer St NE # 360
Salem, OR 97301

And

US Bureau of Reclamation
Mid-Pacific Region
Klamath Area Office
6600 Washburn Way
Klamath Falls, Oregon, 97603

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*Current address: Klamath Basin Rangeland Trust, 700 Main St. #210A, Klamath Falls, OR 97601

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EXECUTIVE SUMMARY

The Nature Conservancy has monitored water quality on the Williamson River Delta (the Delta) for two years following restoration: from fall 2007 when the first major breaches in Tulana flooded approximately 3,500 acres to fall 2009 after another 2,000 acres were flooded in Goose Bay. One of the fundamental goals of the wetlands restoration is to facilitate improvement in water quality in Upper Klamath and Agency Lakes by removing a major external nutrient source to the lakes originating from former agricultural fields at the Delta, and by nutrient sequestration through wetland ecosystem processes. The objective of water quality monitoring is to quantify and describe the effects of the restoration on surface water chemistry and phytoplankton community structure within and surrounding the Delta. Specific questions addressed by this monitoring effort and presented in this report include: (1) the extent to which the Delta wetlands provided a source or sink for nutrients within the two years after restoration; (2) the effects of restoration on water quality and phytoplankton assemblages; and (3) the magnitude and timing of water quality conditions in the Delta that may have been detrimental to endangered suckers. This report summarizes data collection from November 2007–2009. Annual summary reports for one year and two years post-restoration can be found at the following website: www.conserveonline.org.

From April–November 2008 and March–November 2009 we collected surface water grab samples for nitrogen and phosphorus at 27 sites; carbon, chlorophyll *a*, and phytoplankton samples at 21 sites; and continuous (hourly) water chemistry parameters including temperature, dissolved oxygen, pH, and specific conductance at nine sites in the Delta, Upper Klamath and Agency Lakes, and the Williamson River. We modified our sampling design in 2009 by moving four sites in Tulana, one from Agency Straits, and one from the Williamson River to the newly restored Goose Bay portion of the Delta.

Phosphorus concentrations in 2009 were overall lower at lake and Tulana wetland sites compared to concentrations in 2007 and 2008, with TP concentrations up to 1.8 times lower in the open water and deep water wetlands (permanently flooded wetlands) and 1.4 times lower in the lakes from July–November. Phosphorus concentrations were higher in Tulana compared to concentrations at lake sites in all years, with maximum TP concentrations in the permanently flooded wetlands in Tulana up to 6.3, 2.7, and 1.4 times greater than in the lakes in 2007, 2008, and 2009, respectively. At most lake and permanently flooded wetland sites, increases in chlorophyll *a* concentration were coincident with increases in total nitrogen concentration, dissolved oxygen concentration, and pH, while declines in chlorophyll *a* concentration corresponded to peaks in ammonium concentration and declines in total nitrogen concentration, dissolved oxygen concentration, and pH. These latter trends are typical for this lake system, where water quality is often driven by the bloom and crash dynamics of the blue-green algae,

Aphanizomenon flos-aquae (AFA) (Lindenberg and Wood 2008). Among all wetland sites and years, dissolved organic carbon concentrations ranged from 4–22 mg/L, a range considerably lower than the 24–270 mg/L range observed in a nearby wetland (Carpenter et al. 2010).

Continuous monitoring data showed that water quality conditions in the Delta exceeded high stress thresholds for endangered Lost River (*Deltistes luxatus*) and shortnose (*Chasmistes brevirostris*) suckers, conditions which are defined by dissolved oxygen concentration<4 mg/L, pH>9.7, and temperature>28°C (Loftus 2001). The parameters, locations, and timings in which conditions were most severe (prolonged throughout the day) included pH and dissolved oxygen in the lakes and permanently flooded wetlands during AFA bloom and crash periods (June and August for pH, and July and September for dissolved oxygen concentration). The dissolved oxygen threshold was exceeded for 80% of the hours recorded in August 2008 in the deep water wetland– a phenomenon which did not occur at any other location or time. In the emergent and transitional wetlands (seasonally flooded wetlands), dissolved oxygen concentrations reached severe conditions in July 2008 and 2009, but pH and temperature conditions were generally not severe for endangered suckers during the larval migration period from mid-May to mid-July.

Phytoplankton analyses indicated 247 identified species present among all sites and years, including 231 species in the Delta wetlands, 58 at lake sites, and 84 in the river. Phytoplankton diversity was greatest in the river and seasonally flooded wetlands compared to the lakes and permanently flooded wetlands. In the lakes and permanently flooded wetlands, the phytoplankton assemblages were dominated by AFA, but *Microcystis aeruginosa* was also prevalent in the blue-green algae assemblage from July–November at these locations at densities exceeding the Oregon Public Health's Harmful Algal Blooms advisory guideline (≥40,000 cells/mL).

Overall, trends in nutrient and physical water chemistry reveal that the wetlands system was likely in a state of transition in which nutrients were initially released from benthic sources after being flooded. Gradients in water chemistry and phytoplankton abundance and community structure across the Delta wetlands also reveal the hydrologic influence of lake waters in permanently flooded areas of the Delta, and the influence of river waters in seasonally flooded areas of the Delta, particularly in Goose Bay. Site-to-site variability was also observed within habitat types of the Delta, which may be explained by a number of different factors including differences in water depth, wind exposure, vegetation, soil types, historical land management, and other biological, chemical, and physical factors.

Results from two years of water quality monitoring on the Delta provide important information for assessing trends in water chemistry following wetland restoration. As wetland ecosystem processes are restored to the system, changes in surface water chemistry are expected. Documenting these changes is vital, especially considering the wide-ranging efforts by multiple agencies and organizations in the Upper Klamath Basin to restore and manage wetlands.

INTRODUCTION

The widespread loss of wetlands in the Upper Klamath Basin (the Basin) in southern Oregon is extensively cited as one of the underlying factors contributing to the degradation of water quality in Upper Klamath and Agency Lakes (Snyder and Morace 1997, Bradbury et al. 2004, Eilers et al. 2004, Natural Research Council 2004). Since the late 1800s, 85–90% of wetlands in the Basin have been drained and converted for agriculture (Gearhart 1995). The drainage of these wetlands and the concurrent expansion of development and agricultural activities over the past century is believed to have increased nutrient loading into the lakes and contributed to their hypereutrophic states (Snyder and Morace 1997, Bradbury et al. 2004, Eilers et al. 2004, Natural Research Council 2004).

At present, near monocultural blooms of the cyanobacteria, *Aphanizomenon flos-aquae*, occur seasonally in Upper Klamath and Agency Lakes and frequently drive poor water quality conditions including highly variable dissolved oxygen concentrations (anoxic to supersaturated), elevated pH (9–10), and high un-ionized ammonia concentrations (above 0.5 mg/L) (Lindenberg et al. 2008). Both directly through habitat loss and indirectly through water quality impairment, the loss of lake-fringe wetlands has also contributed to the decline of two federally endangered fish species which are endemic to the Basin– the Lost River sucker (*Deltistes luxatus*) and shortnose sucker (*Chasmistes brevirostris*) (US Fish and Wildlife Service 1988, Gearhart et al. 1995, National Research Council 2004). Water quality impairment in the lakes and associated fish die-off episodes has highlighted the need to address water quality issues in the Basin.

Entities in the Basin are heavily invested in wetland restoration and management projects in order to rehabilitate the diverse functions that wetlands provide, including habitat for fish and wildlife, water storage, and improved downstream water quality. Projects currently include those at Wood River Wetland, Agency Lake Ranch, Running Y Ranch, and the Williamson River Delta (Figure 1). Since 2000, The Nature Conservancy (TNC) and its partners have restored approximately 5,500 acres of wetlands at the Williamson River Delta (the Delta) in order to restore hydrologic connectivity between the Williamson River, Upper Klamath and Agency Lakes, and the Delta wetlands. The two primary goals of the wetland restoration effort at the Delta are to restore rearing habitat for larval and juvenile endangered suckers and to facilitate improvement in water quality in Upper Klamath and Agency Lakes by eliminating the return of agricultural tail water originating in the Delta to the lakes, and by nutrient removal through wetland ecosystem processes.

In fall 2007, large-scale restoration began with the breaching of levees surrounding the western half of the Delta, and a long term water quality monitoring program on the Delta was implemented by TNC and project collaborators. The objective of the monitoring is to quantify and describe the effects of wetland restoration at the Delta on surface water chemistry. The fundamental questions being investigated include: (1) the extent to which the Delta wetlands

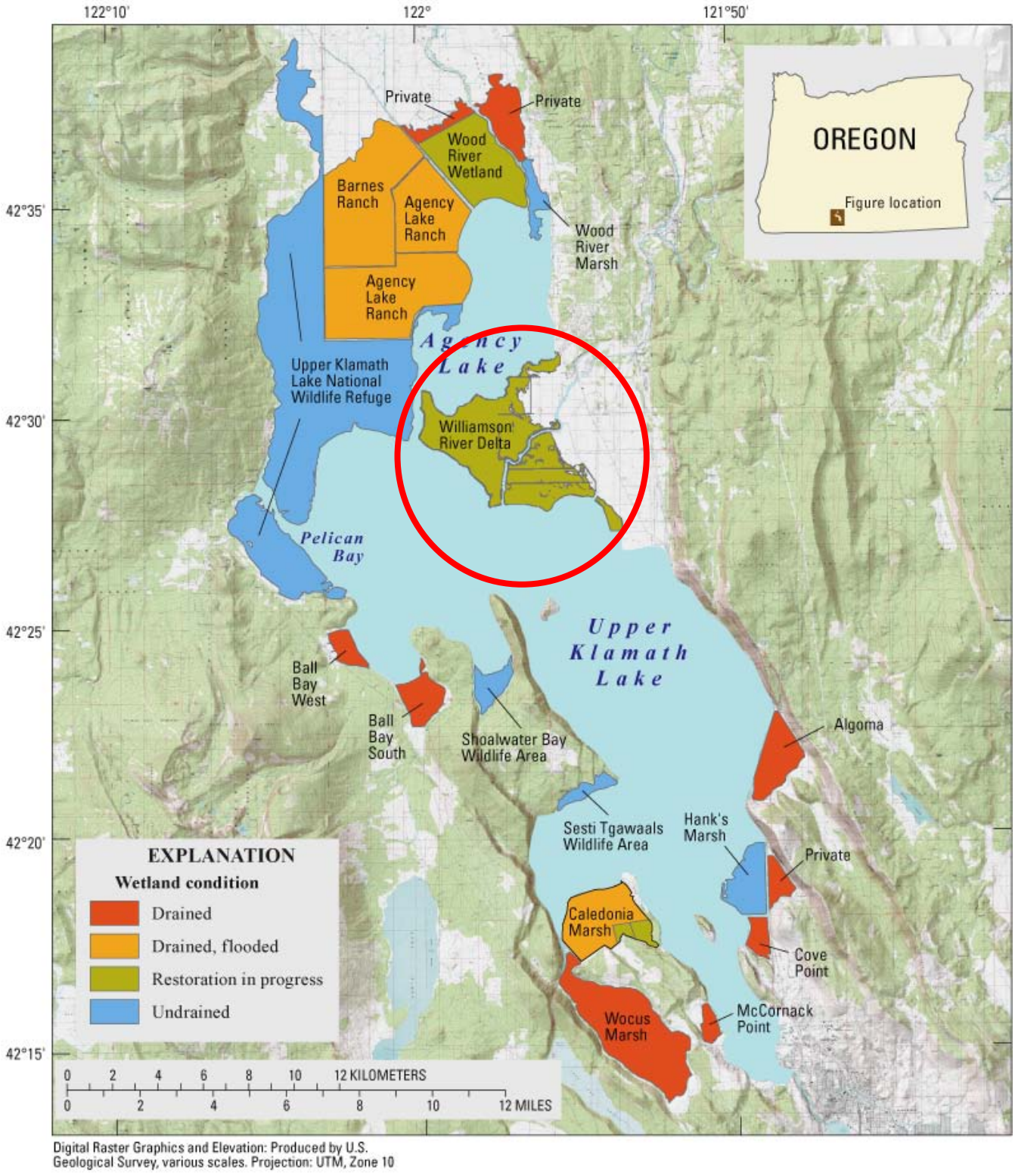

Figure 1. Location of Williamson River Delta, Oregon in relation to other wetlands surrounding Upper Klamath and Agency Lakes. Map edited from Lindenberg and Wood (2009). Caledonia Marsh currently drained.

provide a source or sink of nutrients; (2) the effects of the restoration on surface water chemistry and phytoplankton assemblages in the Delta wetlands and Upper Klamath and Agency Lakes; and (3) the magnitude and timing of water quality conditions in the Delta that may have been detrimental to endangered suckers. This report presents results from the past two years of water quality monitoring at the Delta from November 2007–November 2009.

STUDY AREA

Restoration Background

The Delta is located in south-central Oregon and straddles the last four miles of the Williamson River before the river empties into Upper Klamath Lake (Figure 1). Historically, the Delta was a fully functional freshwater wetland ecosystem which hydrologically connected the Williamson River and Upper Klamath and Agency Lakes. Beginning in the 1940s, the Delta wetlands were separated from the lakes and river by levees, then drained and cultivated for crops including alfalfa, potatoes, and barley until the 1990s.

Restoration of the Delta wetlands was initiated in 1996 by TNC. Early action projects in 2000 and 2003 involved the breaching of levees at three locations, re-establishing hydrologic connectivity between the wetlands and surrounding lake and river at small portions of the Delta. In October 2007, larger scale restoration occurred with the breaching of levees surrounding the western half of the Delta (known as Tulana) using mechanical excavation and explosives, flooding about 3,500 acres. In November 2008, levees surrounding the eastern half of the Delta (known as Goose Bay) were breached by means of excavation, flooding about 2,000 acres.

Breach locations on the Delta perimeter were sited based on hydrologic modeling (Daraio et al. 2004). On the Tulana portion of the Delta, four breaches ranging 2,100–2,700 feet (ft) in length occur along the northern and southwest perimeters, and three breaches ranging 500–1700 ft in length occur along the Williamson River (Figure 2). On the Goose Bay portion of the Delta, three breaches ranging 1,000–3,000 ft in length occur along the southern perimeter, and three breaches occur along the Williamson River. Levees between breaches were lowered to a surface elevation ranging 4,139–4,142 ft, allowing water to overflow the levees during seasonally high water levels.

Hydrology

Surface water levels are regulated by the US Bureau of Reclamation and fluctuate by about five feet through the year, with highs (~4,143 ft) typically occurring in April and lows (~4,138 ft) by the end of October. At high water levels, lake waters flow across vast portions of the Delta, and wetland areas along the river are flooded. At low water levels, waters from Upper Klamath and Agency Lakes flow predominately through four half-mile long openings within the perimeter breaches of the Delta. During this time, waters from the Williamson River are largely cut off from the wetlands. Substantial soil subsidence has occurred on the western portion of

Tulana as a result of repeated draining and flooding of the land during cultivation. Current elevations in these areas are as much as eight feet below average lake levels (David Evans and Associates, Inc. 2005). The overall hydrologic effect is the seasonal flooding of shallow emergent and riparian wetlands, which include eastern portions of Tulana and the majority of Goose Bay, and year-round inundation of western portions of Tulana, which now resemble open water conditions. Neither groundwater discharge nor recharge is a significant part of the water balance in the Delta (David Evans and Associates, Inc. 2005).

Vegetation and Soils

Vegetation across the Delta is largely influenced by water depth and flooding tolerances of various plant species. Additionally, management of the land prior to restoration is likely to have influenced vegetative cover during the monitoring period. Immediately upon inundation in fall 2007, vegetation within Tulana consisted of a mosaic of flooded upland flora, crop stubble from former agricultural fields, and decomposing wetland vegetation which had been established prior to restoration by means of managed pumping. During the growing seasons in 2008 and 2009, eastern portions of Tulana were dominated by riparian and emergent species including golden dock (*Rumex maritimus*), Norwegian cinquefoil (*Potentilla norvegica*), and hardstem bulrush (*Schoenoplectus acutus*) (Elseroad et al. 2009). On western portions of Tulana, open water conditions prevent the establishment of substantial vegetation; however, species such as water smartweed (*Polygonum amphibium*) and hardstem bulrush have been observed in these areas. Prior to flooding in fall 2008, Goose Bay had not been managed as a wetland. After flooding in 2009, wetland vegetation colonized this area for the first time since being drained and converted for agriculture. During the monitoring period, vegetation in Goose Bay consisted primarily of flooded upland vegetation and sparse coverage of riparian and emergent species of which included exotics such as false mayweed (*Tripleurospermum maritimum*) and quackgrass (*Elymus repens*), native annual forbs such as *Symphyotrichum frondosum* and *Rorippa curvisiliqua*, and other natives such as Norwegian cinquefoil, broadleaf cattail (*Typha latifolia*), creeping spike-rush (*Eleocharis palustris*), and hardstem bulrush (Elseroad et al. 2010).

Soils at the Delta consist primarily of Lather muck and Tulana silt loam (Cahoon 1985). Lather muck soils are poorly drained organic soils found at lower elevations on western portions of Tulana. Silt loam soils are mineral soils found at higher elevations of the Delta nearer the Williamson River and in Goose Bay. Because of soil subsidence and high exposure to waves and turbidity, re-colonization of substantial wetland vegetation on western portions of Tulana would be difficult in the short-term. Vegetative cover within shallow portions of the Delta was overall variable during the 2007–2009 monitoring period, with the majority of Goose Bay and some areas in eastern Tulana appearing more sparsely covered than other areas. Vegetation in these riparian and emergent wetlands are expected to re-colonize, and post-restoration vegetation monitoring at the Delta is currently in place to track changes in vegetation over the longer term (Elseroad et al. 2009, Elseroad et al. 2010).

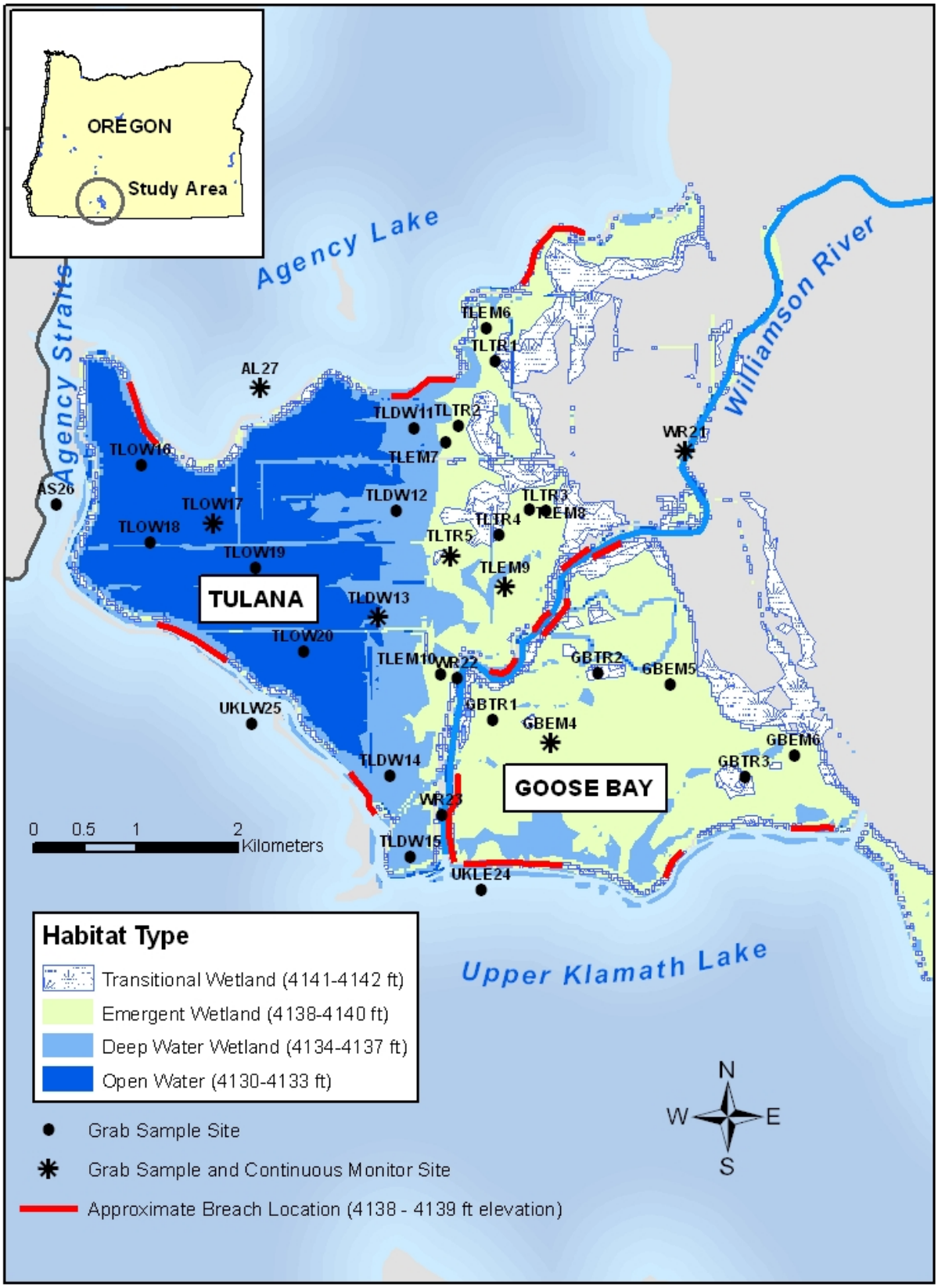

Figure 2. Map of the Williamson River Delta, Oregon showing wetland habitat types and water sampling sites, 2007–2009.

METHODS

Study Design

Water sampling sites within the Delta were stratified based on water depth ranges in which different plant communities were expected to colonize upon flooding (Elseroad 2004) and by water movement patterns across the Delta as predicted by a hydrodynamic circulation model developed by the US Geological Survey (USGS) (T. Wood, USGS, personal communication). The water depth ranges used in the stratification of sampling sites within the Delta were classified as the following: transitional wetland (maximum water depth 0.6 m), emergent wetland (1.5 m), deep water wetland (2.7 m), and open water (4 m) (Elseroad 2004). Transitional and emergent wetlands are the two distinct, seasonally flooded, vegetative zones and occur on eastern portions of Tulana and the majority of Goose Bay (Figure 2). Deep water wetland and open water are the two permanently flooded, less or non-vegetative zones and occur on western portions of Tulana and the southern-most areas of Goose Bay.

Monitoring at the Delta consisted of two components: surface water grab sampling and continuous in-situ water chemistry monitoring. During the 2007–2009 monitoring period, 33 fixed sites were selected for grab sample collection and a subset of nine sites for continuous monitoring (Table 1, Figure 2). Grab sampling sites were located in each of four habitat types inside the Delta, in the Williamson River, and in Upper Klamath and Agency Lakes near the Delta shore. Continuous monitoring sites were located at the following: one in each of the four habitat types in Tulana, one in Goose Bay, one in the Williamson River upstream of the project area, and three in Upper Klamath and Agency Lakes near the Delta shore. In fall 2007, sampling occurred only at ten sites within Tulana in open water and deep water wetland as well as seven sites surrounding the Delta in the lakes and river since these were the only areas inundated. Beginning in 2008, monitoring occurred at existing sites sampled in 2007 and at ten sites in the newly flooded emergent and transitional wetlands within Tulana. In 2009, four sites in Tulana (one site in each of the habitat types), one site in Agency Straits, and one in the Williamson River were moved to the newly restored Goose Bay portion of the Delta (Table 1).

Grab Sampling

Surface water grab samples were collected and analyzed for constituents of phosphorus (P), nitrogen (N), and carbon (C), as well as for chlorophyll *a* and phytoplankton composition. Phosphorus constituents included total phosphorus (TP) and orthophosphate (PO_4). Nitrogen constituents included total nitrogen (TN), nitrate+nitrite (NO_3+NO_2), nitrite (NO_2), and ammonium (NH_4). Carbon constituents included dissolved organic carbon (DOC) and total organic carbon (TOC).

In 2007, samples were collected for N and P in open water, deep water wetland, and lake and river sites. Beginning in 2008, sampling for C, chlorophyll *a*, and phytoplankton was initiated at a subset of the grab sampling sites (Table 1). Samples were collected bi-weekly from

Table 1. List of water sampling sites, water quality variables measured, and years sampled for each site at the Williamson River Delta, Oregon. 'X' denotes sample collected. '--' denotes not sampled. 'Sonde' refers to hourly measurements of temperature, dissolved oxygen, pH, and specific conductance.

	Site ID	Location	Water Quality Variable						Year Sampled		
			Nitrogen	Phosphorus	Carbon	Chlorophyll *a*	Phytoplankton	Sonde	2007	2008	2009
Tulana Wetlands	TLTR1	Transitional Wetland	X	X	X	X	X	--	--	X	X
	TLTR2	Transitional Wetland	X	X	--	--	--	--	--	X	--
	TLTR3	Transitional Wetland	X	X	X	X	X	--	--	X	X
	TLTR4	Transitional Wetland	X	X	--	--	--	--	--	X	X
	TLTR5	Transitional Wetland	X	X	X	X	X	X	--	X	X
	TLEM6	Emergent Wetland	X	X	X	X	X	--	--	X	X
	TLEM7	Emergent Wetland	X	X	--	--	--	--	--	X	--
	TLEM8	Emergent Wetland	X	X	--	--	--	--	--	X	X
	TLEM9	Emergent Wetland	X	X	X	X	X	X	--	X	X
	TLEM10	Emergent Wetland	X	X	X	X	X	--	--	X	X
	TLDW11	Deep Water Wetland	X	X	X	X	X	--	X	X	X
	TLDW12	Deep Water Wetland	X	X	X	X	X	--	X	X	X
	TLDW13	Deep Water Wetland	X	X	X	X	X	X	X	X	X
	TLDW14	Deep Water Wetland	X	X	--	--	--	--	X	X	X
	TLDW15	Deep Water Wetland	X	X	--	--	--	--	X	X	--
	TLOW16	Open Water	X	X	X	X	X	--	X	X	X
	TLOW17	Open Water	X	X	X	X	X	X	X	X	X
	TLOW18	Open Water	X	X	--	--	--	--	X	X	X
	TLOW19	Open Water	X	X	--	--	--	--	X	X	--
	TLOW20	Open Water	X	X	X	X	X	--	X	X	X
Goose Bay Wetlands	GBTR1	Transitional Wetland	X	X	X	X	X	--	--	--	X
	GBTR2	Transitional Wetland	X	X	X	X	X	--	--	--	X
	GBTR3	Transitional Wetland	X	X	X	X	X	--	--	--	X
	GBEM4	Emergent Wetland	X	X	X	X	X	X	--	--	X
	GBEM5	Emergent Wetland	X	X	X	X	X	--	--	--	X
	GBEM6	Emergent Wetland	X	X	X	X	X	--	--	--	X
River	WR21	Williamson River	X	X	X	X	X	X	X	X	X
	WR22	Williamson River	X	X	X	X	X	--	X	X	--
	WR23	Williamson River	X	X	--	--	--	--	X	X	X
Lake	UKLE24	Upper Klamath Lake	X	X	--	--	--	X	X	X	X
	UKLW25	Upper Klamath Lake	X	X	X	X	X	X	X	X	X
	AS26	Agency Straits	X	X	--	--	--	--	X	X	--
	AL27	Agency Lake	X	X	X	X	X	X	X	X	X

March/April–November in 2008–2009, and from October–November one week before and two and three weeks after the breaching of levees surrounding Tulana in 2007. At transitional and emergent wetland sites, samples were collected until July and August of each sampling year, after which insufficient water was present to collect samples due to seasonally low water levels.

Water samples were collected using a 3.2 liter Van Dorn horizontal beta sample collection device. At sites less than 1 m deep, water was collected at mid-depth in the water column. At sites 1–2 m deep, water was collected at mid-depth in the water column and at 0.5 m below the water surface. At sites greater than 2 m deep, water was collected at 1 m and 0.5 m below the water surface. Water was transferred from the Van Dorn to a churn splitter and mixed slowly and evenly ten times before filling bottles with sample water, and was also mixed as bottles were being filled with sample water. Samples for N, P, C, chlorophyll *a*, and phytoplankton analyses were collected from the same mixed water. All samples were stored in a cooler on ice at about 4°C until further processing immediately after field sampling.

Site parameters including water depth, water transparency (measured using a secchi disk), density of surface algal bloom (measured on a 0–5 scale), and presence or absence of vegetation were recorded at each sampling site. Water temperature, dissolved oxygen concentration (DO), pH, and specific conductance were also measured instantaneously at each site using a multi-probe instrument (YSI 600 XLM).

Nitrogen and P samples were analyzed by the Klamath Tribes' Sprague River Water Quality Laboratory in Chiloquin, Oregon. Approximately 120 mL of unfiltered sample water was transferred to triple-rinsed 125 mL amber polyethylene bottles and acidified with 1 mL 4.5 Normal H_2SO_4 for analysis of TN and TP. Total P and TN samples were digested using potassium persulfate, autoclaved, and analyzed on an automated spectrophotometer (SM 4500-P H and Enzymatic NO3). Samples for dissolved N and P analysis were filtered on the day of sampling through 0.45 µm sterile membrane filters (Millipore®) using a vacuum pump and a 300 mL magnetic filter funnel (Pall Gelman ®). Filtered samples were transferred to triple-rinsed 125 mL amber polyethylene bottles. Analyses of samples for PO_4, NO_3+NO_2, NO_2, and NH_4 were completed using the colorimetric method on the same automated spectrophotometer (SM 4500-P F, Enzymatic NO3, SM 4500-NO2, and MD Krom). All N and P samples were stored at 4°C and analyzed within 28 days.

Carbon samples were analyzed by Basic Laboratory, Inc. in Redding, California using the persulfate-ultraviolet oxidation method (SM5310, SM5310C). Samples for TOC were preserved with 4.5 Normal H_2SO_4 and DOC samples were filtered prior to analysis. Chlorophyll *a* samples were preserved with 4.5 Normal H_2SO_4 and analyzed by Aquatic Research, Inc. in Seattle, Washington (SM10200H). All C and chlorophyll *a* samples were shipped on ice overnight to the respective laboratories. Phytoplankton samples were preserved with Lugol's solution on the day of sampling and analyzed by PhycoTech, Inc. in St. Joseph, Michigan.

Concentrations of N, P, and C were reported and included in analyses if they occurred above the reporting limit or between the reporting limit and detection limit. Concentrations less than the detection limit were reported and analyzed at half the detection limit value. Reporting and detection limits for all constituents can be found in Appendix A. Un-ionized ammonia

concentrations were calculated based on water temperature and pH collected concurrently with each sample using the following equations (Emerson et al. 1975):

1) $pK_a=0.09018+2729.92/T_{k,}$ where T_k=temperature in degrees Kelvin (273.2+temp°C)

2) fraction of un-ionized ammonia (fNH_3)= $1/(1+10^{(pK-pH)})$

3) un-ionized ammonia (NH_3) = $f(NH_3)*NH_4$

SAS® System for Windows, Release 9.1.3 (SAS Institute Inc. 2004) was used for all data analysis including the calculation of means and standard errors.

In order to assess grab sample precision and accuracy, equipment and laboratory blank samples were collected at least once and twice per year, respectively, split samples at 10% of the total number of samples collected each sampling day, and duplicate samples at least once per sampling event. Protocols for quality assurance sample collection followed methods described in the Williamson River Delta Water Quality Monitoring Project Plan (The Nature Conservancy 2008). Quality assurance results are provided in Appendix B.

Continuous In-situ Monitoring

Multi-probe instruments (YSI 600 XLM sondes) were deployed at each continuous monitoring site for the collection of hourly data including water temperature, DO, pH, and specific conductance. Sondes were placed at mid-depth in the water column or at 1 m below the water surface if water depth exceeded 2 m. Monitoring lasted from March/April–November during the 2008–2009 sampling periods. At transitional and emergent wetland sites, monitoring occurred until July and August, after which insufficient water was present to continue monitoring. At the UKLW25 site, data collected from June 9–September 29, 2008/2009 were provided by the USGS, which had approximately the same monitoring site location in Upper Klamath Lake as TNC. Hourly data collected by the USGS and presented in this report are provisional and subject to revision.

Calibrations were performed prior to sonde deployment to verify accuracy of each instrument. Sonde performance was checked for precision against a freshly calibrated reference instrument during weekly site visits. Sondes were cleaned, checked, and either redeployed or replaced such that an individual sonde was deployed at a site for no longer than two weeks at a time. Post-calibration checks were performed to verify accuracy of each sonde following a deployment. Data quality objectives adhered to requirements defined in the Williamson River Delta Water Quality Monitoring Project Plan (The Nature Conservancy 2008). Three levels of quality assurance criteria were used (Appendix C) to determine whether data were deemed acceptable to include in analysis. Instances where data did not meet requirements are reported in Appendix D.

Raw data collected from sondes were quality-checked before computing statistics. Data passing quality assurance criteria were deemed acceptable. Daily statistics were computed only for days with at least 20 hours of acceptable data recorded in a single day. All statistics were computed using SAS® System for Windows, Release 9.1.3 (SAS Institute Inc. 2004).

RESULTS

Nutrient, chlorophyll *a*, water chemistry, and phytoplankton composition results are described temporally (seasonally and annually) as well as spatially across the Delta wetlands and near-shore lakes and river. The terms 'early season', 'mid-season', and 'late season' are used to generally describe the periods March–June, July–September, and October–November, respectively. We also explore water chemistry results in relation to high stress threshold conditions for endangered suckers. Additionally, relationships between nutrients and chlorophyll *a* concentrations are explored because these relationships can provide information about nutrient limitation of algal growth in this wetland system.

Nutrients and Chlorophyll *a*

Tulana transitional and emergent wetlands generally had the highest maximum TP and PO_4 concentrations compared to all other locations (Table 2). In 2009, Goose Bay transitional and emergent wetlands had higher mean PO_4 concentrations than river and lake locations but were slightly lower than concentrations observed in Tulana transitional and emergent wetlands (Table 2, Figure 3). Deep water wetland and open water generally had higher P concentrations than the lakes in November 2007 (up to six times greater TP concentration) and the mid–late season periods in 2008 and 2009 (about 2.5 and 1.5 times greater TP concentration in 2008 and 2009, respectively) (Figures 3 & 4). Mean TP concentrations in deep water wetland, open water, and lake locations gradually increased beginning about mid June and peaked in late August/early September (Figure 4). Mean PO_4 concentrations generally followed similar seasonal trends as TP in 2008 and 2009 at all locations. As a percentage of TP in 2008 and 2009, PO_4 comprised on average 71% and 53% in the wetlands and 59% and 37% in the lakes, respectively. Phosphorus concentrations were generally lower in 2009 than 2008 at all locations except the Williamson River during the mid–late season periods (Figures 3 & 4). This difference is most apparent in deep water wetland and open water, where mean TP concentrations during the mid–late season periods were about 1.8 times lower in 2009 than in 2008. In the lakes, mean TP concentrations during the mid–late season periods were about 1.4 times lower in 2009 than 2008.

Deep water wetland and open water tended to have higher NH_4 and NO_3+NO_2 concentrations than the lakes during the mid-season periods in 2008, while in 2009 concentrations appeared more comparable between deep water wetland, open water, and lake locations (Figures 5 & 6). Nitrogen concentrations were generally comparable among habitat types in Tulana, although some variability occurred within habitat types during the mid–late

season periods. Total N concentrations at all locations began increasing about early June, while NH_4 and NO_3+NO_2 concentrations began to increase about mid-July at Tulana and lake locations (Figures 5–7). At deep water wetland, open water, and lake locations, NO_3+NO_2 concentrations generally increased through November, while NH_4 and TN concentrations generally peaked at two points during the mid–late season periods. Averaged over all locations and years, dissolved inorganic N comprised about 10% TN. In November 2007, NO_3+NO_2 concentrations in deep water wetland and open water were lower than in November 2008 and 2009, while TN and NH_4 concentrations within these habitat types in November of all three years were more comparable (Figures 5–7). In Tulana emergent and deep water wetlands, NH_4 concentrations were generally higher in 2008 compared to 2009 during the mid–late season periods.

Total and dissolved organic C concentrations at all locations except the Williamson River and Goose Bay wetlands increased beginning about late June and peaked in late July (Figures 8 & 9). Total organic C concentrations ranged from 3.7–23.1 mg/L among all habitat types and years in Tulana with the exception of one anomaly that occurred late August in open water, when a TOC concentration of 84.7 mg/L was observed at site TLOW20. Dissolved organic C followed similar trends as TOC and constituted the majority of TOC (about 90% of TOC among all locations and years) (Figure 9). Trends in C concentrations were generally comparable among Tulana and lake locations except at the end of each season, when C concentrations in open water and deep water wetland habitats were slightly higher than lake concentrations. At lake, open water, Tulana emergent, and deep water wetland locations, higher C concentrations were observed in 2008 compared to 2009 during the mid–late summer period.

Peaks in chlorophyll *a* concentration generally occurred in late June/early July and late August/early September at open water, deep water wetland, and lake locations (Figure 10). In Tulana transitional and emergent wetlands, peaks in chlorophyll *a* also occurred between mid-June and early August, while chlorophyll *a* concentrations in the Goose Bay wetlands were generally comparable to the Williamson River. In Tulana, chlorophyll *a* concentrations were lowest in transitional and emergent wetlands. Seasonal trends in chlorophyll *a* concentration in open water, deep water wetland, and lake locations were overall comparable in both 2008 and 2009. In Tulana, some variability in chlorophyll *a* occurred within habitat types during the mid–late season periods. Timings of seasonal peaks in chlorophyll *a* varied between monitoring years at Tulana and lake locations. Seasonal trends in secchi depth were usually inversely related to seasonal trends in chlorophyll *a* at both lake and Delta locations, although at shallow wetland sites this was not always the case (e.g. TLTR5 shown in Figure 11). Additionally, seasonal trends in chlorophyll *a* were generally inversely related to trends in dissolved inorganic N (DIN: sum of NH_4 and NO_3+NO_2) (Figure 12) and PO_4 in the mid-late season period (Figure 13) at wetland and lake sites.

To examine relationships between nutrients and chlorophyll *a* in the wetlands, we attempted to fit the data into a simple linear regression model using log-transformed data in order to correct for heteroscedasticity (increasing variance with increasing mean). *(continued on p.28)*

Table 2. Yearly median, minimum, and maximum concentrations by location for grab sampling constituents collected within and surrounding the Williamson River Delta, Oregon, 2007–2009. In 2007, sampling occurred October–November.

	Total Phosphorus (mg/L)									Orthophosphate (mg/L)								
	2007			2008			2009			2007			2008			2009		
Location	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max
Tulana-Transitional Wetland	NA	NA	NA	0.38	0.09	1.41	0.30	0.13	0.89	NA	NA	NA	0.31	0.05	1.22	0.194	0.065	0.684
Tulana-Emergent Wetland	NA	NA	NA	0.32	0.07	1.51	0.25	0.08	1.40	NA	NA	NA	0.23	0.05	1.68	0.161	0.014	0.894
Tulana-Deep Water Wetland	0.46	0.17	0.63	0.34	0.09	1.07	0.190	0.075	0.560	0.25	0.11	0.53	0.208	0.006	0.770	0.073	0.005	0.210
Tulana-Open Water	0.150	0.100	0.260	0.308	0.070	1.050	0.168	0.071	0.566	0.114	0.050	0.240	0.193	0.042	0.724	0.085	0.010	0.240
Goose Bay-Transitional Wetland	NA	NA	NA	NA	NA	NA	0.145	0.104	0.522	NA	NA	NA	NA	NA	NA	0.103	0.060	0.352
Goose Bay-Emergent Wetland	NA	NA	NA	NA	NA	NA	0.175	0.090	0.722	NA	NA	NA	NA	NA	NA	0.13	<0.003	0.433
Williamson River	0.0680	0.0500	0.0700	0.08	0.07	0.23	0.085	0.067	0.251	0.0707	0.0700	0.0700	0.074	0.045	0.196	0.067	0.020	<0.003
Lake Sites	0.065	0.040	0.100	0.153	0.054	0.392	0.125	0.041	0.406	0.026	0.020	0.070	0.091	0.019	0.344	0.051	0.004	0.176

	Total Nitrogen (mg/L)									Nitrate + Nitrite (mg/L)								
	2007			2008			2009			2007			2008			2009		
Location	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max
Tulana-Transitional Wetland	NA	NA	NA	0.86	0.45	4.13	0.95	0.48	2.55	NA	NA	NA	<0.008	<0.008	0.013	<0.008	<0.008	0.054
Tulana-Emergent Wetland	NA	NA	NA	0.89	0.16	5.24	1.01	0.45	3.20	NA	NA	NA	<0.008	<0.008	0.034	<0.008	<0.008	0.157
Tulana-Deep Water Wetland	1.7	0.9	2.5	1.98	0.45	8.71	1.61	0.44	5.81	0.022	<0.008	0.170	0.017	<0.008	0.375	0.008	<0.008	0.313
Tulana-Open Water	1.10	0.85	1.54	1.71	0.48	9.34	1.59	0.42	5.92	0.119	<0.008	0.170	0.028	<0.008	0.400	<0.008	<0.008	0.348
Goose Bay-Transitional Wetland	NA	NA	NA	NA	NA	NA	0.65	0.38	1.30	NA	NA	NA	NA	NA	NA	<0.008	<0.008	0.018
Goose Bay-Emergent Wetland	NA	NA	NA	NA	NA	NA	0.58	0.42	1.77	NA	NA	NA	NA	NA	NA	<0.008	<0.008	0.015
Williamson River	0.088	0.070	0.150	0.26	0.10	1.43	0.32	0.08	2.21	0.0078	0.0100	0.0100	0.0105	<0.008	0.0400	0.0095	<0.008	0.0380
Lake Sites	0.83	0.09	1.51	1.27	0.19	2.11	1.14	0.08	3.59	0.143	0.010	0.200	0.016	<0.008	0.249	<0.008	<0.008	0.292

	Ammonium (mg/L)									Chlorophyll *a* (µg/L)								
	2007			2008			2009			2007			2008			2009		
Location	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max
Tulana-Transitional Wetland	NA	NA	NA	0.024	0.003	0.393	0.018	0.007	0.482	NA	NA	NA	9	2	250	17	6	148
Tulana-Emergent Wetland	NA	NA	NA	0.02	0.01	1.14	0.020	0.006	0.796	NA	NA	NA	17	4	288	23	3	221
Tulana-Deep Water Wetland	0.068	0.020	0.150	0.05	0.01	1.57	0.021	<0.006	0.478	NA	NA	NA	56	1	750	76	12	589
Tulana-Open Water	0.057	0.020	0.150	0.039	0.014	0.555	0.021	0.007	0.517	NA	NA	NA	63	3.7	964	61	6	443
Goose Bay-Transitional Wetland	NA	NA	NA	NA	NA	NA	0.015	0.007	0.156	NA	NA	NA	NA	NA	NA	5	1	65
Goose Bay-Emergent Wetland	NA	NA	NA	NA	NA	NA	0.014	<0.006	0.118	NA	NA	NA	NA	NA	NA	6.5	1	45
Williamson River	0.0118	0.0100	0.0200	0.023	0.006	0.194	0.019	<0.006	0.108	NA	NA	NA	1.4	0.5	14.0	1.00	<0.0001	2.00
Lake Sites	0.128	0.010	0.220	0.031	0.011	0.430	0.015	0.007	0.445	NA	NA	NA	71	4	331	47	6	246

	Total Organic Carbon (mg/L)									Dissolved Organic Carbon (mg/L)								
	2007			2008			2009			2007			2008			2009		
Location	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max
Tulana-Transitional Wetland	NA	NA	NA	9.3	6.3	22.2	8.8	5.9	13.1	NA	NA	NA	9	7	22	7.8	4.4	11.9
Tulana-Emergent Wetland	NA	NA	NA	8.2	5.4	16.6	8.0	5.8	11.6	NA	NA	NA	8.2	6.0	13.4	7.21	4.80	10.30
Tulana-Deep Water Wetland	NA	NA	NA	11.1	5.4	23.1	8.0	5.8	14.1	NA	NA	NA	9.7	5.4	15.7	6.60	4.80	11.40
Tulana-Open Water	NA	NA	NA	10.3	4.1	84.7	8.50	6.20	11.20	NA	NA	NA	8.8	4.0	14.7	7.53	4.70	10.50
Goose Bay-Transitional Wetland	NA	NA	NA	NA	NA	NA	6.05	4.70	8.10	NA	NA	NA	NA	NA	NA	5.80	4.60	7.95
Goose Bay-Emergent Wetland	NA	NA	NA	NA	NA	NA	6.2	3.7	12.9	NA	NA	NA	NA	NA	NA	5.85	4.00	10.40
Williamson River	NA	NA	NA	2.5	1.2	7.6	2.3	1.1	6.2	NA	NA	NA	2.8	0.7	7.7	2.3	1.0	6.0
Lake Sites	NA	NA	NA	8.1	4.0	14.1	7.00	4.30	9.10	NA	NA	NA	6.9	3.5	10.8	6.10	4.20	8.50

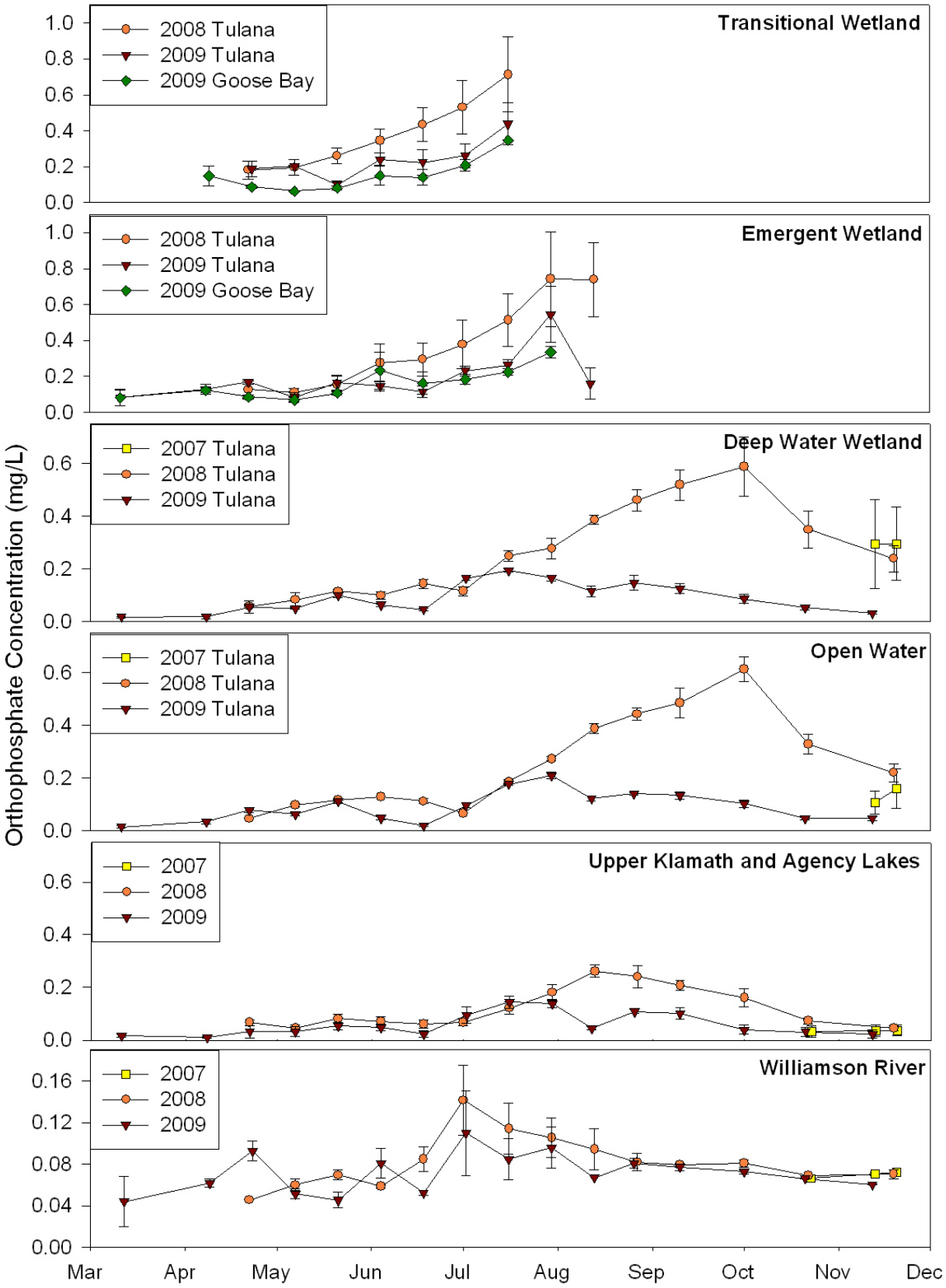

Figure 3. Seasonal trends in mean orthophosphate concentration, Williamson River Delta, Oregon, 2007–2009.Shown are means (± standard error) within each location by sampling event. Note different scales.

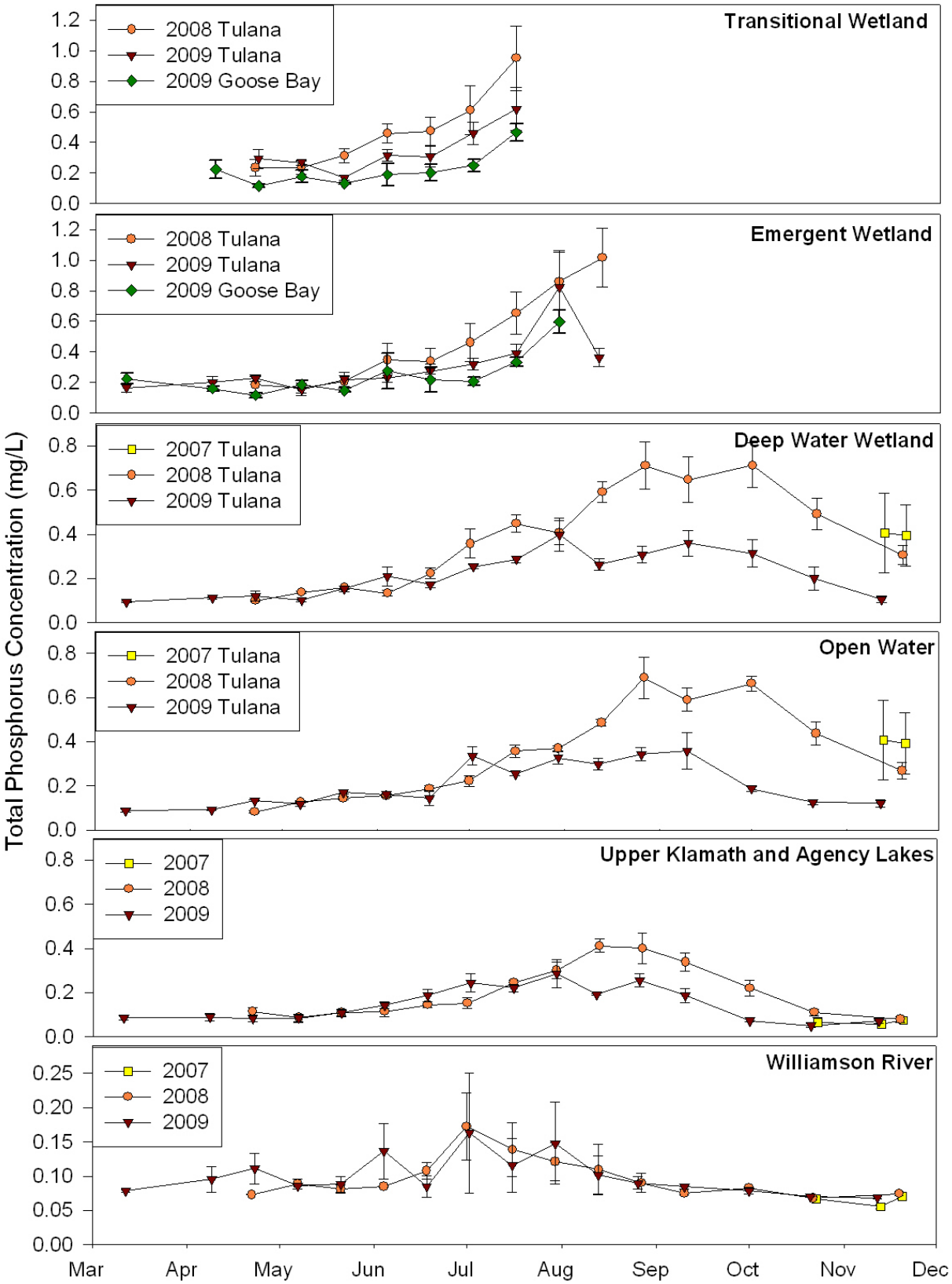

Figure 4. Seasonal trends in mean total phosphorus concentration, Williamson River Delta, Oregon, 2007–2009.Shown are means (± standard error) within each location by sampling event. Note different scales.

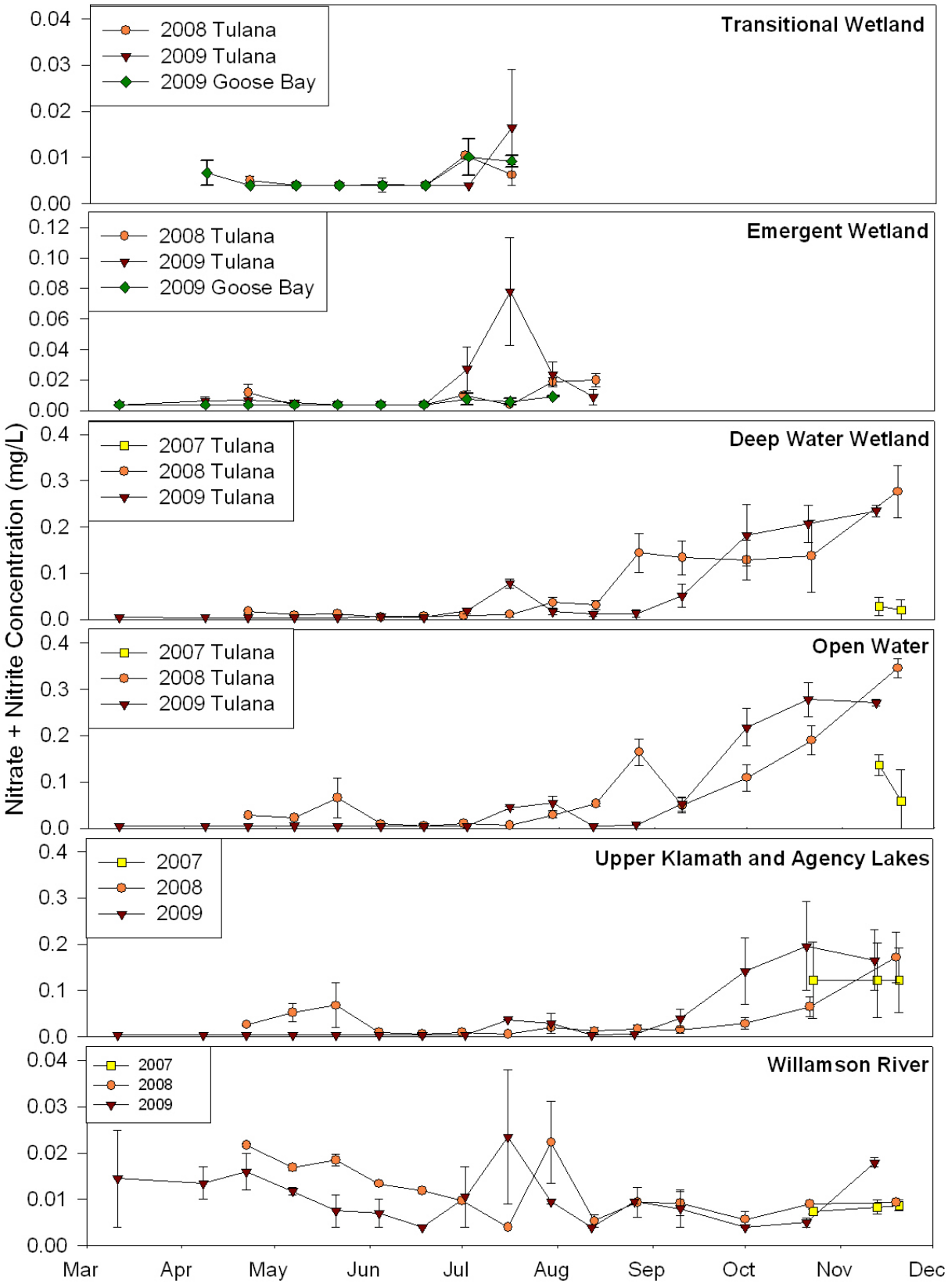

Figure 5. Seasonal trends in mean nitrate+nitrite concentration, Williamson River Delta, Oregon, 2007–2009. Shown are means (± standard error) within each location by sampling event. Note different scales.

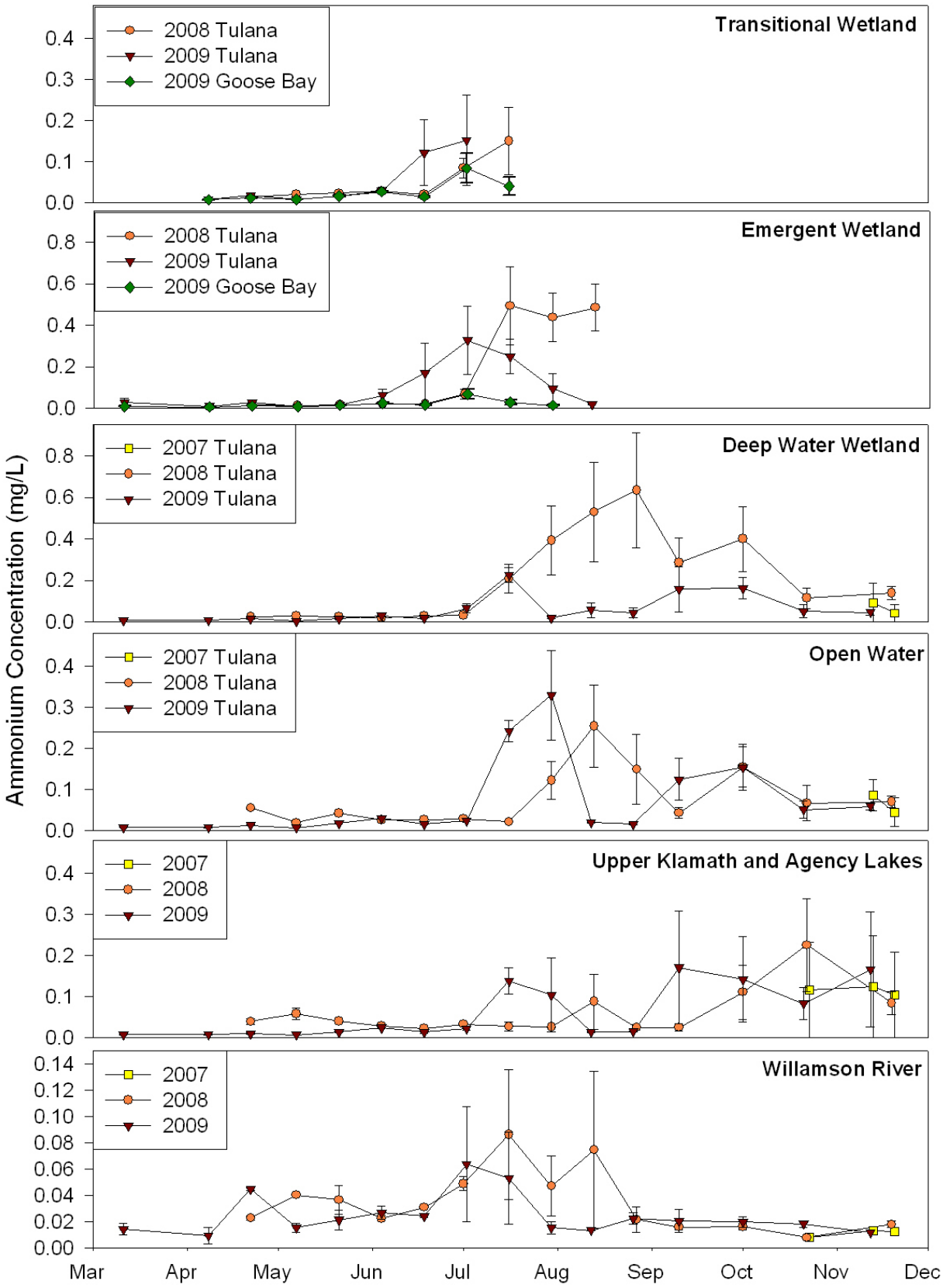

Figure 6. Seasonal trends in mean ammonium concentration, Williamson River Delta, Oregon, 2007–2009. Shown are means (± standard error) within each location by sampling event. Note different scales.

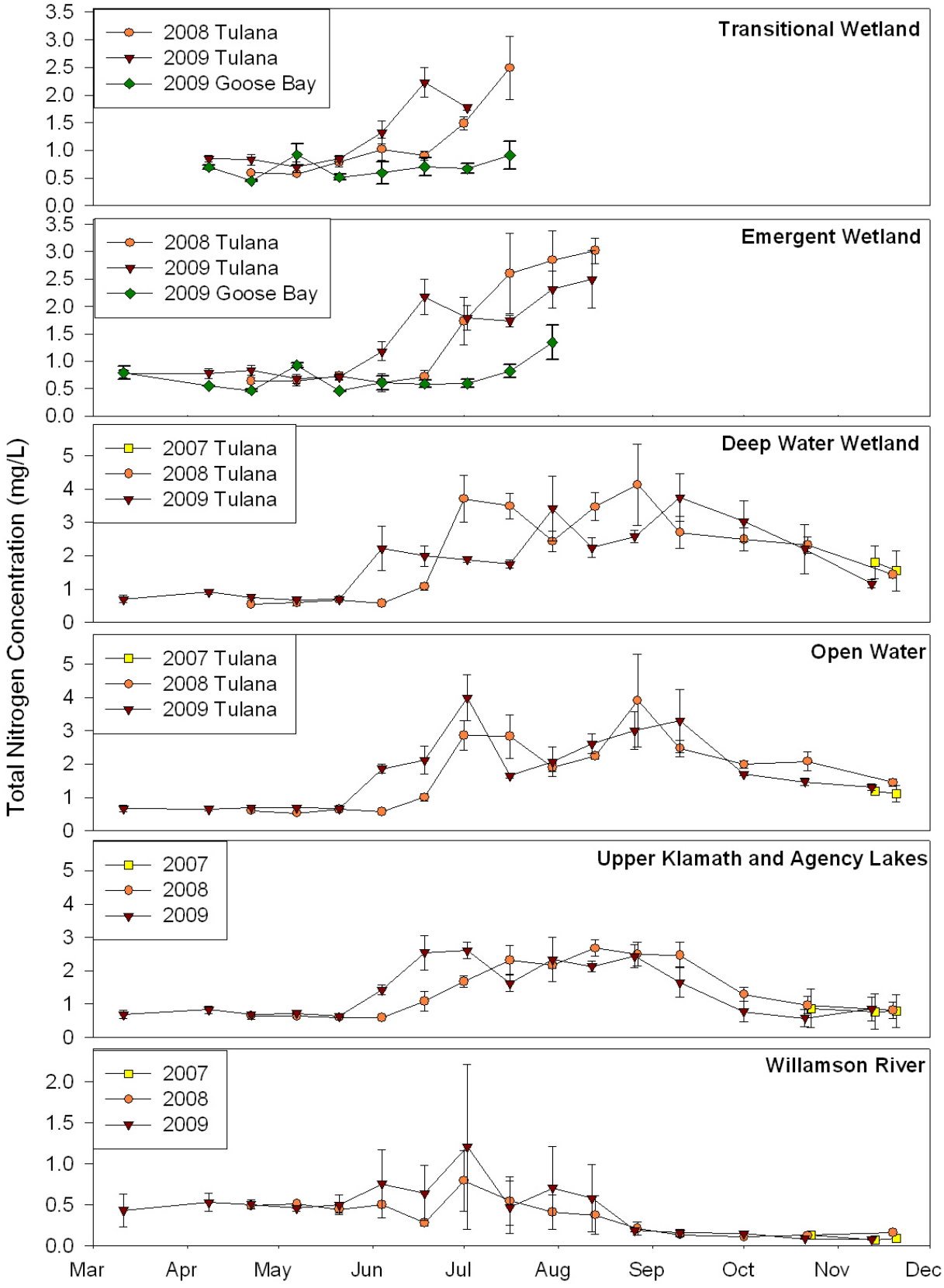

Figure 7. Seasonal trends in mean total nitrogen concentration, Williamson River Delta, Oregon, 2007–2009. Shown are means (± standard error) within each location by sampling event. Note different scales.

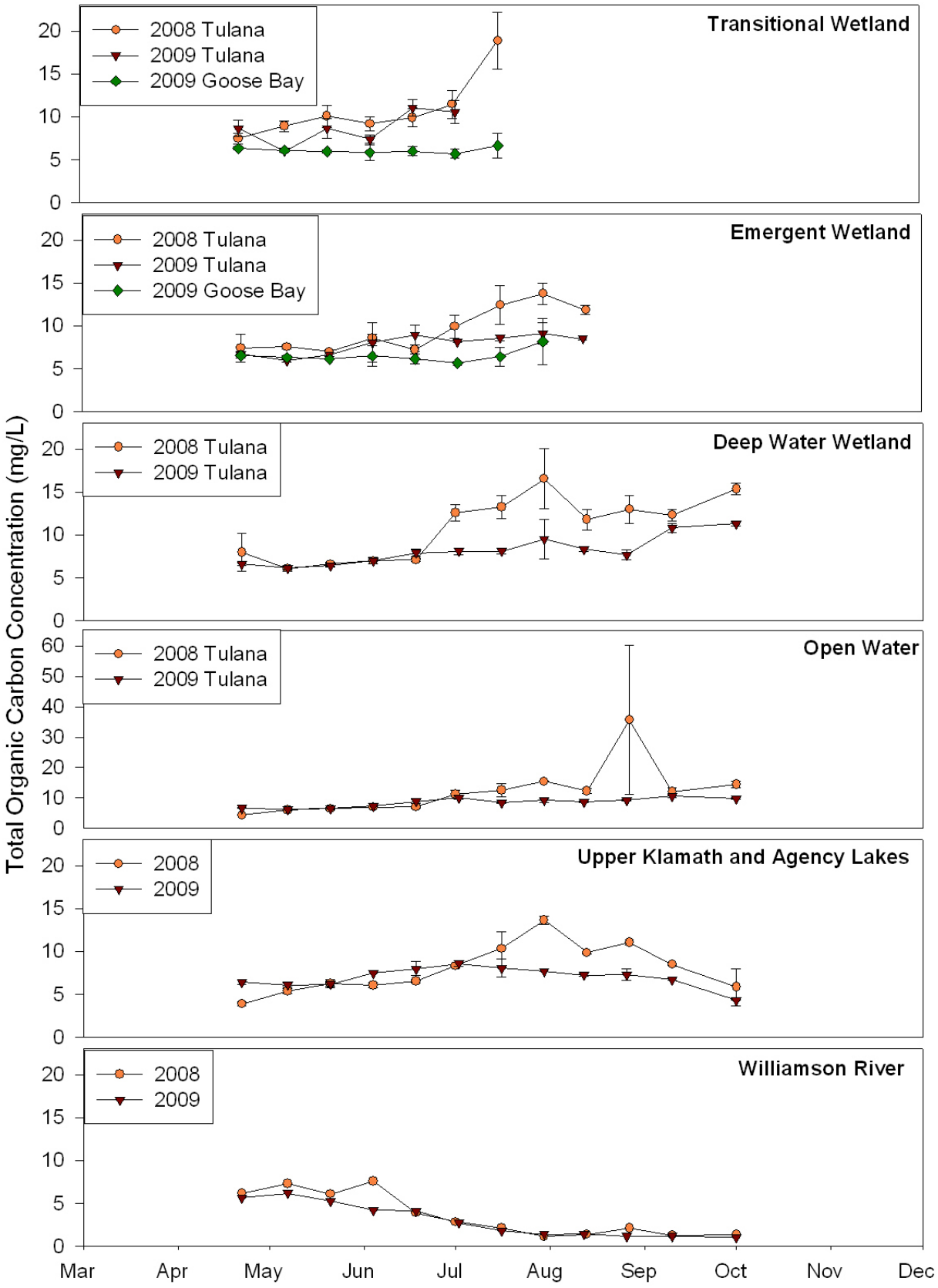

Figure 8. Seasonal trends in mean total organic carbon concentration, Williamson River Delta, Oregon, 2008–2009. Shown are means (± standard error) within each location by sampling event. Note different scales.

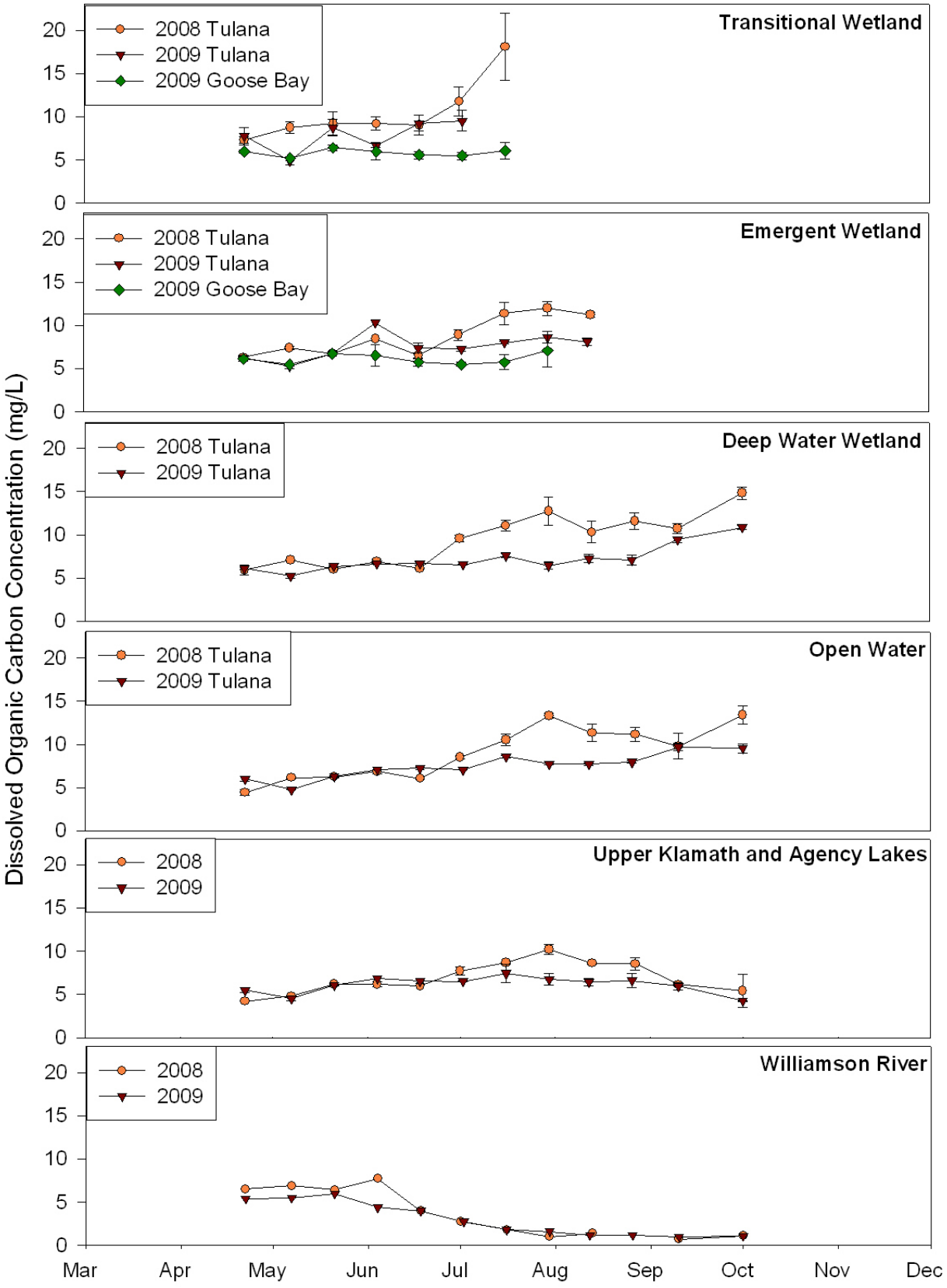

Figure 9. Seasonal trends in mean dissolved organic carbon concentration, Williamson River Delta, Oregon, 2008–2009. Shown are means (± standard error) within each location by sampling event.

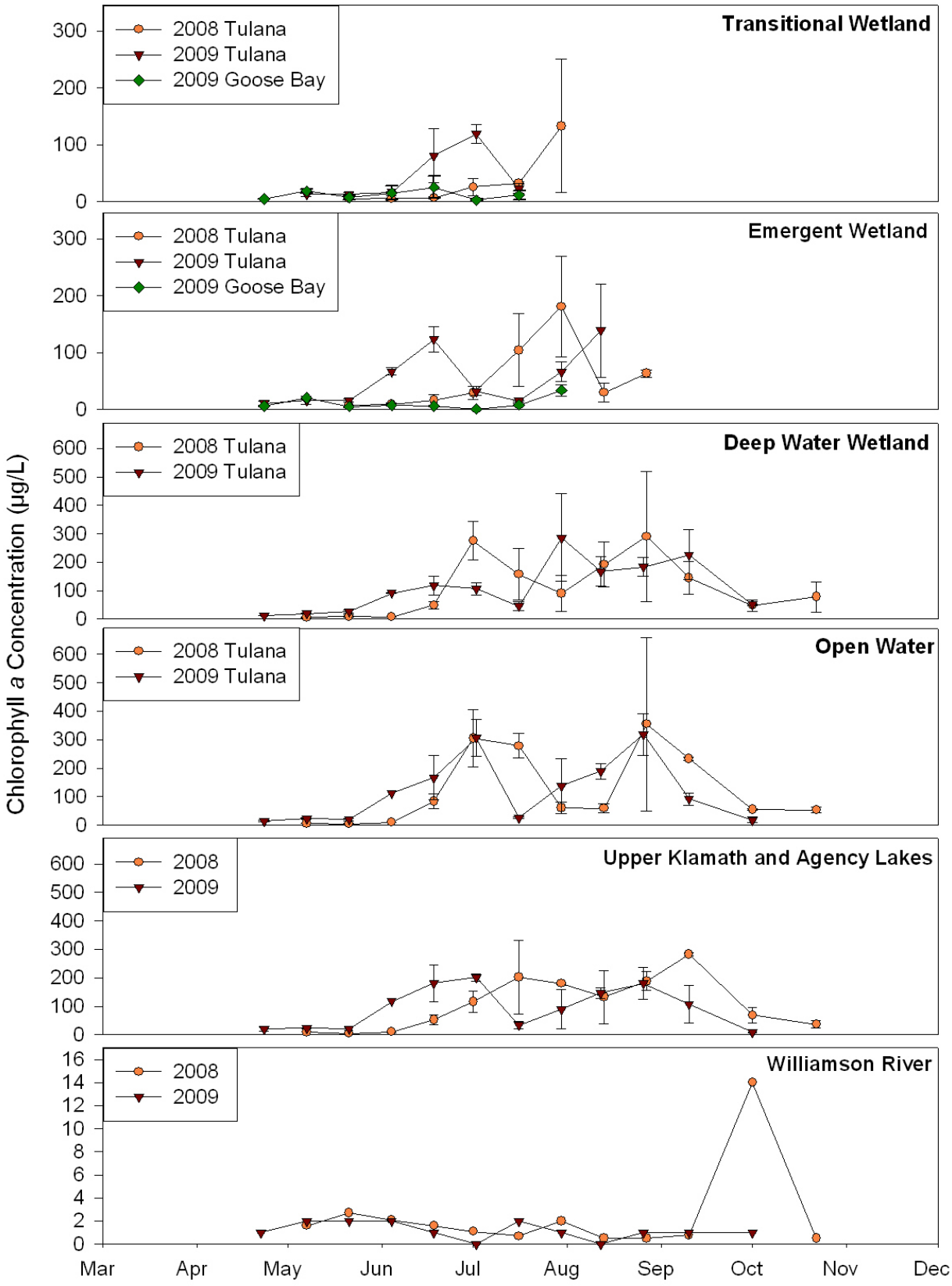

Figure 10. Seasonal trends in mean chlorophyll *a* concentration, Williamson River Delta, Oregon, 2008–2009. Shown are means (± standard error) within each location by sampling event. Note different scales.

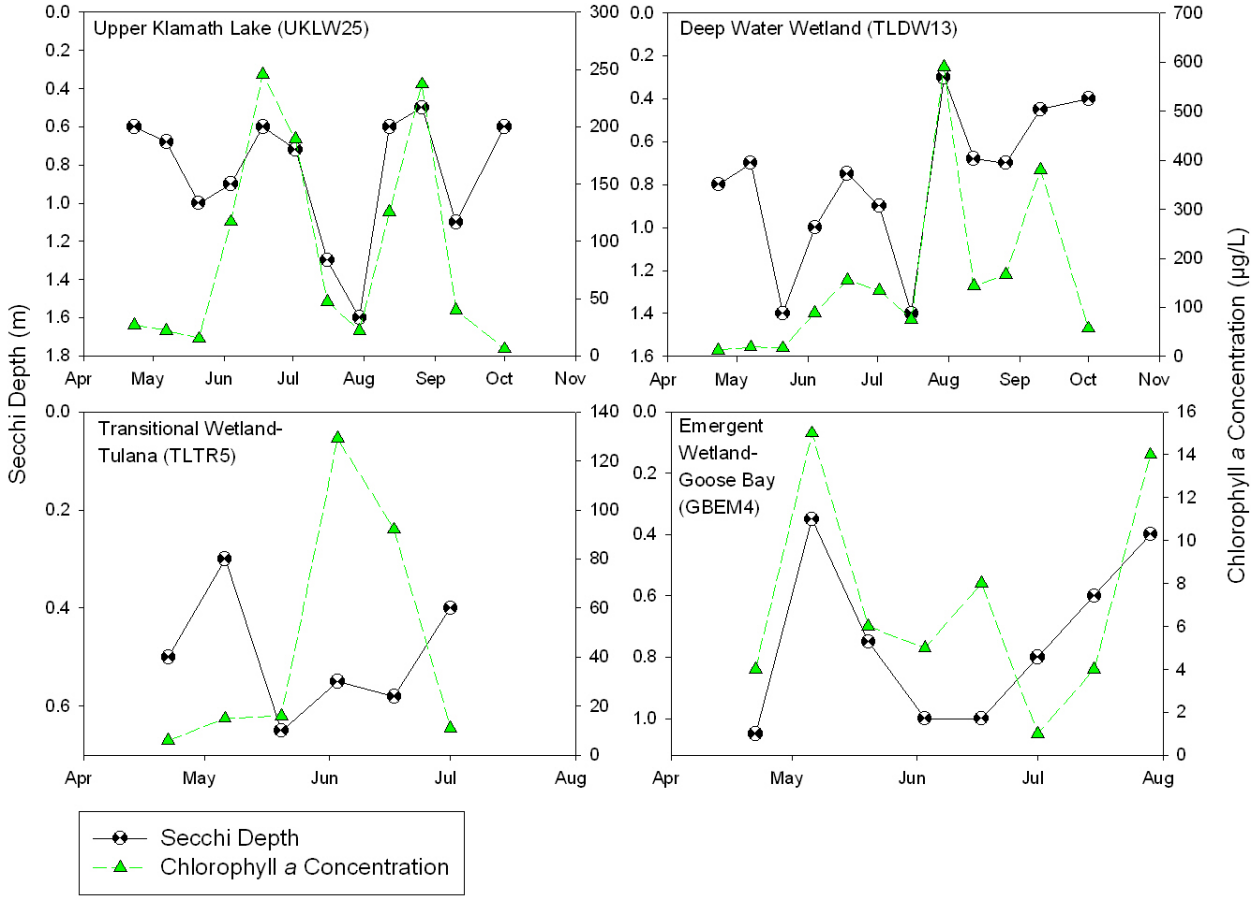

Figure 11. Seasonal trends in secchi depth in relation to chlorophyll *a* concentration at selected sites, Williamson River Delta, Oregon, 2009.

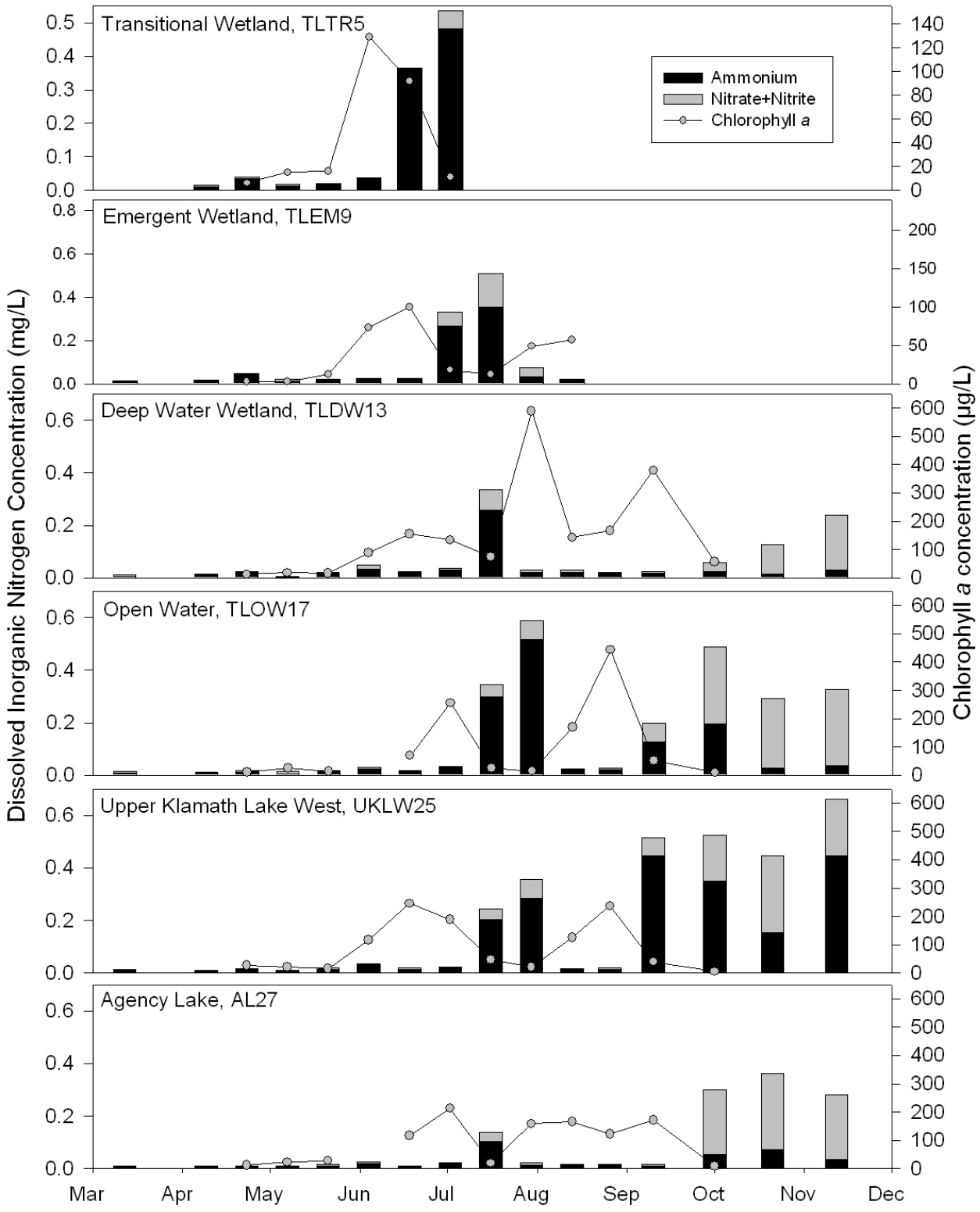

Figure 12. Seasonal trends in dissolved inorganic nitrogen in relation to chlorophyll *a* concentration at selected sites, Williamson River Delta, Oregon, 2009.

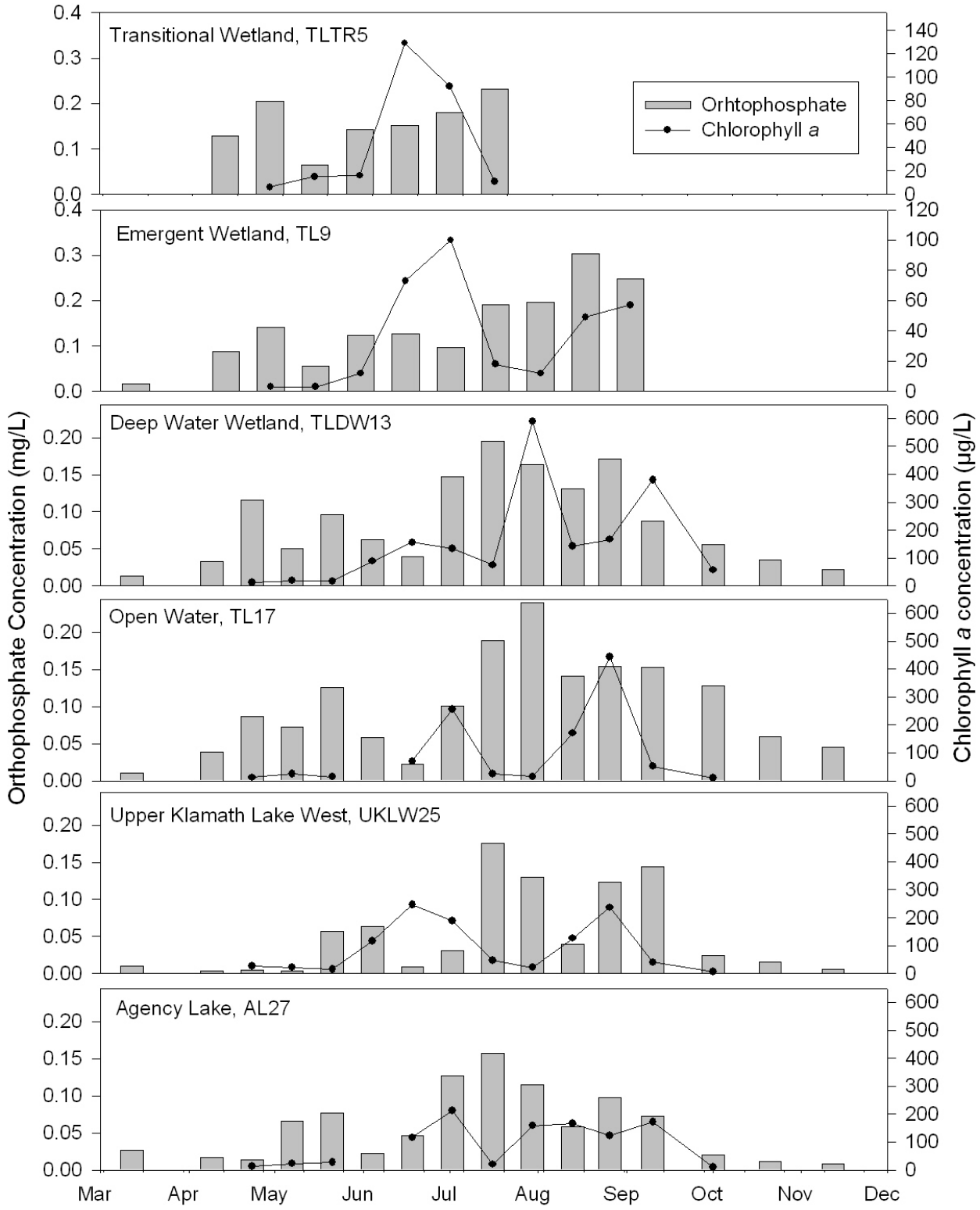

Figure 13. Seasonal trends in orthophosphate in relation to chlorophyll *a* concentration at selected sites, Williamson River Delta, Oregon, 2009.

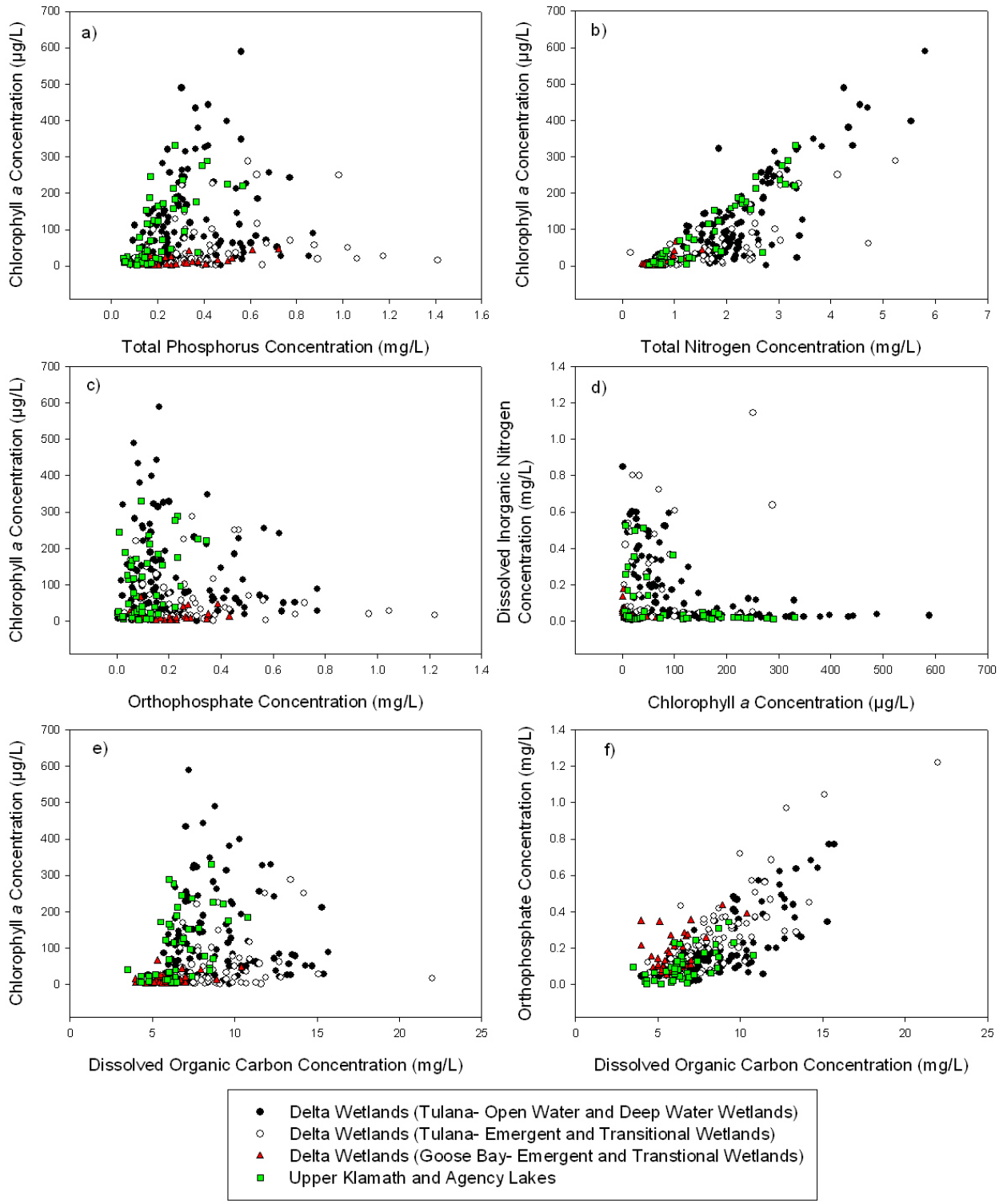

Figure 14. Scatterplots of chlorophyll *a* and nutrient constituent concentrations (panels a-e) and dissolved organic carbon and orthophosphate concentrations (panel f), Williamson River Delta, Oregon, 2008–2009.

In most cases, data did not meet the assumptions of a linear regression model (not shown) and a more robust analysis may be needed to examine these data. However, based on scatterplots of non-transformed data there appears to be a linear, positive relationship between TN and chlorophyll *a* (Figure 14b), as well as a curvilinear, inverse relationship between DIN and chlorophyll *a*, where DIN rises with low chlorophyll *a*, and chlorophyll *a* rises with low DIN (Figure 14d). We plotted the data with different symbols for each habitat type, and there were no apparent strong differences among these. Contrary to expectations, there did not appear to be strong relationships between P and chlorophyll *a*, nor between DOC and chlorophyll *a*.

Continuous In-situ Water Chemistry

Ranges in water chemistry parameters at all locations during the 2008–2009 monitoring period are shown in Table 3, while seasonal trends are shown in Figures 15 and 16. Water temperatures at all sites peaked in late July/early August. Seasonal trends in water temperature at lake and wetland sites followed trends in the Williamson River until about mid-June, when temperatures increased and diverged from river temperatures. The highest temperatures were

Table 3. Yearly median, minimum, and maximum temperature, dissolved oxygen concentration, pH, and specific conductance values recorded hourly in each monitoring location, Williamson River Delta, Oregon, 2008–2009.

	Temperature (°C)						Dissolved Oxygen (mg/L)					
	2008			2009			2008			2009		
Location	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max
Tulana- Transitional Wetland (TLTR5)	16.7	6.4	30.1	15.6	1.2	31.3	6.2	0.2	18.4	8.7	0.2	19.3
Tulana- Emergent Wetland (TLEM9)	20.0	7.3	31.9	17.9	4.0	30.6	7.3	0.1	16.1	9.0	0.9	24.1
Tulana- Deep Water Wetland (TLDW13)	16.4	1.8	26.4	17.0	1.0	27.6	7.1	0.2	21.9	9.6	1.5	23.4
Tulana- Open Water (TLOW17)	15.8	2.2	26.0	17.1	1.7	26.8	9.0	1.5	21.8	9.6	1.1	19.2
Goose Bay- Emergent Wetland (GBEM4)	NA	NA	NA	16.9	2.5	31.9	NA	NA	NA	9.4	2.4	15.2
Williamson River (WR21)	13.1	2.4	20.4	13.3	2.0	20.4	9.5	7.2	12.6	9.6	6.9	12.4
Agency Lake (AL27)	15.7	1.7	28.1	16.9	1.0	27.0	9.8	2.9	22.4	10.1	1.6	20.9
Upper Klamath Lake East (UKLE24)	9.0	2.4	22.5	14.9	0.8	26.8	10.4	6.1	16.2	9.8	1.3	18.3
Upper Klamath Lake West (UKLW25)	15.9	1.6	25.7	16.3	0.2	27.2	9.3	3.0	23.2	9.8	1.3	17.9

	pH						Specific Conductance (µS/cm)					
	2008			2009			2008			2009		
Location	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max
Tulana- Transitional Wetland (TLTR5)	7.6	6.7	10.0	7.9	6.8	10.5	128	81	275	122	81	265
Tulana- Emergent Wetland (TLEM9)	7.4	6.8	9.5	7.7	6.9	10.2	119	75	247	117	75	261
Tulana- Deep Water Wetland (TLDW13)	7.3	6.6	10.4	8.0	6.7	10.4	143	77	203	120	87	164
Tulana- Open Water (TLOW17)	7.8	7.0	10.4	7.9	6.7	10.5	137	100	193	123	104	168
Goose Bay- Emergent Wetland (GBEM4)	NA	NA	NA	7.6	6.6	9.4	NA	NA	NA	102	77	169
Williamson River (WR21)	7.8	7.0	9.0	8.0	6.9	8.8	93	73	103	94	60	105
Agency Lake (AL27)	8.6	6.8	10.4	8.2	6.9	10.6	113	96	184	112	95	151
Upper Klamath Lake East (UKLE24)	7.7	6.9	9.7	8.0	6.7	10.2	101	90	145	107	87	152
Upper Klamath Lake West (UKLW25)	8.5	6.9	10.4	8.0	6.9	10.2	111	88	157	111	80	139

generally observed in the shallow transitional and emergent wetlands. During the mid-season period, daily median water temperatures were on average about 5–6°C higher at Tulana sites compared to the river. During the period May–June, water temperatures were about 1–2°C higher in transitional and emergent wetlands compared to the river, and temperatures were slightly higher at all locations in 2009 than 2008 during this early season period.

Dissolved oxygen concentrations were generally variable spatially and temporally. At lake sites, peaks in DO concentration generally occurred at two points during the season: mid-late June and late August-early September (Figure 15). During peak periods, DO concentrations in the lakes reached well above 100% saturation, with maximum concentrations above 20 mg/L. Peaks in DO at lake sites were generally about two weeks earlier in 2009 compared to 2008, and peak and crash cycles generally appeared more distinct in 2009. Trends in DO at open water and deep water wetland sites followed similar trends as in the lakes (Figure 16). The exception is in 2008 in the deep water wetland, where low DO concentrations persisted from late July until the end of August. During this period, low DO conditions were persistent throughout the day in deep water wetland, with hourly mean DO concentrations below 3 mg/L during the majority of August (Figure 17). At Tulana transitional and emergent wetland sites, DO concentrations declined after mid-late June, with concentrations reaching below 1 mg/L (Figure 16). Concentrations of DO inside Goose Bay wetlands were generally comparable with those in the Williamson River for most of the 2009 monitoring year. Strong diel trends in DO were evident at transitional and emergent wetland sites, with the strongest trends occurring in August in the emergent wetlands and in June in the transitional wetlands (Figure 17).

Similar to trends in DO, peaks in pH occurred at two points during the season (mid-late June and late August-early September), with values reaching well above 10 (Figures 15 & 16). Peaks in pH were generally about two weeks earlier in 2009 compared to 2008 at lake sites, while cycles of peak and decline in pH were more distinct in 2009. Trends in pH at the open water and deep water wetland sites followed similar trends as in the lakes in 2009. In 2008, however, noticeable drops in pH occurred in August in the open water and deep water wetlands that were not observed at lake sites. In Tulana transitional and emergent wetlands, pH values were generally higher in 2009 than 2008, and values and trends in 2009 were generally more comparable to those in open water and deep water wetlands in 2009 than in 2008. For most of the year, pH trends in Goose Bay followed trends in the Williamson River. Strong diel trends in pH were also evident in the transitional and emergent wetlands (data not shown), similar to diel patterns in DO at these shallow wetland sites.

Specific conductance values were highest inside Tulana, with higher values corresponding to shallower water depths (Table 3, Figures 15 & 16). In open water and deep water wetland, values reflected those at lake sites until about mid July–August when values increased through the season and diverged from lake values. At Tulana emergent and transitional wetland sites and in Goose Bay, values reflected those in the river until June, when values increased and diverged from river values. While lake trends in daily median specific conductance

appear similar from 2008 to 2009, values in open water and deep water wetland appear slightly lower in 2009 compared to 2008 during the mid–late season periods.

Occurrences of High Stress Threshold Conditions for Endangered Suckers

We examined the seasonal timing, location, and duration of conditions potentially harmful to the health of endangered suckers in the Delta wetlands and in near-shore lake waters during the 2008–2009 monitoring period. These conditions were based on high stress thresholds for Lost River and shortnose suckers in Upper Klamath Lake, and are characterized by water temperature>28°C, DO concentration<4 mg/L, pH > 9.7 (Loftus 2001), and un-ionized ammonia concentrations greater than 0.48–1.06 mg/L NH_3 (96-hour LC_{50} range for larval and juvenile Lost River and shortnose suckers) (Saike et al. 1999).

Exceedances of the pH threshold most prominently occurred at the near-shore lake sites (except at site UKLE24) and in open water and deep water wetlands, with exceedance conditions often persisting 100% of the day during summer months (Figure 18). At these locations, pH threshold exceedances occurred during the seasonal cycles of high pH, which corresponded with peaks in chlorophyll *a* concentrations (Figures 10, 15, & 16). In 2008, pH threshold exceedances were observed in open water and deep water wetland similar to lake sites during the early chlorophyll *a* peak period, but exceedances were not observed during the late peak period in the wetlands as they were observed in the lakes. In contrast, pH threshold exceedances were observed in open and deep water wetlands and lake sites during both the early and late chlorophyll *a* peak periods in 2009 (Figure 18).

Exceedances of DO threshold were observed seasonally at all Tulana sites, with conditions often lasting up to 100% of the day. At lake, open water, and deep water wetland sites, exceedances generally occurred following periods of peak pH and after seasonal declines in chlorophyll *a* concentration. This trend is most apparent in 2009. However, in 2008, DO concentrations exceeded the 4 mg/L threshold at the deep water wetland site for 80% of the total hours recorded in August.

Temperature exceedances were only observed in the shallow transitional and emergent wetlands; however, these exceedances appeared neither prolonged through the season nor severe during the day. Un-ionized ammonia concentrations in the wetlands were below the 96-hour LC_{50} range for larval and juvenile Lost River and shortnose suckers (0.48–1.06 mg/L NH_3) (Saike et al. 1999). Un-ionized ammonia concentrations were below the range of 0.01–0.06 mg/L except for several occurrences where one-time concentrations reached 0.06–0.17 mg/L in mid-July at three individual emergent wetland sites in 2008 and at one transitional wetland site in 2009. At the Williamson River site, no threshold exceedances were observed for any of the four parameters.

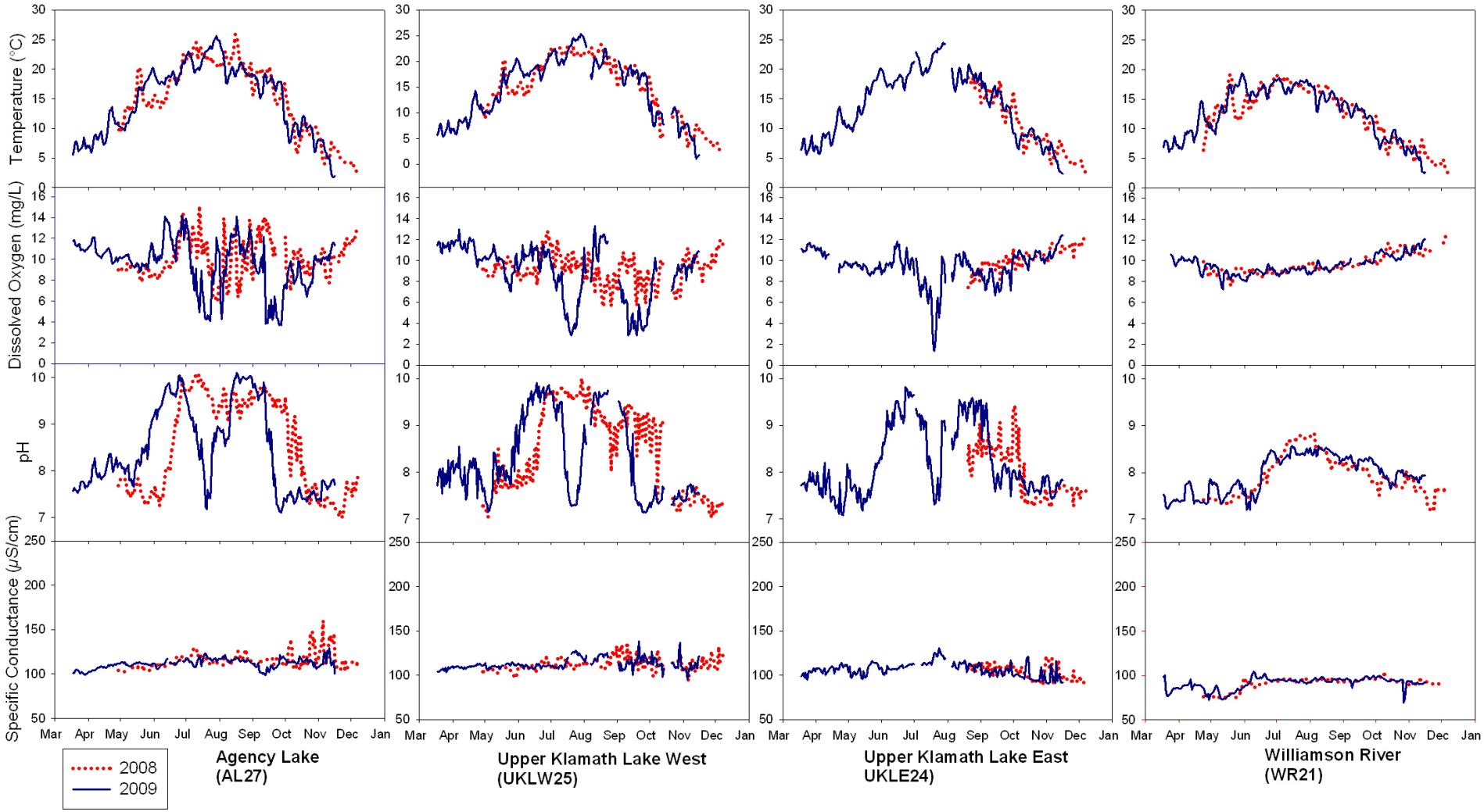

Figure 15. Seasonal trends in daily median temperature, dissolved oxygen concentration, pH, and specific conductance at near-shore lake and river continuous monitoring sites surrounding the Williamson River Delta, Oregon, 2008–2009.

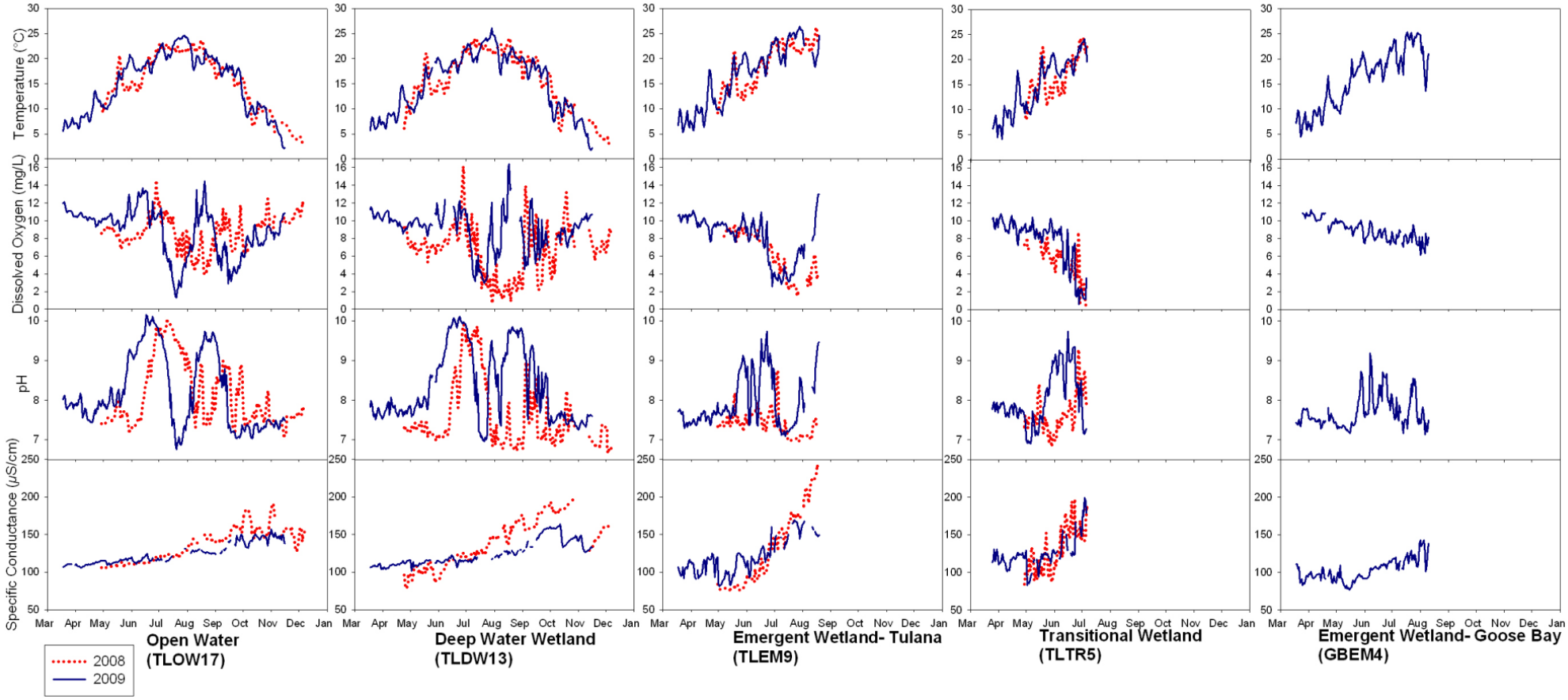

Figure 16. Seasonal trends in daily median temperature, dissolved oxygen concentration, pH, and specific conductance at continuous monitoring sites in the Delta wetlands, Williamson River Delta, Oregon, 2008–2009.

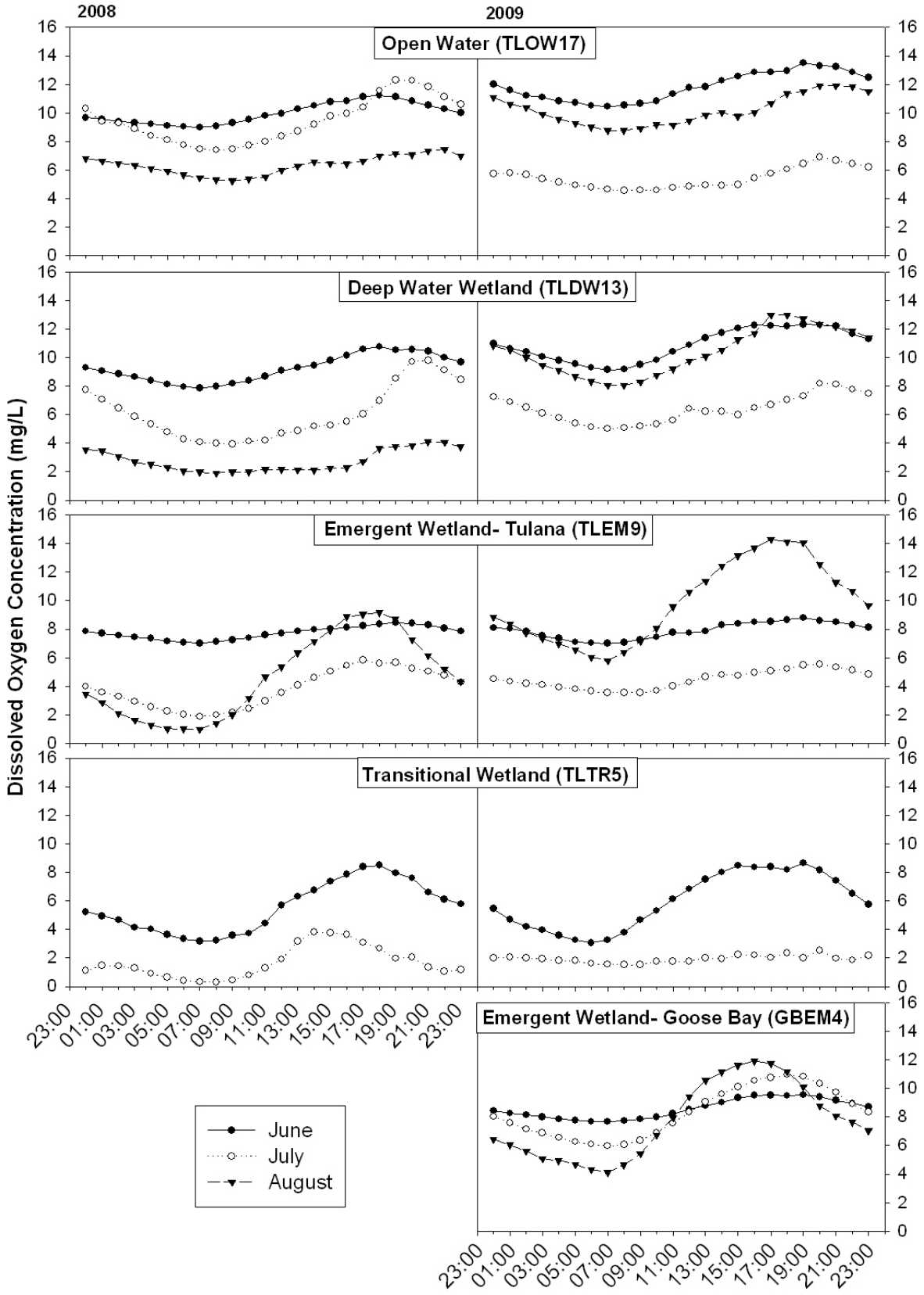

Figure 17. Diel trends in mean hourly dissolved oxygen concentration by month at continuous monitoring sites in the delta wetlands, Williamson River Delta, Oregon, 2008–2009.

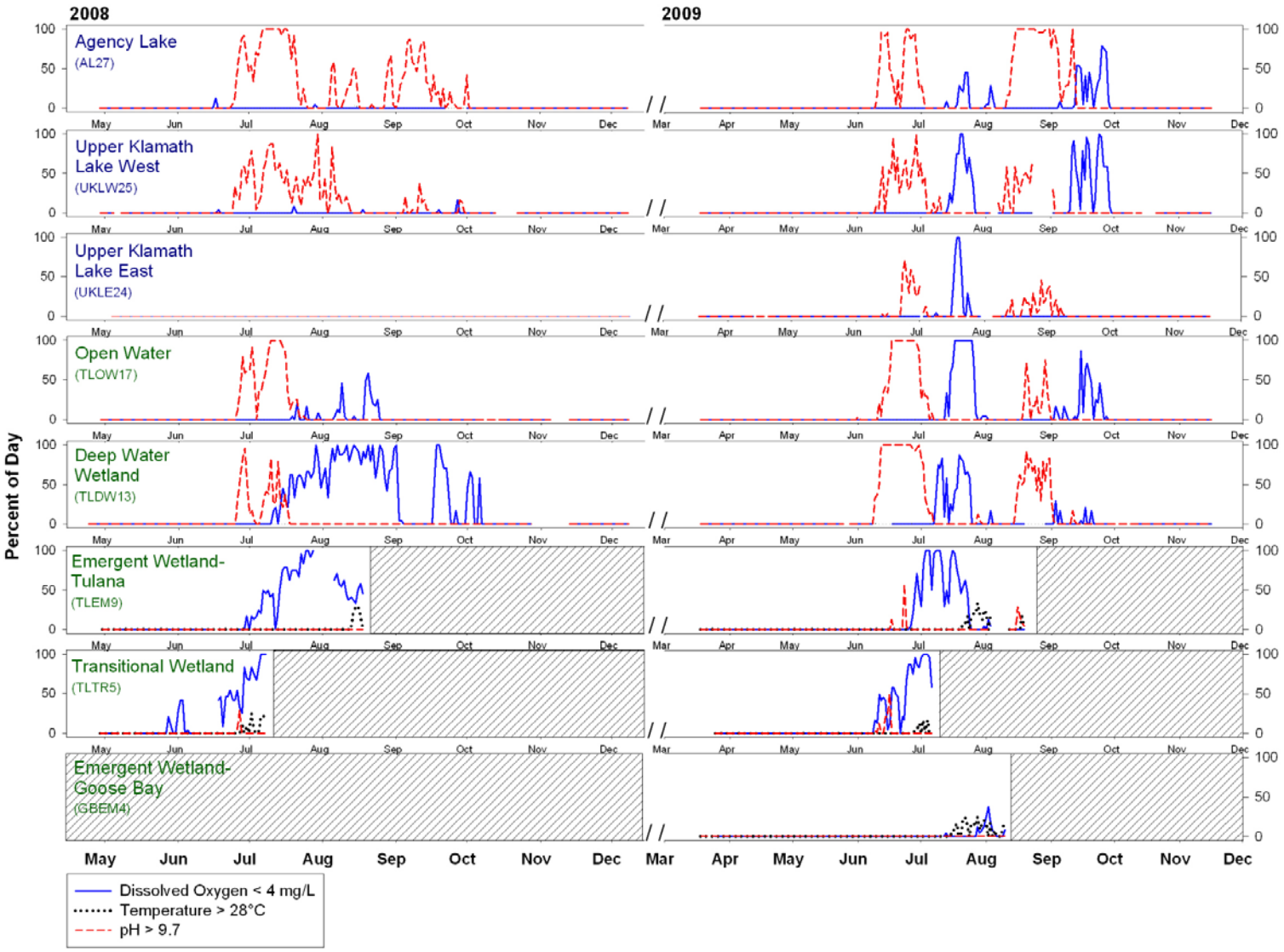

Figure 18. Time of year, location, and duration (percent of day) of water quality conditions potentially harmful to Lost River and shortnose suckers, Williamson River Delta, Oregon, 2008–2009. Hatched areas indicate time of year not sampled.

Phytoplankton

A list of all phytoplankton species encountered during the 2008–2009 sampling period is shown in Appendix E. Overall, total algal biovolumes (total algal biomass measured as total volume of algal cells per unit sample volume) were greatest at lake, open water, and deep water wetland sites, and lowest in the Williamson River (Figure 19). A total of 247 species were identified among all sites during the 2008–2009 sampling period, which includes 231 species observed inside the Delta wetlands (Tulana and Goose Bay), 58 at lake sites, and 84 in the river. Of the 247 species, 59 were identified only once during the two-year period. A schematic showing the number of overlapping and unique phytoplankton species among lake, river, and Delta wetland locations is shown in Figure 20. Broken down by habitat type, species richness in both years was greatest in transitional and emergent wetlands of Tulana and Goose Bay, and was lowest in open water and deep water wetlands (Figure 21).

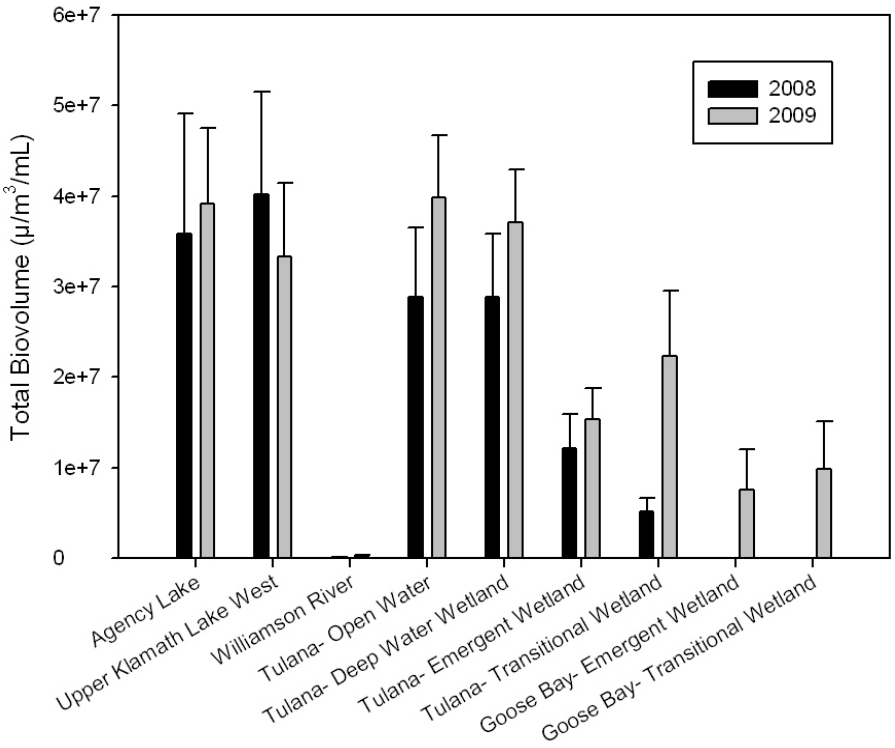

Figure 19. Mean (bars) and standard error (whiskers) total algal biovolume in 2008 and 2009 by location, Williamson River Delta, Oregon, 2008-2009.

Shannon's diversity index (H) accounts for both abundance and evenness of the species present, thus providing a useful metric of biodiversity other than species richness. PhycoTech, Inc. calculated the Shannon diversity index for each sample based on total biovolume for the algal sample (Magurran 1988). Mean Shannon diversity index values in open water and deep water wetlands were similar to values found in lake sites in both years (Figure 22). Values in the river, transitional wetlands, and emergent wetlands were greater and more consistent seasonally and in both 2008 and 2009.

Trends by Division

Representation of major phytoplankton groups (taxonomic divisions) overall varied by site, time of year, and sampling year, with some similarities observed within habitat types. Among all sites and years, the major groups most commonly represented were the cyanophytes (blue-green algae), bacillariophytes (diatoms), chlorophytes, cryptophytes, and chrysophytes. Total biovolumes generally peaked at some point during June–September at the majority of sites (Figures 23–25). Emergent and transitional wetland sites in Tulana and Goose Bay showed the greatest representation of groups throughout the entire sampling season and the lowest total biovolumes through the season in both years. In the Williamson River, the diatoms dominated the algal assemblage throughout the season. In lake, open water, and deep water wetland sites, the early season period was mostly represented by the cryptophytes and diatoms in 2008 and the diatoms in 2009, while the mid–late season periods were dominated by the cyanophytes. At lake and wetland sites, AFA appeared to be driving the trends in chlorophyll *a* concentrations during the mid–late seasons (Figure 26), and overall the species dominated the blue-green algae assemblage among all locations (Figures 27 & 28). In Goose Bay, total biovolume was higher

than in the river but lower than in lake and Tulana locations, and the major phytoplankton groups were well-represented throughout the season at most sites (Figure 25).

At least two noticeable differences in relative percent biovolume of the major groups occurred between the two sampling years. First, in 2009, all lake, open water, and deep water wetland sites were dominated by diatoms in the early season period (>80% April–May) compared to 2008, when the diatoms made up less than 50% of the algal assemblage at most of these sites and dates in the early season from early–late May (Figures 23 & 24). Second, in 2009, the cyanophytes made up a larger percentage of the algal assemblages at Tulana emergent and transitional wetland sites beginning in late May.

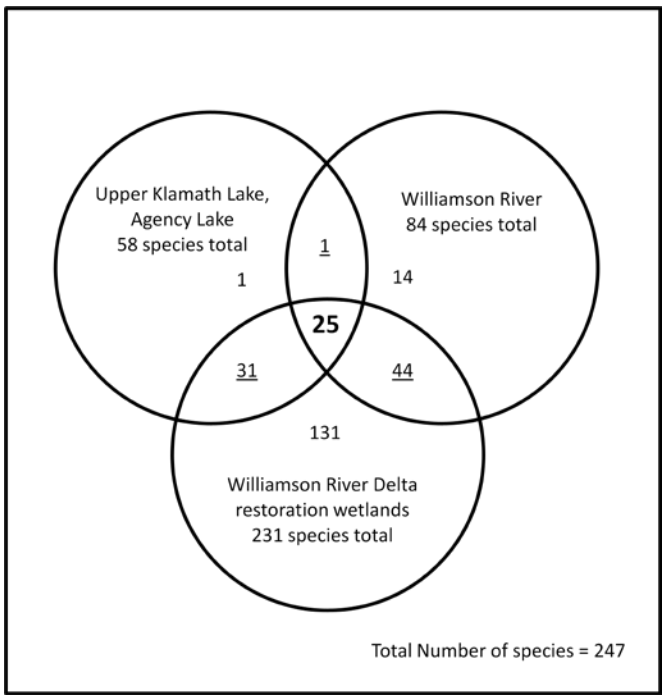

Figure 20. Venn diagram showing the number of unique and shared phytoplankton species observed in the Williamson River, lakes, and Delta wetlands, 2008–2009.

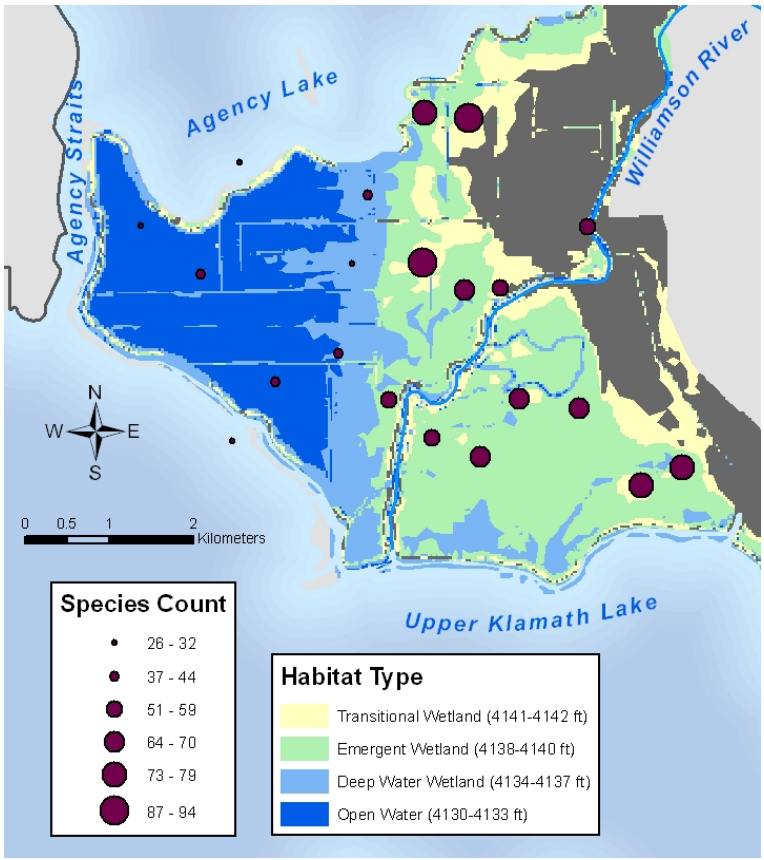

Figure 21. Spatial representation of total phytoplankton species count at sites sampled across the Williamson River Delta and at near-shore lake and river sites in 2009.

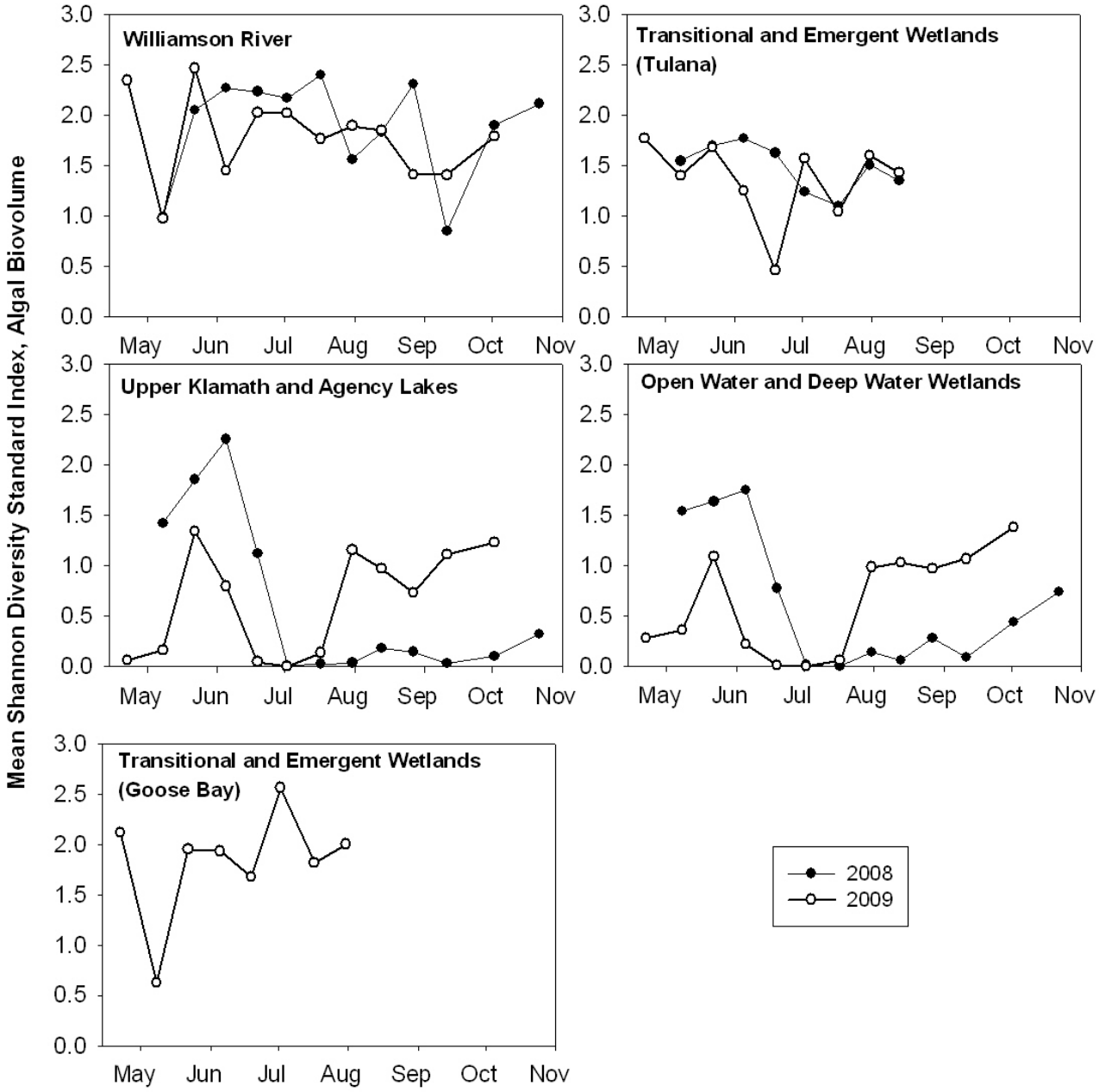

Figure 22. Mean algal diversity (Shannon diversity standard index on algal biovolume) in sampling locations within and surrounding the Williamson River Delta, Oregon, 2008–2009.

Tulana-Transitional Wetlands:

Tulana-Emergent Wetlands:

Tulana-Deep Water Wetlands:

Tulana-Open Water:

River/Lake:

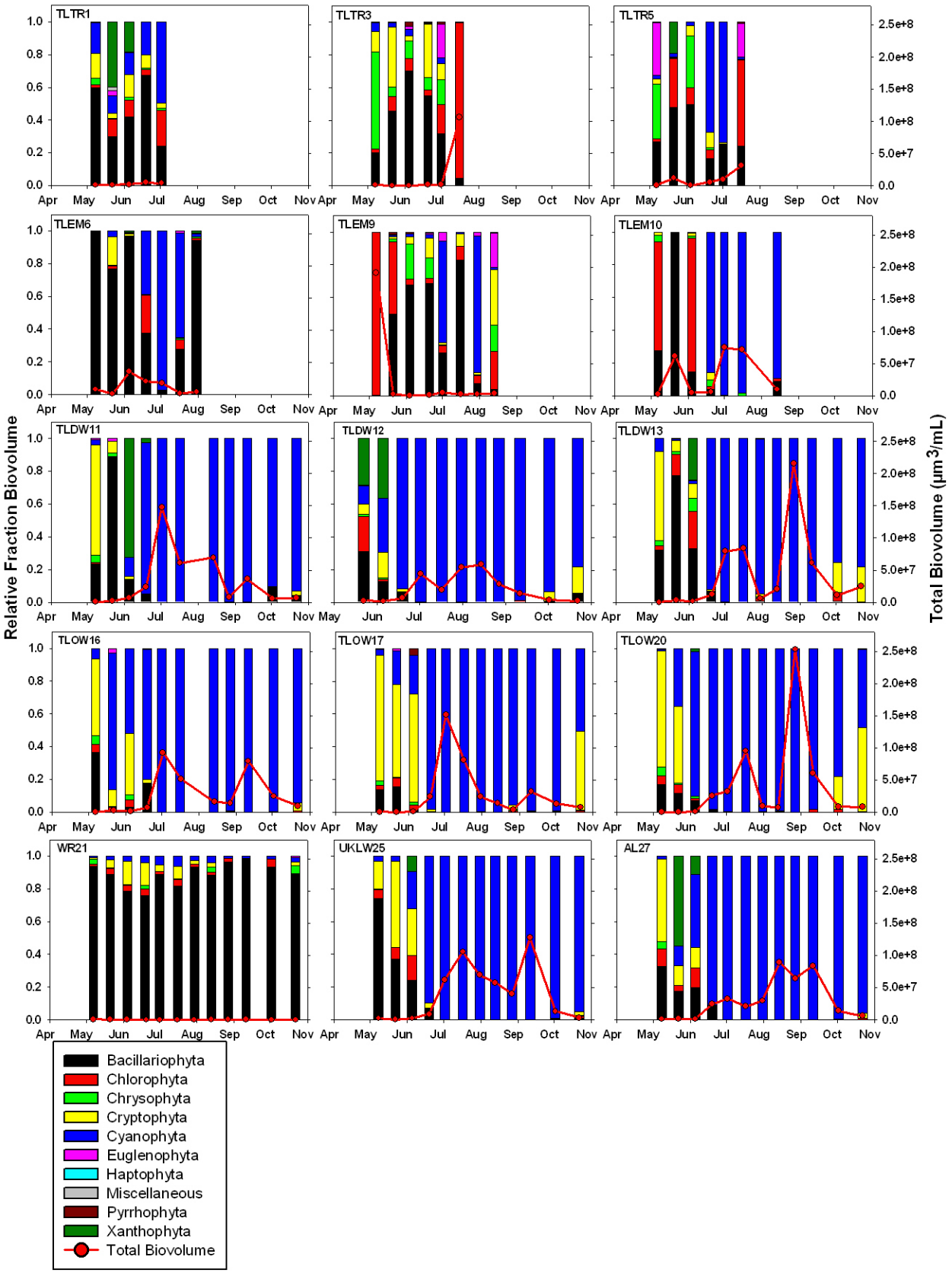

Figure 23. Total biovolume (red line) and relative fraction biovolume (bars) of major phytoplankton taxonomic groups by sampling event in Tulana, river, and lake locations in 2008. Sidebar to the left indicates location of sites in each row.

Tulana-Transitional Wetlands:

Tulana-Emergent Wetlands:

Tulana-Deep Water Wetlands:

Tulana-Open Water:

River/Lake:

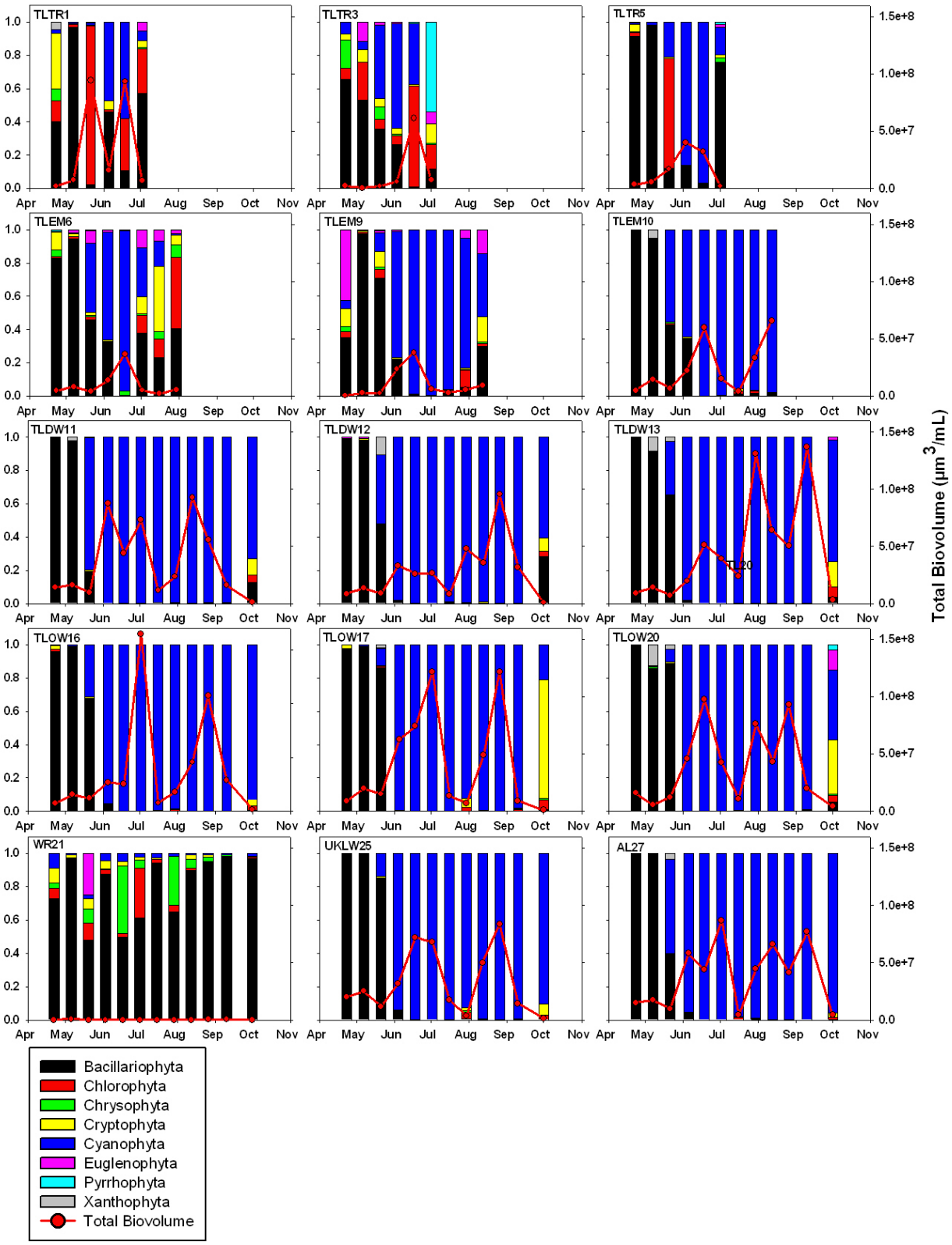

Figure 24. Total biovolume (red line) and relative fraction biovolume (bars) of major phytoplankton taxonomic groups by sampling event in Tulana, river, and lake locations in 2009. Sidebar to the left indicates location of sites in each row.

Goose Bay-Transitional Wetlands:

Goose Bay-Emergent Wetlands:

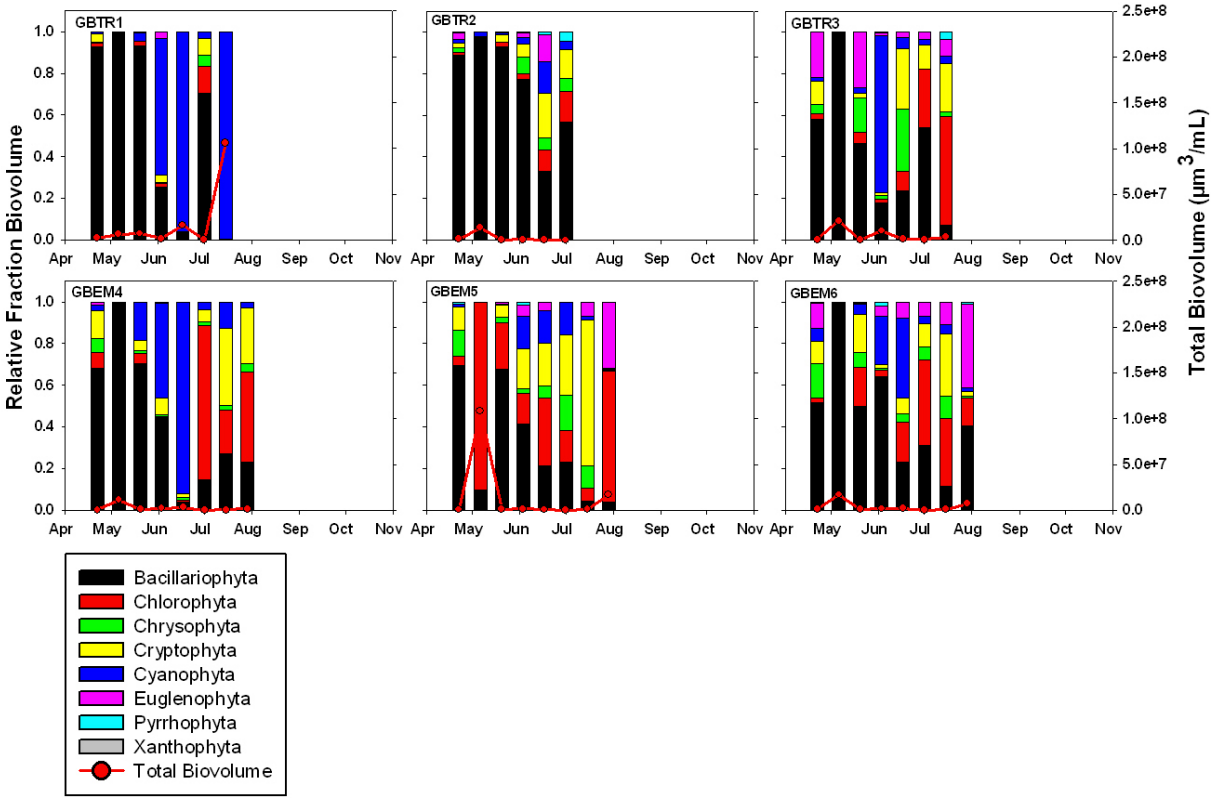

Figure 26. Total biovolume (red line) and relative fraction biovolume (bars) of major phytoplankton taxonomic groups by sampling event in Goose Bay in 2009. Sidebar to the left indicates location of sites in each row.

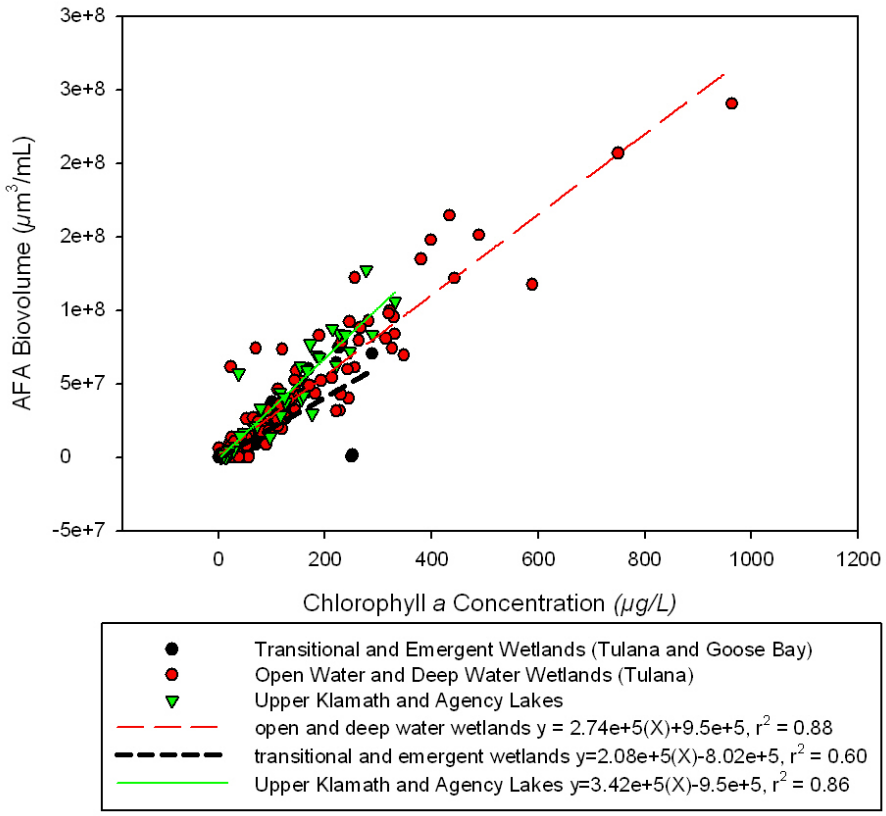

Figure 25. Relationship between chlorophyll *a* concentration and AFA biovolume, Williamson River Delta, Oregon 2008–2009. Each dot represents a sample taken at a given site and day. Linear equations and r squared values for wetland types and lakes are also included.

Species Breakdown within Divisions

A simplified breakdown of dominant species by biovolume within each major phytoplankton group is shown in Figures 27 and 28. Although some variation occurred between sampling years, the overall breakdown in species appeared similar. One noticeable exception is species dominance within the diatoms. In 2009, *Asterionella formosa* made up 74% of the diatom assemblage. In 2008, the diatoms were dominated by *Fragillaria capucina* (46%) and *Melosira varians* (28%), and *Asterionella formosa* made up less than 2% of the diatoms.

The diatoms and chlorophytes were commonly represented in the algal assemblages within transitional and emergent wetlands in Tulana and Goose Bay and were represented by many different species (60–100 species). The cryptophytes and chrysophytes were also fairly common in the algal assemblage within transitional and emergent wetlands, and particularly in the early season of 2008 within lake, open water, and deep water wetland sites, but were composed of relatively few species (<16 species). Cyanophyta was by far the most represented group in the algal assemblage (>90% of the assemblage by biovolume in both years), and was composed predominantly of AFA, which made up over 90% of the cyanophyte assemblage over the entire year. The Pyrrophytes, Xanthophytes, and Haptophytes were rarely observed and were represented by few species (<5 species).

Trends in Microcystis aeruginosa and AFA

Figures 29 and 30 show seasonal trends of the non-heterocystous cyanophyte, *Microcystis aeruginosa*, and AFA in 2008 and 2009. In general, peaks in *Microcystis* occurred during the mid–late season periods and usually occurred after the first seasonal peak in AFA. *Microcystis* densities exceeded Oregon Public Health guidelines for reporting a harmful algae bloom (≥40,000 *Microcystis* cells/mL) at both lake and wetland sites during 2008 and 2009 (Table 4). *Microcystis* densities above 100,000 cells/mL were reached multiple times in both years. In 2008, *Microcystis* density exceeded 183,000 cells/mL in Tulana open water (site TLOW20). In 2009, *Microcystis* density peaked at just over 250,000 cells/mL in Tulana deep water wetland (site TLDW11). In both years, *Microcystis* appeared at two sites in the Tulana transitional and emergent wetlands, but at lower densities than in the lake, open water, and deep water wetlands. *Microcystis* was not observed in the Goose Bay wetlands. *Microcystis* first appeared in samples from Agency Lake (site AL27) in late April–May of both years before being detected at other lake and wetland sites (about six weeks later at sites TLOW17 and TLEM9 in 2008 and twelve weeks later at sites TLOW16 and UKLW25 in 2009). Trends in AFA and *Microcystis* across the Delta wetlands and at near-shore lake and river sites are depicted spatially and seasonally in a GIS animation developed by Charles Erdman of The Nature Conservancy (Erdman and Wong 2010), and are accessible at www.conserveonline.org.

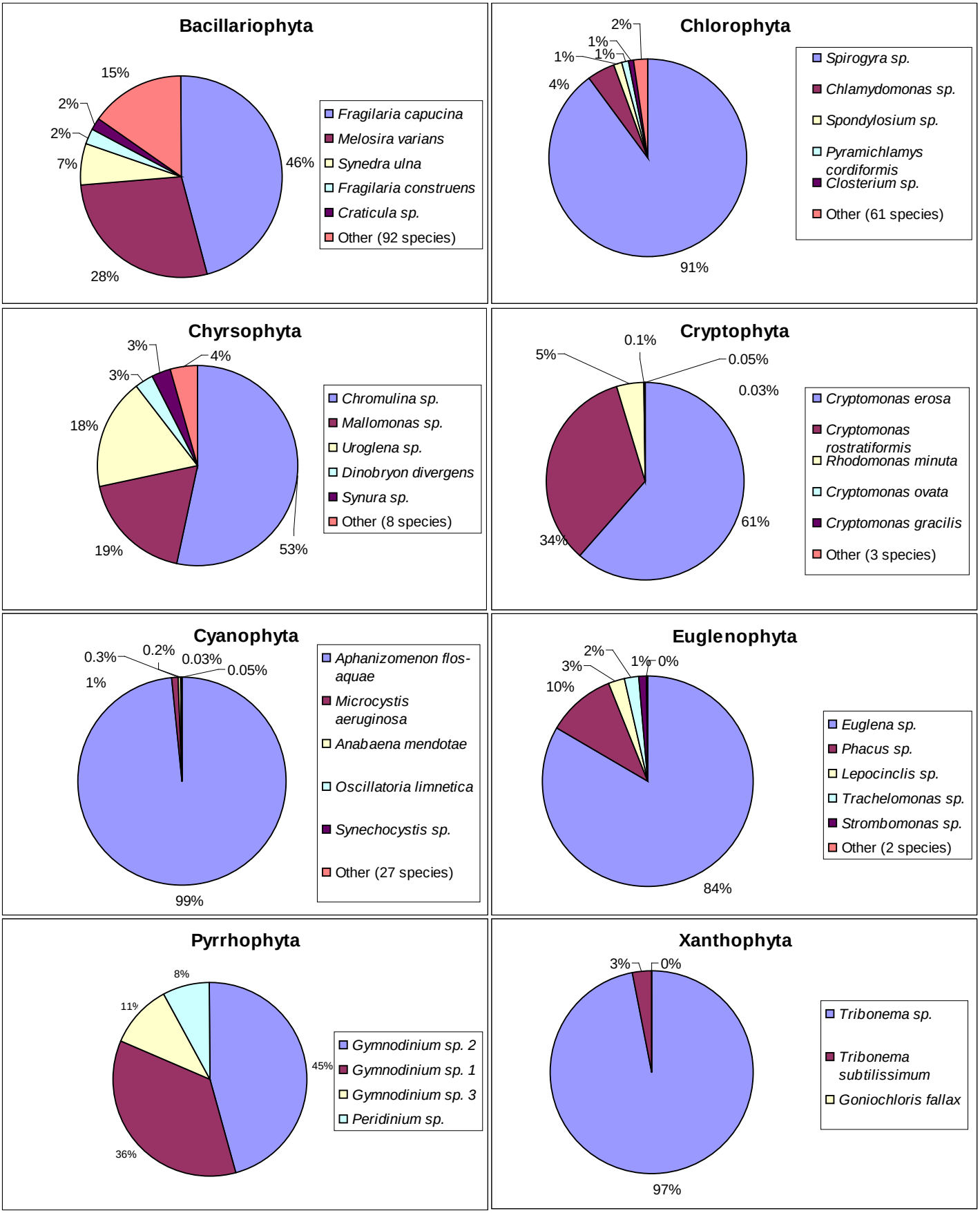

Figure 27. Percent composition (by biovolume) of phytoplankton species by major phytoplankton groups in 2008. The top five species in each group are listed in order of dominance. Remaining species are grouped into the category 'Other'. The taxonomic group 'Haptophyta' consisted of one species and is not shown.

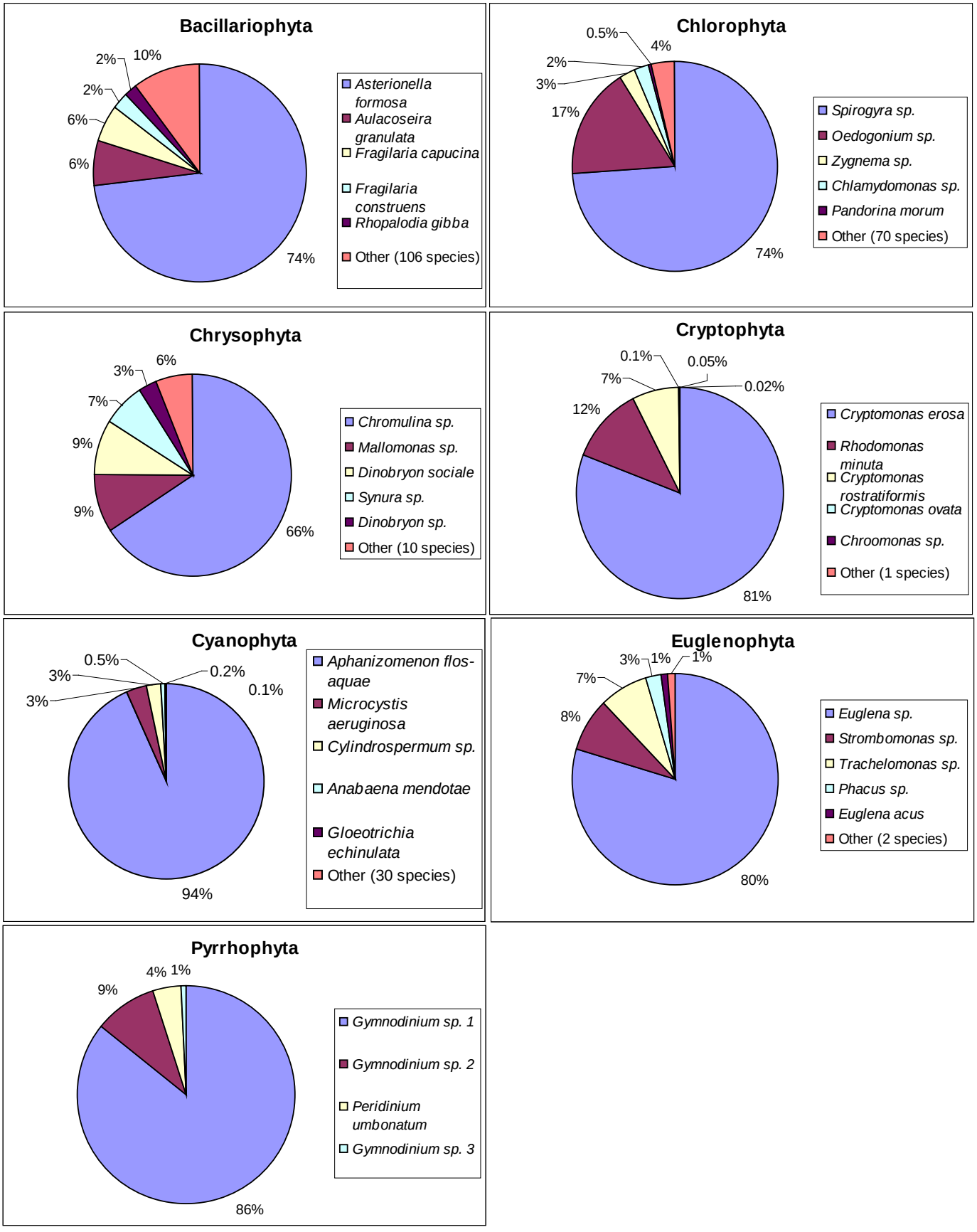

Figure 28. Percent composition (by biovolume) of phytoplankton species by major phytoplankton groups in 2009. The top five species in each group are listed in order of dominance. Remaining species are grouped into the category 'other'. The taxonomic group 'Xanthophyta consisted of one species and is not shown.

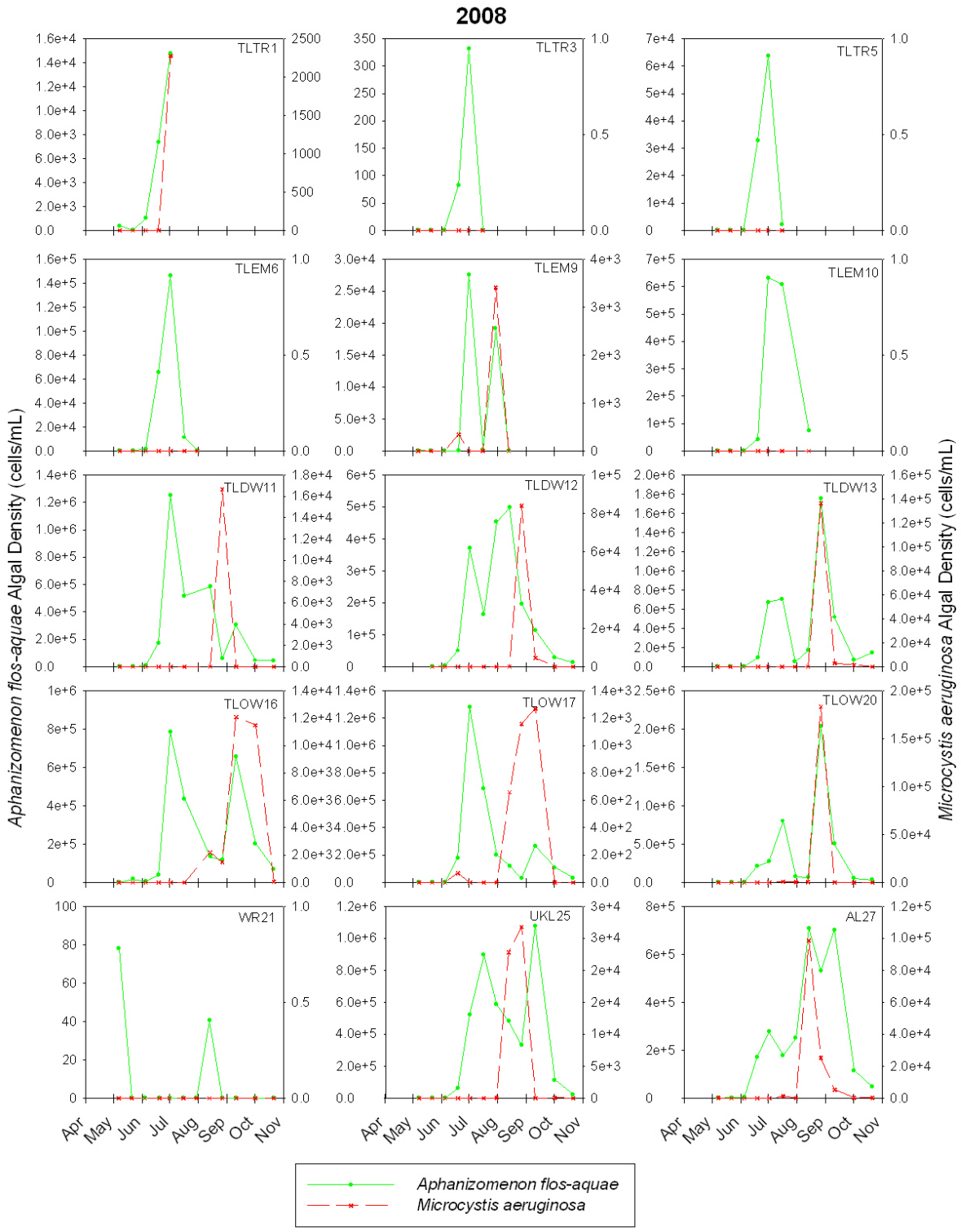

Figure 29. Seasonal trends in *Aphanizomenon flos-aquae* and *Microcystis aeruginosa* in Tulana, river, and lake locations in 2008. Note different scales. Sidebar to the left indicates the location of sites in each row.

Tulana-Transitional Wetlands:

Tulana-Emergent Wetlands:

Tulana-Deep Water Wetlands:

Tulana-Open Water:

River/Lake:

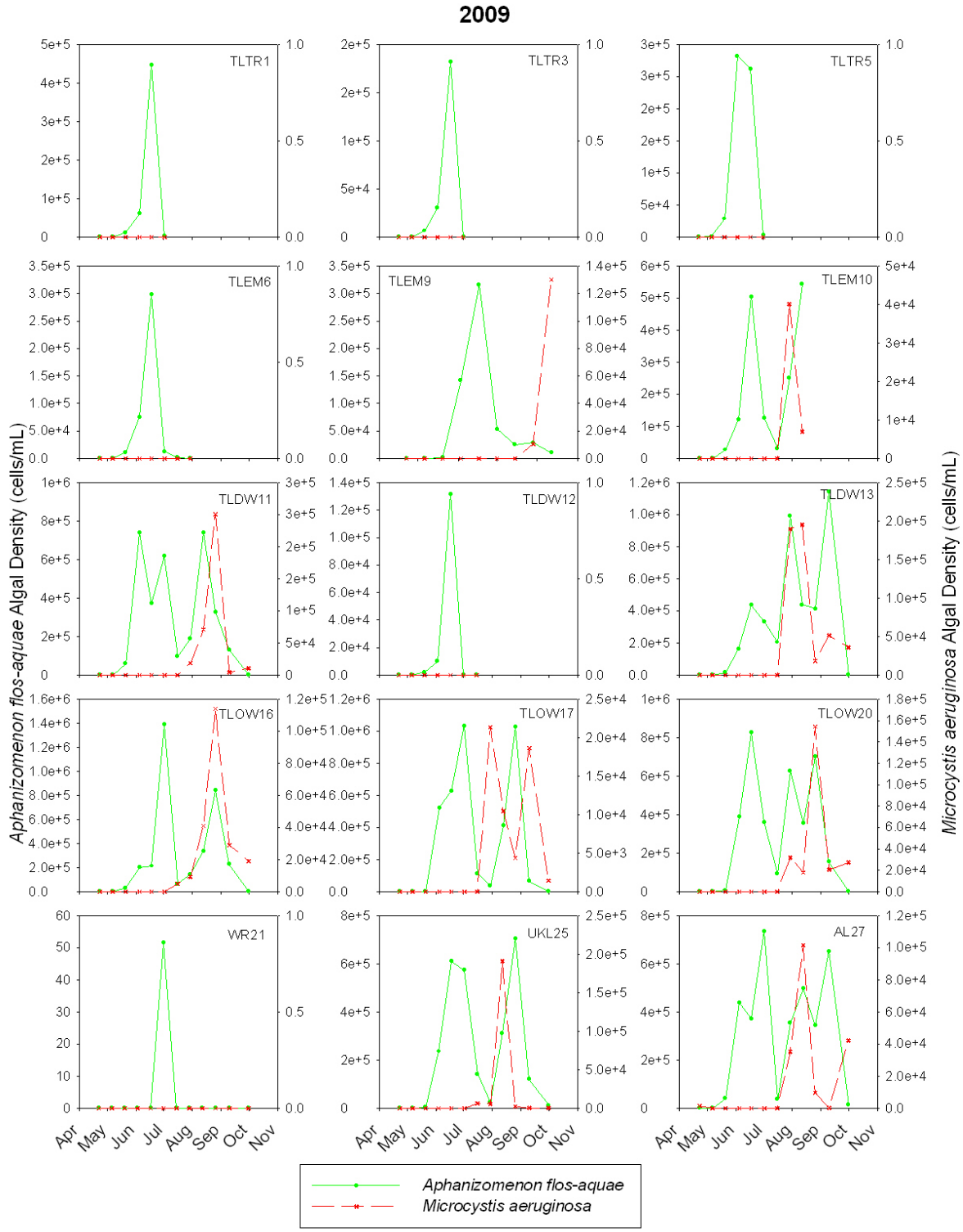

Figure 30. Seasonal trends in *Aphanizomenon flos-aquae* and *Microcystis aeruginosa* in Tulana, river, and lake locations in 2009. Note different scales. Sidebar to the left indicates the location of sites in each row.

Table 4. Date, site, and location of counts of *Microcystis aeruginosa* that exceed Oregon Public Health Guidelines for reporting a harmful algal bloom (>40,000 Microcystis cells/mL). Highlighted rows indicate instances when >100,000 *Microcystis* cells/mL occurred.

Date	Site	Location	*Microcystis* cells/mL
8/14/2008	TL27	Agency Lake	98,647
8/27/2008	TL12	Deep Water Wetland	83,862
8/27/2008	**TL13**	**Deep Water Wetland**	**136,467**
8/27/2008	**TL20**	**Open Water**	**183,238**
7/29/2009	TL 10	Emergent Marsh	40,107
7/30/2009	TL 12	Deep Water Wetland	92,922
7/30/2009	**TL 13**	**Deep Water Wetland**	**189,781**
8/12/2009	**TL 9**	**Emergent Marsh**	**129,954**
8/12/2009	**TL 25**	**Upper Klamath Lake**	**190,804**
8/12/2009	**TL 13**	**Deep Water Wetland**	**195,234**
8/13/2009	TL 16	Open Water	40,989
8/13/2009	TL 12	Deep Water Wetland	48,076
8/13/2009	TL 11	Deep Water Wetland	70,960
8/13/2009	**TL 27**	**Agency Lake**	**101,580**
8/26/2009	TL 12	Deep Water Wetland	92,922
8/26/2009	**TL 16**	**Open Water**	**113,975**
8/26/2009	**TL 20**	**Open Water**	**154,255**
8/26/2009	**TL 11**	**Deep Water Wetland**	**250,669**
9/10/2009	TL 13	Deep Water Wetland	51,270
10/1/2009	TL 27	Agency Lake	42,257

DISCUSSION

Controls on Nutrient Concentrations in the Delta Wetlands

Two major inter-related processes appear to exert seasonal control on nutrient concentrations in the newly restored wetlands. The first is benthic fluxes of N, P, and possibly C from the wetland and lake soils and sediments. The second is the cycling of these elements through the abundant algal and cyanobacterial biomass that appears to dominate lake and wetland productivity, especially in areas with deeper water. We discuss each of these processes below.

In the two years following restoration of the Delta, there is evidence that the wetlands were likely in a state of chemical transition. Higher P concentrations in the wetlands compared to Upper Klamath and Agency Lakes in 2007 indicated a benthic release of P from the restored wetlands within three weeks of initial flooding (Figures 3 & 4). Positive benthic P fluxes from the wetlands immediately after the breaching was simultaneously documented by Kuwabara et al. (2010). The P release from the wetlands after initial flooding was expected to occur, as

previous agricultural use of the land had likely led to substantial P-enrichment in the soils. Furthermore, P release from newly flooded soils on former agricultural land has been well-documented by others (Coveney et al. 2002, Pant and Reddy 2003, Novak et al. 2004, Aldous et al. 2005, Aldous et al. 2007, Montgomery and Eames 2008, Stevens 2008, Lindenberg and Wood 2009). Using measured surface water nutrient concentrations at sites in the Delta, water depths measured at each sampling site, and the approximate area flooded (based on lake surface elevation during sampling dates and areal coverage of the Delta), we estimated that about 2.47 metric tons TP were released from the flooded wetlands within three weeks after the breaching in 2007 (Wong et al. *in press*). This value is more than an order of magnitude less than the 64 tons TP predicted based on soil-core flood experiments conducted prior to the restoration (Aldous et al. 2007). The initial P release represents less than ten percent of the estimated annual P load (21–25 metric tons TP) from the Delta during its time under cultivation (Snyder and Morace 1997). The P release overall did not appear to affect lake-wide P concentrations in Upper Klamath Lake within two weeks after the levee breaching (Kannarr et al. 2010). Although we did not conduct carbon sampling in fall 2007, Kuwabara et al. (2010) observed positive benthic DOC flux from the restored Delta wetlands within a few days of breaching. Kannarr et al. (2010) observed no evidence of increased DOC concentration lake-wide within two weeks of the breaching.

In 2008, higher P concentrations in the Delta wetlands compared to Upper Klamath and Agency Lakes might have indicated processes occurring in the wetlands that were not occurring in the lakes. For example, elevated P concentrations in the wetlands could have been caused by P release from the soils or from microbial decomposition of organic matter, the latter which may be suggested by the appearance of a positive relationship between DOC and PO_4 in the wetlands (Figure 14f). Lower P concentrations within the Delta wetlands in 2009 compared to 2008 may indicate a P release in the wetlands that was less in 2009 than in 2008, the occurrence of P uptake in the Delta wetlands, or inter-year variability related to other factors. For example, in regard to the latter, lake P concentrations also appeared slightly lower in 2009 than in 2008 (Figure 4).

In addition to a benthic flux of P, there appeared to be benthic releases of N and C, as these nutrients increased seasonally in a similar pattern to P. Positive C and N fluxes were documented in micro flux chambers by Kuwabara et al. (2010) at several sites in this wetland.

Nutrients and Algal Growth

The second major process controlling wetland and lake nutrient concentrations is uptake and release by primary producers. This is most clearly seen with dissolved N and P, where concentrations rise and fall out of phase with chlorophyll *a* concentrations (Figures 12 & 13). A positive relationship between chlorophyll *a* and TN (Figure 14b) may reflect the ability of AFA to fix atmospheric N and then release it into the water column after algal cell senescence (Kann 1997). This hypothesis appears to be supported by the timing of rise in both chlorophyll *a* and DIN concentrations, where chlorophyll *a* concentrations rise before the increase in DIN,

indicating the N is released after the AFA crash (Figure 12). Alternatively, the primary producers may be taking up all available DIN in the growth phase. Although N:P ratios are less than 10 in the wetlands and may indicate N-limitation, N may be sufficiently available so it might be that neither nutrient is limiting primary production. Ironically, it may be that primary production regulates dissolved nutrient concentrations, rather than the other way around.

The apparent lack of any distinct relations between N and P constituents (other than TN) and chlorophyll *a* in the wetlands (Figure 14a,c,d) suggests that no relationship exists between the variables, there are other factors confounding associations between variables (e.g. seasonality and light conditions), or a simple linear model is inadequate to explain patterns between the variables. In the latter case, a more rigorous regression analysis may be warranted. With high P concentrations, it is likely that the relationship between P and primary production cannot be detected, even if the cyanobacteria circulate a significant amount of P among various forms.

It has been hypothesized that humic substances resulting from organic matter decay may act to inhibit algal growth through toxicological effects (Milligan et al. 2009), by binding with essential nutrients and making them biologically unavailable (Wetzel 1983), or by modifying the light environment which can affect algal productivity (Rodríguez and Pizarro 2007). We examined this hypothesis using DOC concentration as a surrogate for humic substances (which are comprised of 41–59% C; Reddy and Delaune 2008) and chlorophyll *a* concentration as a measure of algal growth. Based on this hypothesis, an inverse relationship between DOC and chlorophyll *a* concentration could be expected. A scatterplot of the two variables, however, did not yield a much defined relationship (Figure 14e), although a more thorough statistical analysis may be needed to examine these data. It could be that ranges in DOC concentrations at the Delta (4–22 mg/L) were generally low compared to other wetlands (24–270 mg/L DOC; Carpenter et al. 2009), or other factors may have influenced chlorophyll *a* concentrations to a greater extent than C concentrations. Additionally, in a more natural setting, DOC production from wetlands is expected in the fall through the spring when vegetation is decomposing and releasing products of incomplete decomposition into the water column (Wetzel 1983). In this case, it appears that DOC production was a result of benthic release (different than DOC generated from the breakdown of vegetation), given that seasonal patterns of DOC concentrations increased over the course of the summer similar to P.

Spatial and Temporal Variation

Site characteristics such as hydrology, water depth, vegetation, soils, and exposure to wind are all factors that may have influenced observed gradients in water chemistry and algal abundance and diversity across the Delta. Variability in water chemistry within habitat types of the Delta may also be related to differences in site characteristics (for example, certain emergent and transitional wetland sites may have had more vegetative cover than others; depending on proximity to breach locations, certain sites may be more lake-influenced and others more river-

influenced). The quantification and relative importance of each factor on water quality parameters is beyond the scope of this report.

The influence of lake and river water chemistry at sites within the Delta is readily apparent in seasonal and spatial trends in water quality parameters. Trends in nutrient and chlorophyll *a* concentrations, physical water chemistry, and algal abundance and diversity at the permanently flooded open water and deep water wetland sites largely reflect trends in Upper Klamath and Agency Lakes, which are largely driven by seasonal cycles of AFA (Lindenberg et al. 2008). However, higher PO_4 and NH_4 concentrations and lower DO and pH values in open and deep water wetland sites relative to the lakes during the mid–late season periods in 2008 may indicate biological, physical, and chemical processes that were present at these locations but not in the lakes. Any or all of these processes could have contributed to prolonged low DO conditions in the deep water wetland in August 2008 that exceeded the high stress threshold for endangered suckers. Seasonal trends in water chemistry in the Goose Bay wetlands suggest that wetland areas within Goose Bay were largely influenced by flows from the Williamson River. Shallow water depth may relate to observed trends in water chemistry at the seasonally flooded transitional and emergent wetlands in Tulana, such as high temperatures and nutrient concentrations relative to other locations. Diel and seasonal trends in DO concentration at these shallow wetland sites may be related to biological processes such as photosynthesis/respiration where vegetation may be present, and by heightened microbial activity during the summer months which can produce near-anoxic conditions in the water column nearer the sediments (Reddy and DeLaune 2009).

Phytoplankton Community Structure

Phytoplankton sampling indicated seasonal and spatial differences across the Delta wetlands and surrounding lake and river locations. Greater algal diversity in the emergent and transitional wetlands relative to the open water and deep water wetlands and lake was apparent during the mid-season period. Lower abundance (biovolume) was also observed in the emergent and transitional wetlands relative to all other locations except the river. Additionally, over 100 identified species were unique to the Delta wetlands (not found at lake or river sites). The underlying reasons for these differences are not investigated here, but may include differences in spatial heterogeneity as well as differences in nutrient water chemistry, other physical variables, or competition from AFA or other species with high rates of net primary production. Furthermore, it should be noted that phytoplankton composition and abundance at lake sites sampled in this study may not be representative of Upper Klamath and Agency Lakes in their entirety.

Seasonal differences include higher abundance and lower diversity at most permanently flooded sites within the Delta during the mid-season period as AFA begins to dominate the algal assemblage. This trend is typical in eutrophic lakes, where phytoplankton community structure changes from one of low abundance and high diversity to one of high abundance (commonly of a

blue-green algae species) and low diversity during the summer bloom period (Vázquez et al. 2005). In particular, the early season diatoms declined at most lake and permanently flooded Delta sites and eventually disappeared from the assemblage during the mid-season. This trend did not always hold up in the transitional and emergent wetlands, where AFA was less prevalent.

Microcystis appeared first in Agency Lake in low densities in the spring and several weeks later at non-shallow sites within Tulana and in Upper Klamath Lake. Concentrations greater than Oregon Public Health's Harmful Algal Blooms advisory guideline (≥40,000 *Microcystis* cells/ml) occurred more often in 2009 compared to 2008. *Microcystis* was not present or not as prevalent at sites in the Tulana and Goose Bay emergent and transitional wetlands. However, the presence of *Microcystis* in the lakes and open water areas of Tulana at densities above the Oregon advisory guideline may be of concern regarding public health as well as the health of endangered suckers that may inhabit these areas. For example, age-0 suckers in Upper Klamath Lake have been found to exhibit pathology consistent with microcystin exposure, and research is underway to improve understanding of the health threats imposed by algal toxins to juvenile suckers (VanderKooi et al. 2010).

Overall, a characterization of phytoplankton in the Delta wetlands reveals the capacity of these wetlands to support a diverse biological community relative to the Upper Klamath Lake system (Figure 21). An important question remains as to what environmental variables associated with wetlands (e.g. vegetation, nutrient water chemistry, temperature, light conditions) are important in regulating algal growth and composition. Given that the lake system is currently dominated by a single species during the mid-season period, investigation as to why the Delta wetlands function differently than the lake in terms of phytoplankton assemblages may be a key to better understanding of how the significant loss of wetlands may have contributed to single-species dominance over the past century (Eilers et al. 2004), and how the restoration of wetlands may impact phytoplankton assemblages. Documentation of seasonal and spatial trends in phytoplankton within the wetlands (as was done here) is a valuable first step.

POTENTIAL FUTURE STUDIES

The two years of monitoring after restoration in 2007 have shown that the Delta wetlands were likely in a state of transition in terms of nutrient water chemistry. Further changes over time in water chemistry within the wetlands are expected as vegetation re-establishes and as wetland functions are restored. Future monitoring efforts on the Delta will look at long term trends in nutrient water chemistry to assess the capacity of these wetlands to retain or release nutrients. Given that one of the fundamental goals of the restoration is to help reduce the external nutrient load entering into Upper Klamath Lake, establishing a long term nutrient dataset at the Delta is necessary to determine if this restoration goal is successful. Monitoring of other water quality variables will support continued efforts of endangered sucker sampling at the Delta. Other

additional studies may include comparing water quality in the Delta to long term data trends observed in Upper Klamath and Agency Lakes, comparing phytoplankton assemblages in the Delta to those found in the lakes and nearby wetlands, as well as more in-depth examination of factors controlling algal community structure in the Delta wetlands. We also plan on integrating water quality monitoring results with a hydrodynamic model of the Delta (T. Wood, personal communications) in an attempt to model nutrient and algal dynamics and how they change with lake elevation, Williamson River flow, and localized wind conditions. We currently have plans to continue monitoring N and P concentrations and chlorophyll *a* and C concentrations at the Delta in 2010–2011.

CONCLUSIONS

Water quality across the Delta forms a distinct gradient from areas nearest the Williamson River, where conditions are characterized by cooler water temperatures, less variable DO concentrations, low algal abundance and high diversity, and lower nutrient concentrations, to areas further away from the river and nearer Upper Klamath and Agency Lakes, where conditions include higher nutrient concentrations, high algal abundance and low diversity, more variable DO concentrations, warm water temperatures, and higher pH. Depending on various factors not explored in this report (e.g. wind, flow, and lake level) the mixing zone where river meets lake shifts and dynamic conditions exist. Other factors lead to dynamic conditions and site-to-site variability within a habitat type: localized vegetation (or lack thereof) and soil type, historical land use prior to flooding, bioturbation from fish, birds, and invertebrates, and physical and chemical processes such as decomposition and redox reactions. Despite the dynamic nature of water quality in the Delta, some basic trends were observed both spatially and seasonally, and from one year to the next.

Key findings in the post-restoration monitoring from November 2007–2009 include:

- Within three weeks of flooding, about 2.47 tons P were released from the Delta wetlands, a release that was more than an order of magnitude less than anticipated based on previous soil core flood experiments (Wong et al., *in press*).

- Phosphorus concentrations in the Delta in 2007 and 2008 were elevated relative to the lakes, followed by a decline in concentrations within the wetlands from 2008 to 2009. Whether or not this is a continuing trend toward more stable conditions in the wetlands in terms of water chemistry remains to be investigated.

- Nitrogen concentrations in the wetlands generally followed patterns in chlorophyll *a* concentration, with increases in TN concentration corresponding to increases in

chlorophyll *a* concentration, and peaks in NH_4 concentration corresponding to declines in chlorophyll *a* concentration at most sites.

- No strong relationship between carbon and chlorophyll *a* concentration was elucidated, and observed DOC concentrations ranging from 4–22 mg/L in the wetlands suggest that DOC concentrations—used as a surrogate for humic substances—were probably not high enough to see any appreciable suppression of phytoplankton growth.
- Water quality conditions in the permanently flooded wetlands of the Delta exceeded high stress thresholds for endangered suckers (Loftus 2001), similar to the lakes, while conditions in the seasonally flooded wetlands were generally not as severe as in the lakes and permanently flooded wetlands. In August 2008, noticeably low DO conditions in the deep water wetland resulted in threshold exceedances for 80% of the hours in August.
- Phytoplankton abundance (biovolume) was lowest in the seasonally flooded wetlands compared to the permanently flooded wetlands and lakes, where AFA represented over 90% of the algal assemblage after June, while diversity was overall greatest in the seasonally flooded wetlands.

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APPENDICES

Appendix A. Detection and reporting limits for sample constituents, standard method*s*, and laboratory conducting the analysis.

Nutrient Constituent	Detection Limit (mg/L)	Reporting Limit (mg/L)	Method	Laboratory
Total Phosphorus	0.009	0.012	SM4500-P H	Sprague River Water Quality Laboratory, OR
Orthophosphate	0.003	0.006	SM4500- PF	
Ammonia	0.006	0.01	MD Krom methods	
Nitrate + Nitrite	0.008	0.01	Enzymatic NO3; SM4500-NO2	
Total Nitrogen	0.01	0.03	Enzymatic NO3	
Total Organic Carbon	0.3	0.5	SM 5310	Basic Laboratory, CA
Dissolved Organic Carbon	0.3	0.5	SM5310C	
Chlorophyll *a*	0.0001	NA	SM10200H	Aquatic Research, WA

Appendix B. Quality assurance results for split, duplicate, blank, and spike samples, 2008–2009.

2008 Split Samples	Number of Samples		% Total Samples	Difference between splits	
Analyte	Duplicates	Total		Median (mg/L)	Median (%)
Total Phosphorus	35	320	11%	0.004	0
Orthophoshate-P	35	320	11%	0.001	1
Total Nitrogen	35	320	11%	0.032	1
Ammonia	35	320	11%	0.002	0
Nitrate + Nitrite	35	320	11%	0	0
Chlorophyll *a*	20	147	14%	0.004	1
Total Organic Carbon	19	153	12%	0.2	3
Dissolved Organic Carbon	19	148	13%	0.2	3

2008 Duplicate Samples	Number of Samples		% Total Samples	Difference between duplicates	
Analyte	Duplicates	Total		Median (mg/L)	Median (%)
Total Phosphorus	14	320	4%	0.006	0.02
Orthophoshate	14	320	4%	0.004	0.02
Total Nitrogen	14	320	4%	0.061	4.24
Ammonia	14	320	4%	0.004	0.02
Nitrate + Nitrite	14	320	4%	0.001	0.03

2008 Lab Blanks	Number of Samples		% Total Samples	Minimum Reporting Level (mg/L)	Value of blank samples greater than reporting limit
Analyte	Blank	Total			Maximum (mg/L)
Total Phosphorus	5	320	2%	0.012	0.01
Orthophoshate-P	5	320	2%	0.03	NA
Total Nitrogen	5	320	2%	0.03	0.004
Ammonia	5	320	2%	0.01	0.007
Nitrate + Nitrite	5	320	2%	0.01	NA
Chloropyhll a	1	147	1%	0.0001	0.0011

2008 Equipment Blanks	Number of Samples		% Total Samples	Minimum Reporting Level (mg/L)	Value of blank samples greater than reporting limit
Analyte	Blank	Total			Maximum (mg/L)
Total Phosphorus	1	320	0.3%	0.012	NA
Orthophoshate-P	1	320	0.3%	0.03	NA
Total Nitrogen	1	320	0.3%	0.03	NA
Ammonia	1	320	0.3%	0.01	0.014
Nitrate + Nitrite	1	320	0.3%	0.01	NA

2008 Rinsate Blanks	Number of Samples		% Total Samples	Minimum Reporting Level (mg/L)	Value of blank samples greater than reporting limit
Analyte	Blank	Total			Maximum (mg/L)
Total Phosphorus	2	320	0.6%	0.012	0.015
Orthophoshate-P	2	320	0.6%	0.03	NA
Total Nitrogen	2	320	0.6%	0.03	NA
Ammonia	2	320	0.6%	0.01	0.013
Nitrate + Nitrite	2	320	0.6%	0.01	NA

2008 Spike Samples	Number of Samples		% Total Samples	Recovery<80% (% Spike Samples)	Recovery>120% (% Spike Samples)
Analyte	Spikes	Total			
Total Phosphorus	48	320	15%	38%	7%
Orthophoshate	48	320	15%	20%	8%
Total Nitrogen	48	320	15%	42%	22%
Ammonia	48	320	15%	31%	4%
Nitrate + Nitrite	48	320	15%	14%	2%

2009 Split Samples	Number of Samples		% Total Samples	Difference between splits	
Analyte	Splits	Total		Median (mg/L)	Median (%)
Total Phosphorus	40	331	12%	0.006	1
Orthophoshate	40	331	12%	0.001	1
Total Nitrogen	40	331	12%	0.022	1
Ammonia	40	331	12%	0.002	2

Nitrate + Nitrite	40	331	12%	0	0
Chlorophyll *a*	19	190	10%	1.5	1
Total Organic Carbon	21	190	11%	0.2	3
Dissolved Organic Carbon	21	190	11%	0.1	3

2009 Duplicate Samples	**Number of Samples**		**% Total Samples**	**Difference between splits**	
Analyte	**Duplicates**	**Total**		**Median (mg/L)**	**Median (%)**
Total Phosphorus	14	331	4%	0.0045	3.28
Orthophoshate	14	331	4%	0.001	7.14
Total Nitrogen	14	331	4%	0.06	5.72
Ammonia	14	331	4%	0.004	4.65
Nitrate + Nitrite	14	331	4%	0.00	0.00

2009 Lab Blanks	**Number of Samples**		**% Total Samples**	**Minimum Reporting Level (mg/L)**	**Value of blank samples greater than reporting limit**
Analyte	**Blank**	**Total**			**Maximum (mg/L)**
Total Phosphorus	3	331	1%	0.036	NA
Orthophoshate-P	3	331	1%	0.006	NA
Total Nitrogen	3	331	1%	0.06	NA
Ammonia	3	331	1%	0.012	NA
Nitrate + Nitrite	3	331	1%	0.016	NA
Chloropyhll a	4	190	2%	0.0001	1.1

2009 Equipment Blanks	**Number of Samples**		**% Total Samples**	**Minimum Reporting Level (mg/L)**	**Value of blank samples greater than reporting limit**
Analyte	**Blank**	**Total**			**Maximum (mg/L)**
Total Phosphorus	2	331	0.6%	0.036	NA
Orthophoshate-P	2	331	0.6%	0.006	NA
Total Nitrogen	2	331	0.6%	0.06	NA
Ammonia	2	331	0.6%	0.012	0.013
Nitrate + Nitrite	2	331	0.6%	0.016	NA

2009 Rinsate Blanks	Number of Samples		% Total Samples	Minimum Reporting Level (mg/L)	Value of blank samples greater than reporting limit
Analyte	Blank	Total			Maximum (mg/L)
Total Phosphorus	1	331	0.3%	0.036	NA
Orthophoshate-P	1	331	0.3%	0.006	NA
Total Nitrogen	1	331	0.3%	0.06	NA
Ammonia	1	331	0.3%	0.012	NA
Nitrate + Nitrite	1	331	0.3%	0.016	NA

2009 Spike Samples	Number of Samples		% Total Samples	Recovery<80% (% Spike Samples)	Recovery>120% (% Spike Samples)
Analyte	Spikes	Total			
Total Phosphorus	48	320	15%	30%	3%
Orthophoshate	48	320	15%	8%	13%
Total Nitrogen	48	320	15%	55%	10%
Ammonia	48	320	15%	8%	0%
Nitrate + Nitrite	48	320	15%	0%	0%

Appendix C. Quality assurance criteria for continuous monitoring data. Level A criteria represent the highest quality data as defined in TNC's Water Quality Monitoring Project Plan. Level B criteria represent data outside Level A criteria, but deemed acceptable for statistical analysis. Level C criteria represent data deemed unacceptable and omitted from analysis.

Data Quality Level	Quality Assurance Plan & Action Steps	Water Temperature	pH	Dissolved Oxygen	Specific Conductance
A	QA Criteria Met Data Accepted	± 0.5°C	± 0.2	± 0.3 mg/L	± 7% of std value
B	QA Criteria Not Met Data Accepted; QA results reported in Appendix D	± 2.0°C	± 0.5	± 1.0 mg/L	± 10% of std value
C	QA Criteria Not Met Data Omitted; QA results reported in Appendix D	> ± 2.0°C	> ± 0.5	> ± 1.0 mg/L	> ± 10% of std value

Appendix D. Quality assurance results for continuous monitoring from 2008–2009. Data meeting Level A quality assurance criteria are not shown. 'No Data' indicates that no data were recorded for all four parameters due to equipment problems.

Continuous Monitor Site	Data Quality Level	Parameter	Dates
AL27	B	DO	4/28/2008 - 5/6/2008
AL27	B	DO	5/20/2008 - 5/28/2008
AL27	B	DO	6/16/2008 - 6/24/2008
AL27	B	DO	7/29/2008 - 8/5/2008
AL27	B	DO	9/3/2008 - 9/9/2008
AL27	C	DO	9/23/2008 - 9/30/2008
AL27	B	DO	10/15/2008 - 10/29/2008
AL27	B	DO	11/6/2008 - 11/12/2008
AL27	B	DO	3/24/2009 - 4/7/2009
AL27	B	DO	4/14/2009 - 4/21/2009
AL27	B	DO	4/29/2009 - 5/8/2009
AL27	B	DO	6/2/2009 - 6/9/2009
AL27	B	DO	6/23/2009 - 6/30/2009
AL27	B	DO	6/30/2009 - 7/7/2009
AL27	B	DO	7/14/2009 - 7/21/2009
AL27	B	pH	7/28/2009 - 8/4/2009
AL27	B	DO	9/9/2009 - 9/15/2009
UKLW25	B	DO	10/29/2008 - 11/6/2008
UKLW25	B	DO	4/29/2009 - 5/8/2009
UKLW25	B	DO	5/19/2009 - 5/27/2009
UKLW25	C	DO	10/8/2009 - 10/15/2009
UKLW25	B	DO	10/27/2009 - 11/3/2009
WR21	B	DO	7/29/2008 - 8/5/2008
WR21	C	DO	11/25/2008 - 12/2/2008
WR21	C	DO	3/17/2009 - 3/24/2009
WR21	B	DO	3/24/2009 - 3/31/2009
WR21	B	DO	4/7/2009 - 4/14/2009
WR21	C	DO	5/8/2009 - 5/13/2009
WR21	B	DO	6/9/2009 - 6/16/2009
WR21	B	DO	6/23/2009 - 6/30/2009
WR21	B	DO	7/21/2009 - 7/28/2009
WR21	B	DO	8/11/2009 - 8/20/2009
WR21	B	DO	8/20/2009 - 8/28/2009
WR21	C	DO	9/9/2009 - 9/15/2009
UKLE24	B	DO	8/19/2008 - 8/26/2008
UKLE24	B	DO	3/24/2009 - 3/31/2009
UKLE24	C	DO	4/14/2009 - 4/21/2009
UKLE24	B	DO	4/21/2009 - 4/29/2009
UKLE24	B	DO	5/27/2009 - 6/2/2009
UKLE24	B	DO	6/16/2009 - 6/23/2009
UKLE24	NO DATA	NO DATA	7/30/2009 - 8/4/2009
UKLE24	B	DO	8/4/2009 - 8/11/2009
UKLE24	B	DO	8/20/2009 - 8/21/2009
UKLE24	B	DO	10/20/2009 - 10/27/2009
TLOW17	B	DO	5/6/2008 - 5/13/2008
TLOW17	B	DO	8/12/2008 - 8/19/2008
TLOW17	B	DO	8/19/2008 - 8/26/2008
TLOW17	C	DO	10/7/2008 - 10/15/2008
TLOW17	NO DATA	NO DATA	11/6/2008 - 11/12/2008
TLOW17	B	DO	4/21/2009 - 5/8/2009
TLOW17	B	DO	7/14/2009 - 7/21/2009
TLOW17	B	DO	10/15/2009 - 10/20/2009
TLDW13	B	DO	5/6/2008 - 5/13/2008
TLDW13	B	DO	7/9/2008 - 7/15/2008
TLDW13	B	DO	7/22/2008 - 7/29/2008
TLDW13	B	DO	8/19/2008 - 8/26/2008
TLDW13	B	DO	10/15/2008 - 10/29/2008

TLDW13	NO DATA	NO DATA	10/29/2008 - 11/12/2008
TLDW13	B	DO	4/29/2009 - 5/8/2009
TLDW13	NO DATA	NO DATA	5/26/2009 - 5/27/2009
TLDW13	C	DO	6/9/2009 - 6/16/2009
TLDW13	B	DO	7/7/2009 - 7/14/2009
TLDW13	B	DO	7/14/2009 - 7/21/2009
TLDW13	B	DO	7/21/2009 - 7/28/2009
TLDW13	B	DO	8/11/2009 - 8/20/2009
TLDW13	C	DO	8/20/2009 - 8/28/2009
TLDW13	B	DO	8/28/2009 - 9/9/2009
TLDW13	B	DO	9/22/2009 - 9/29/2009
TLDW13	C	DO	9/29/2009 - 10/8/2009
TLEM9	C	DO	4/29/2008 - 5/6/2008
TLEM9	B	DO	6/17/2008 - 6/24/2008
TLEM9	B	DO	7/29/2008 - 8/5/2008
TLEM9	B	DO	3/31/2009 - 4/7/2009
TLEM9	B	DO	5/8/2009 - 5/13/2009
TLEM9	B	pH	7/21/2009 - 7/28/2009
TLEM9	NO DATA	NO DATA	8/4/2009 - 8/11/2009
TLTR5	C	DO	5/6/2008 - 5/13/2008
TLTR5	B	DO	6/30/2008 - 7/9/2008
TLTR5	B	DO	3/31/2009 - 4/7/2009
TLTR5	B	DO	4/14/2009 - 4/21/2009
TLTR5	B	DO	6/23/2009 - 6/30/2009
GBEM4	C	DO	3/17/2009 - 3/24/2009
GBEM4	B	DO	4/14/2009 - 4/21/2009
GBEM4	B	DO	5/19/2009 - 5/27/2009
GBEM4	B	DO	6/2/2009 - 6/9/2009
GBEM4	B	SpC	6/16/2009 - 6/23/2009
GBEM4	B	DO	7/14/2009 - 7/21/2009

Appendix E. List of all phytoplankton species encountered during sampling, Williamson River Delta, Oregon, 2008–2009. Asterisks denote species identified only once during the two-year period.

Phytoplankton Group	Species		
Bacillariophyta	Achnanthes lanceolata	Epithemia sorex	Nitzschia amphibia
	Achnanthes levanderi*	Epithemia turgida	Nitzschia capitellata
	Achnanthes minutissima	Fragilaria berolinensis*	Nitzschia constricta
	Amphora ovalis	Fragilaria bidens*	Nitzschia dissipata
	Amphora pediculus	Fragilaria brevistriata*	Nitzschia fonticola
	Amphora veneta	Fragilaria capucina	Nitzschia gracilis
	Anomoeoneis vitrea	Fragilaria construens	Nitzschia inconspicua
	Asterionella formosa	Fragilaria crotonensis	Nitzschia intermedia
	Aulacoseira ambigua	Fragilaria leptostauron*	Nitzschia linearis
	Aulacoseira canadensis	Fragilaria parasitica	Nitzschia palea
	Aulacoseira distans*	Fragilaria pinnata	Nitzschia perminuta
	Aulacoseira granulata	Fragilaria virescens	Nitzschia pumila
	Caloneis amphisbaena*	Gomphoneis herculeana	Nitzschia recta
	Caloneis schumanniana*	Gomphonema augur	Nitzschia sigma
	Caloneis silicula*	Gomphonema clavatum*	Nitzschia sociabilis
	Cocconeis neothumensis	Gomphonema gracile	Nitzschia socialis*
	Cocconeis pediculus	Gomphonema grovei*	Nitzschia subacicularis
	Cocconeis pellucida*	Gomphonema minutum	Pinnularia submicrostauron*
	Cocconeis placentula	Gomphonema olivaceoides	Rhizosolenia longiseta*
	Craticula cuspidata	Gomphonema olivaceum*	Rhoicosphenia curvata
	Cyclotella cf ocellata	Gomphonema parvulum	Rhopalodia brebissonii*
	Cyclotella meneghiniana	Gomphonema pumilum	Rhopalodia gibba

	Cyclotella ocellata	Gomphonema truncatum	Stauroneis phoenicenteron*
	Cyclotella pseudostelligera	Gyrosigma spenceri*	Stephanodiscus hantzschii
	Cyclotella sp. 1	Hantzschia amphioxys	Stephanodiscus medius
	Cymatopleura elliptica*	Mastogloia smithii*	Stephanodiscus minutulus
	Cymatopleura solea	Melosira varians	Stephanodiscus niagarae
	Cymbella affinis*	Navicula capitata*	Stephanodiscus parvus
	Cymbella caespitosa	Navicula cf. lacunolaciniata	Surirella brebissonii*
	Cymbella cf cistula*	Navicula cryptocephala	Surirella minuta
	Cymbella cistula	Navicula cryptotenella	Surirella robusta
	Cymbella cuspidata	Navicula decussis	Surirella visurgis*
	Cymbella microcephala	Navicula gregaria	Synedra arcus*
	Cymbella silesiaca	Navicula minima	Synedra cyclopum
	Cymbella tumida	Navicula pelliculosa	Synedra delicatissima
	Cymbella tumidula	Navicula pupula	Synedra filiformis
	Cymbella turgida*	Navicula radiosa*	Synedra rumpens
	Cymbellonitzschia minima	Navicula radiosafallax	Synedra tenera
	Denticula kuetzingii	Navicula salinarum	Synedra ulna
	Diatoma tenuis	Navicula trivialis	
	Diatoma vulgaris	Nitzschia acicularis	
Chlorophyta	Actinastrum hantzschii	Gloeococcus minor	Scenedesmus dimorphus
	Ankistrodesmus braunii*	Golenkinia radiata	Scenedesmus intermedius
	Ankistrodesmus convolutus	Lagerheimia quadriseta	Scenedesmus opoliensis
	Ankistrodesmus falcatus	Micractinium pusillum	Scenedesmus quadricauda
	Botryococcus braunii	Monomastix astigmata	Scenedesmus semipulcher
	Carteria platyrhyncha	Monomastix minuta	Scenedesmus serratus
	Characium ambiguum*	Monoraphidium capricornutum	Schroederia judayi
	Chlamydomonas globosa*	Oocystis lacustris*	Schroederia setigera
	Chlorogonium fusiforme	Oocystis parva	Selanastrum gracile*
	Closterium moniliferum	Oocystis pusilla*	Selenastrum minutum
	Coelastrum microporum	Pandorina morum	Spermatozopsis exsultans
	Coelastrum pseudomicroporum	Paulschulzia tenera	Sphaerocystis schroeteri
	Cosmarium tenue*	Pediastrum boryanum	Stichococcus pelagicus*
	Crucigenia tetrapedia	Pediastrum tetras	Tetraedron caudatum
	Deasonia Gigantica	Pyramichlamys cordiformis*	Tetraedron minimum
	Dictyosphaerium chlorelloides	Pyramichlamys dissecta	Tetraedron muticum
	Dictyosphaerium pulchellum	Quadrigula lacustris	Tetraedron regulare
	Didymogenes anomala*	Scenedesmus abundans	Tetrastrum staurogeniaeforme
	Dimorphococcus lunatus*	Scenedesmus acutus	Treubaria setigera
	Eudorina elegans	Scenedesmus bijuga	Uronema elongatum*
	Geminella ordinata*	Scenedesmus denticulatus	
Chrysophyta	Chrysolykos planctonicus	Dinobryon sertularia*	Kephyrion gracilis*
	Dinobryon bavaricum	Dinobryon sociale	Mallomonas akrokomas
	Dinobryon cyst	Erkenia subaequiciliata	
	Dinobryon divergens	Gonyostomum ovatum	
Cryptophyta	Cryptomonas erosa		
	Cryptomonas gracilis*		
	Cryptomonas lucens		
	Cryptomonas ovata		
Cyanophyta	Anabaena aphanizomenoides	Aphanothece nidulans	Merismopedia tenuissima
	Anabaena circinalis	Chroococcus minimus	Merismopedia trolleri
	Anabaena eucompacta*	Chroococcus minutus	Merismopedia warmingiana
	Anabaena inaequalis	Coelosphaerium naegelianum	Microcystis aeruginosa
	Anabaena lemmermannii	Cylindrospermopsis raciborskii*	Myxobaktron salinum*
	Anabaena macrospora	Cylindrospermum musciola	Oscillatoria lacustris
	Anabaena mendotae	Dactylococcopsis irregularis	Oscillatoria limnetica
	Anabaena spiroides	Gloeotrichia echinulata	Oscillatoria splendida*
	Anabaena variabilis*	Cryptomonas rostratiformis	Phormidium mucicola

	Aphanizomenon flos-aquae	Rhodomonas minuta	Pseudanabaena galeata
	Aphanizomenon ovalisporum	Gomphosphaeria lacustris	Synechococcus elongatus
	Aphanocapsa delicatissima	Limnothrix redekei*	Synechococcus leopoliensis*
	Aphanocapsa elachista	Merismopedia cf danubiana*	
	Aphanocapsa koordersi*	Merismopedia punctata	
Euglenophyta	Euglena acus		
	Lepocinclis fusiformis*		
	Lepocinclis glabra*		
Pyrrhophyta	Gymnodinium sp. 1		
	Gymnodinium sp. 2		
	Gymnodinium sp. 3		
	Peridinium umbonatum		
Haptophyta	Chrysochromulina sp.		
Xanthophyta	Goniochloris fallax*		
	Tribonema subtilissimum*		