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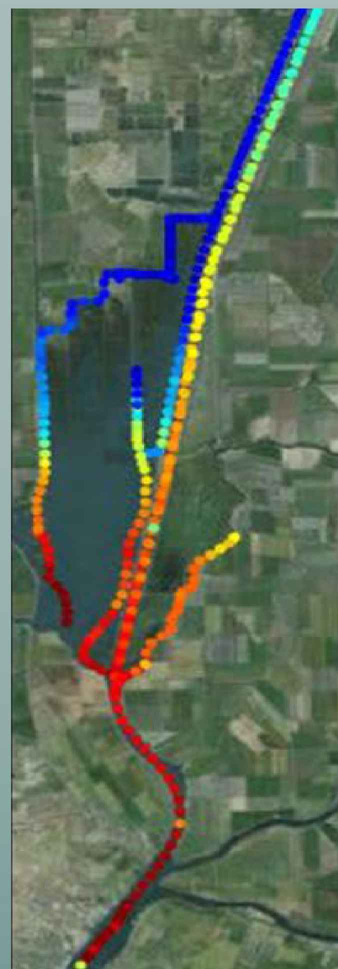
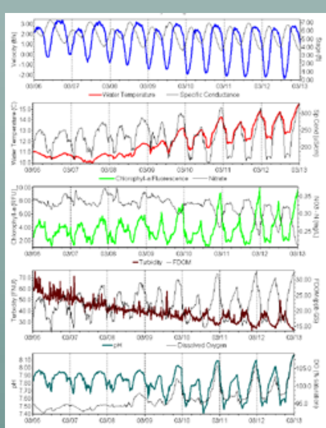
Synthesis of Data from High-Frequency Nutrient and Associated Biogeochemical Monitoring for the Sacramento–San Joaquin Delta, Northern California





Scientific Investigations Report 2017–5066

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FRONT COVER:
Top left: Photograph showing monitoring buoy at Liberty Island, California, being serviced by hydrologic technician.
Photograph by Bryan Downing, December 19, 2013.
Bottom Left: Example of a daily report for the monitoring buoy in Liberty Island, California that is emailed out to interested parties.
Report generated by Frank Anderson, 2014.
Bottom middle: Photograph showing vertical water quality profiler in the Sacramento River.
Photograph by Michael Sauer, April 16, 2013.
Right: Map of nitrate concentrations collected via high speed boat mapping in the Cache Slough Complex/North Delta.
Map created by Travis von Dessonneck and Bryan Downing, October 10, 2014.

BACK COVER:
Top left: Photograph showing monitoring buoy at Liberty Island, California.
Photograph by Bryan Downing, March 8, 2017.
Bottom Left: Photograph showing vertical profiling instrumentation, Sacramento River, Freeport, California.
Photograph courtesy of Michael Sauer, April 16, 2013.
Right: Photograph showing flow monitoring station in Liberty Island, California.
Photograph by Bryan Downing, March 8, 2017.
Bottom: Photograph showing sunset in the northern Delta, Little Holland Tract, California.
Photograph by Bryan Downing, March 8, 2017.

Synthesis of Data from High-Frequency Nutrient and Associated Biogeochemical Monitoring for the Sacramento–San Joaquin Delta, Northern California

By Bryan D. Downing, Brian A. Bergamaschi, and Tamara E.C. Kraus

Prepared in cooperation with the Delta Regional Monitoring Program

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
	Mass	
milligram (mg)	3.5274 × 10-5	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton (ton)

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

$$°F = (1.8 \times °C) + 32.$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Supplemental Information

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

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

Abbreviations

CAWSC	California Water Science Center
Chl-a	chlorophyll-*a*
Delta	Sacramento–San Joaquin Delta
DO	dissolved oxygen
fDOM	fluorescent dissolved organic matter
FNU	Formazin Nephelometric Units
HF	high-frequency
IEP	Interagency Ecological Program
N	nitrogen
NO_3	nitrate
P	phosphorus
psu	practical salinity units
USGS	U.S. Geological Survey
WWTP	wastewater treatment plant
WY	water year

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Executive Summary

This report is the second in a series of three reports that provide information about high-frequency (HF) nutrient and biogeochemical monitoring in the Sacramento–San Joaquin Delta of northern California (Delta). The purpose of this report is to synthesize the data available from a nutrient and water-quality HF (about every 15 minutes) monitoring network operated by the U.S. Geological Survey in the northern Delta. In this report, we describe the network and focus on the purpose of each station. We then present and discuss the available data, at various timescales—first at the monthly, seasonal, and inter-annual timescales, and second, for comparison, at the tidal and event timescales. As expected, we determined that there is substantial variability in nitrate-N concentrations at short timescales within hours, but also significant variability at longer timescales such as months or years. Resolving this variability is made possible by the HF data, with the largest variability caused by storms, tides, and diel biological processes. Given this large temporal variability, calculations of cumulative nutrient fluxes (for example, daily, monthly, or annual loads) is difficult without HF data. For example, in the Cache Slough, calculation of the annual load without the tidal variability resulted in a 30 percent underestimation of the true annual load value. We conclude that HF measurements are important for accurate determination of fluxes and loads in tidal environments, but, more importantly, provide important insights into processes and rates of nutrient cycling.

This report, along with the other two reports of this series (Bergamaschi and others, 2017; Kraus, Bergamaschi, and others, 2017), was drafted in cooperation with the Delta Regional Monitoring Program to help scientists, managers, and planners understand how HF data improve our understanding of nutrient sources and sinks, drivers, and effects in the Delta. The first report in the series (Kraus, Bergamaschi, and others, 2017) provides an introduction to the reasons for and fundamental concepts behind using HF monitoring measurements, including a brief summary of nutrient status and trends in the Delta and an extensive literature review showing how and where other research and monitoring programs have used HF monitoring to improve our understanding of nutrient cycling. The report covers the various technologies available for HF nutrient monitoring and presents the different ways HF monitoring instrumentation may be used for fixed station and spatial assessments. Finally, it presents numerous examples of how HF measurements are currently (2017) being used in the Delta to examine how nutrients and nutrient cycling are related to aquatic habitat conditions.

The third report in the series (Bergamaschi and others, 2017) provides the background, principles, and considerations for designing an HF nutrient-monitoring network for the Delta to address high-priority, nutrient-management questions. The report starts with discussion of the high-priority management questions to be addressed, continues through discussion of the questions and considerations that place demands and constraints on network design, discusses the principles applicable to network design, and concludes with the presentation of three example nutrient-monitoring network designs for the Delta, proposed to address high-priority questions identified by the Delta Regional Monitoring Program (Delta Regional Monitoring Program Technical Advisory Committee, 2015).

An Introduction to the Sacramento–San Joaquin Delta

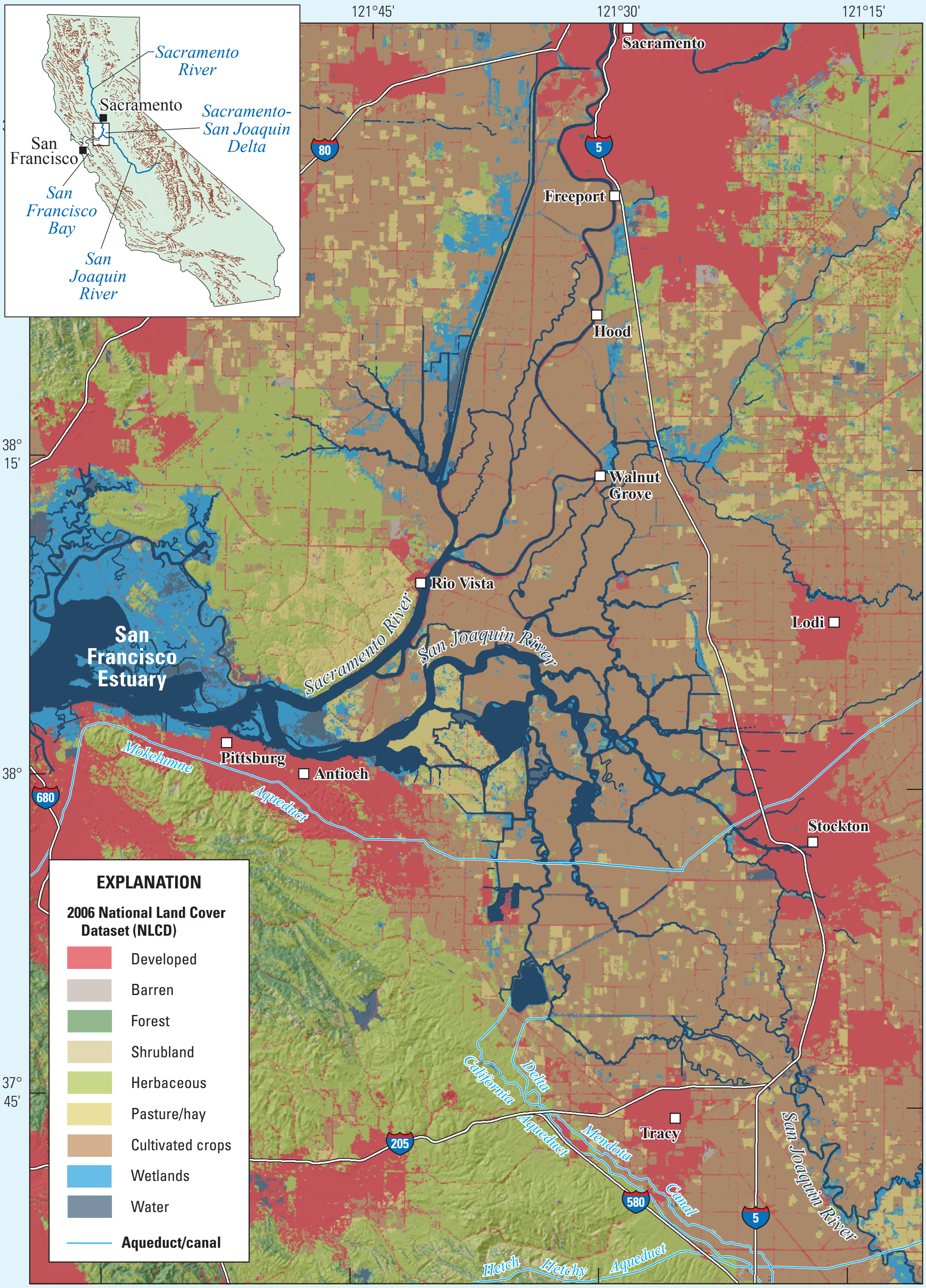
The Sacramento–San Joaquin Delta (Delta) of northern California is a tidal-freshwater river delta comprising about 3,000 km^2 (1,158 mi^2) of the northeastern extent of the San Francisco Estuary (fig. 1). Previously an area dominated by wetlands, the Delta has experienced large-scale alterations to aquatic habitats. Today, the area is a mosaic of deeply subsided islands predominantly maintained as agricultural, protected by more than 1,000 km of levees, and interconnected by an artificial network of deep tidal channels. Freshwater enters the Delta primarily from the Sacramento River to the north, the San Joaquin River to the south, and several other minor tributaries. Flows from these sources depend on seasonal precipitation, upstream reservoir releases, and discharges from agricultural and urban uses. The complex hydrodynamics that result from tidal and river currents propagating through the channel network affect all aquatic processes in the Delta because it alters residence times, causes high levels of mixing, and transports material both landward and seaward. Adding to this complexity is the export of water from the southern Delta by means of State and Federal water projects, which imposes a net north-to-south flow through the Delta during periods of high pumping. It is estimated that the Delta supplies freshwater to more than 1 million ha of agricultural land and more than 27 million people (Delta Stewardship Council, 2016). The Delta also serves as critical habitat for fish, birds, and wildlife, but with ever-growing urban and agricultural demands on this resource, there is an increasing need to understand drivers of ecosystem health, including the role of nutrients.

Nutrients

Nutrient loads delivered by the Sacramento and San Joaquin Rivers comprise the largest source of nutrients to the Delta, with municipal and agricultural discharge contributing the bulk of these nutrients (Kratzer and others, 2011). The loading to the Delta can vary rapidly over time in response to storms, seasonal changes in discharge, and other processes, and is also influenced by long-term trends in climate. Municipal wastewater accounts for about 25 percent of the total nitrogen loads and 20 percent of the total phosphorus loads to the Delta (Domagalski and Saleh, 2015; Saleh and Domagalski, 2015).

There are some ongoing trends in nutrient concentrations and loads. Annual mean nitrate concentration in the Sacramento River has been recently decreasing, but the flow-normalized annual load has remained relatively constant (Schlegel and Domagalski, 2015). Conversely, in the San Joaquin River, no recent decreases are evident in the annual mean nitrate concentrations and loads (Schlegel and Domagalski, 2015). Central Valley watersheds supply only a small fraction of ammonium, the other major form of inorganic nitrogen, to the Delta, with the Sacramento Regional Wastewater Treatment Plant accounting for 90 percent of the total ammonium load (Jassby, 2008). Watershed contributions to concentrations and loads of ammonium and total phosphorus have recently continued to modestly decrease (Schlegel and Domagalski, 2015).

Although there are few data, loading of nutrients within the Delta is thought to be relatively small and constant, arising primarily from Delta island drainage (Novick and others, 2015). However, biological and physical processes within the Delta cause temporal and spatial changes in nutrient concentrations. Uptake of nutrients by phytoplankton and vegetation, nitrification (the biological transformation of ammonium into nitrate), and denitrification (the biological transformation of nitrate to nitrogen gas) vary seasonally and spatially in the Delta and play important roles in determining the local concentration and distribution of nutrients (Foe and others, 2010; Parker and others, 2012; Novick and others, 2015). Phosphate, which primarily travels with sediment, is similarly variable (Morgan-King and Schoellhamer, 2013; Cornwell and others, 2014). Some studies suggest that nutrient forms and ratios affect Delta food webs by changing patterns of phytoplankton productivity and community composition (Glibert, 2010; Parker and others, 2012; Senn and Novick, 2014). Trends in nutrient concentrations in the Delta generally have been flat or decreasing since 1998, which is attributed to management source-control efforts as they run counter to the increasing population density and agricultural intensity in the Central Valley (Novick and others, 2015). The Delta is the largest source of nutrients to the San Francisco Estuary.



Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal Area Projection; North American Datum of 1983

Figure 1. Sacramento–San Joaquin Delta, northern California.

Introduction

Owing to the wide variety of sources and drivers, water-quality conditions in the Sacramento–San Joaquin Delta (Delta) are highly variable. This variation reflects the entwined effects of variation driven by tidal currents (daily and lunar), diurnal cycles, seasonal cycles, annual and inter-annual changes in river discharge, cycles in agricultural activity, water diversion, wastewater effluent, economic development, land use, and recreational use, among other factors. Furthermore, there are other factors driving variability in water quality, such as water transfers, temporary barriers, water withdrawals, droughts, floods, levee failures, atmospheric pressure changes, and storms. Quantifying water-quality conditions in the context of this high variability is challenging, requiring new techniques and approaches (Pellerin and others, 2016). Analyses of physical and biogeochemical data from the Delta have shown that if this high-frequency (HF) variation is not appropriately captured, the results may not accurately represent true trends or the timing of observed changes (Schoellhamer and others, 2007; Kraus, Bergamaschi, and others, 2017).

Historically, continuous-monitoring networks in the Delta have targeted HF measurement of flow and water-quality characteristics such as temperature, conductance, and turbidity. HF monitoring of key aquatic habitat parameters, such as chlorophyll, dissolved organic matter, and nutrients has been limited because of the lack of reliable and accurate instrumentation and field methodologies to make these kinds of measurements possible. Recent technological advances in water-quality instrumentation that better measure habitat quality indicators continuously in situ help bridge the information gap between historical weekly or monthly grab sampling and rapidly changing conditions in the Delta. The data and analyses developed from this type of HF monitoring improve understanding of how flow dynamics affect concentration and distribution of nutrients, phytoplankton, dissolved oxygen (DO), and dissolved organic material, and present these results in real time to managers and scientists. The HF measurements not only increase understanding of food web dynamics, but also allow real-time visualization and rapid evaluation of variability and effects due to natural variation, management, or experimental manipulation, and ultimately provide long-term data to track these changes. These networks measure key habitat-quality characteristics, fundamental in establishing relationships to flow conditions and linkages to intensive ongoing discrete sampling and other research efforts spatiotemporally in the Delta.

Currently (2017), there is a limited network of HF stations in the northern Delta measuring nitrate and other water-quality parameters used to assess aquatic habitat conditions. Water entering this area under normal flow conditions receives a substantial contribution of nutrients from effluent discharged by the Sacramento Regional Wastewater Treatment Plant (WWTP; Novick and others, 2015) into the Sacramento River. During high flows in the winter, nutrient concentrations are elevated due to runoff from the watershed. There is concern that elevated nutrient loading to the northern Delta may adversely affect aquatic habitat quality and may affect phytoplankton production in the northern Delta wetlands, perhaps contributing to the growth of harmful algal blooms or invasive submerged aquatic vegetation. Many actions currently (2017) are underway or contemplated that will change nutrient concentrations in the northern Delta, including upgrades to the Sacramento Regional WWTP, wetland restoration, and changes in flows through the Yolo Bypass. Greater understanding of how nutrients are transported to the northern Delta and the effects of those nutrients on phytoplankton productivity and aquatic habitat quality will help managers assess the potential changes that may result from any of these actions.

Existing U.S. Geological Survey High-Frequency, Nutrient-Monitoring Network

The overarching purpose of the ongoing HF nutrient-monitoring network run by the U.S. Geological Survey (USGS) California Water Science Center (CAWSC) in the northern Delta is to continuously measure the tidally dependent variation in nutrients and water quality and to investigate the causes and effects of such variation on habitat conditions and phytoplankton productivity. The goal of the network is to provide continuous real-time habitat status and trends information to managers and researchers and thereby to assist in operational management and environmental assessment. The network is not specifically designed to measure the loading of nutrients into the Delta, although in some cases such loading can be calculated. The existing HF nutrient-monitoring network (fig. 2) is an extension of a proof-of-concept HF monitoring station originally installed for the Interagency Ecological Program (IEP) with funding from the Bureau of Reclamation at Liberty Island, along with habitat characterization measurements made for the IEP fall low salinity habitat (FLaSH) study. Liberty Island lies within the northern Delta range of the delta smelt (*Hypomesus transpacificus*) distribution, which includes the Cache Slough Complex and the Sacramento Deepwater Shipping Channel. As part of the "North Delta Arc" (Durand, 2015), it also is an important region for salmon and other native species. Features of the northern Delta habitats include strong tidal exchanges with the Sacramento River, occasional winter flood flows from the Yolo Bypass to its north, subsidies of phytoplankton productivity from numerous tributaries and dead-end sloughs, and low salinity (about 0.5 practical salinity units [psu]) from the lower Sacramento River.

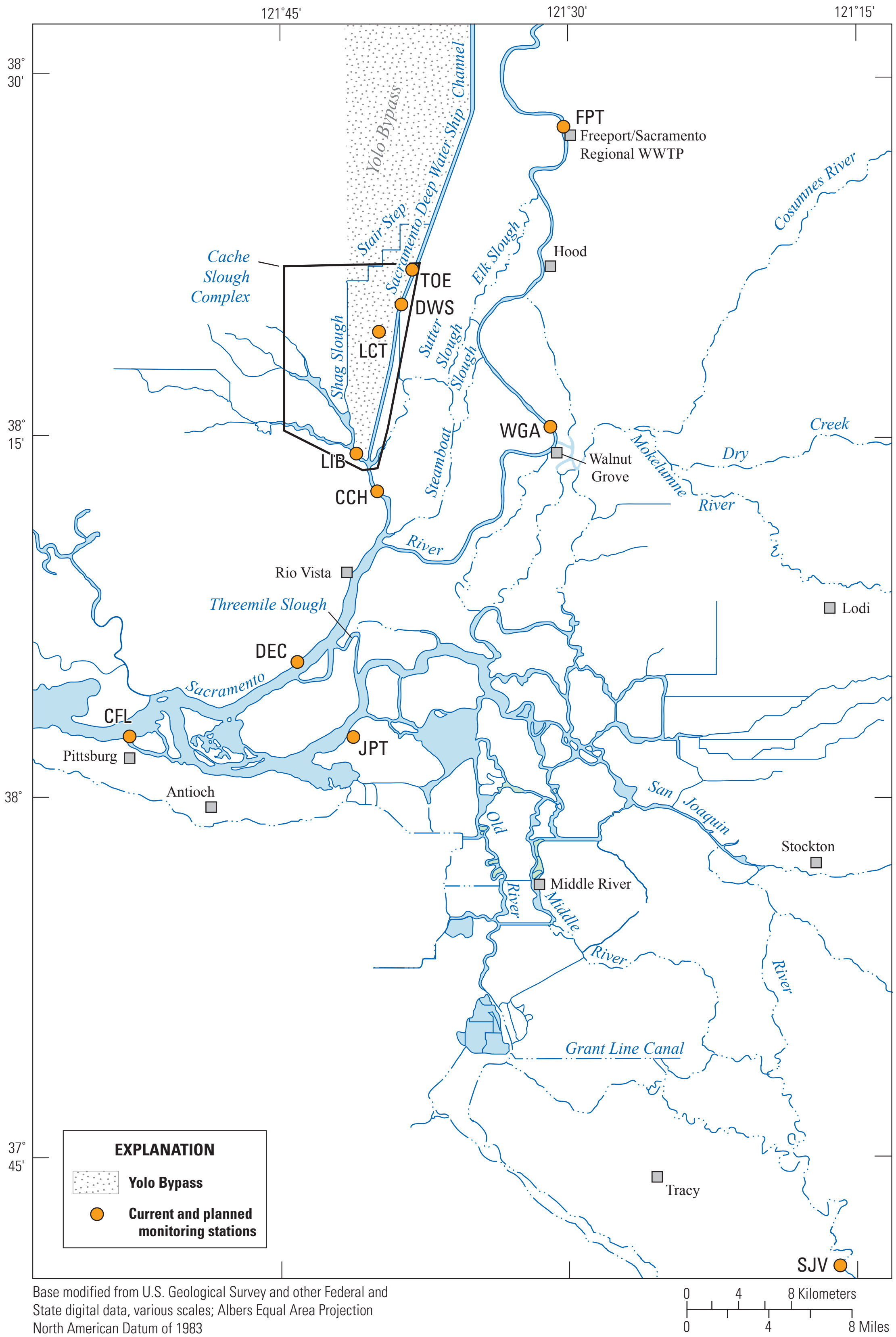


Figure 2. Location of high-frequency, nutrient-monitoring stations operated in the Sacramento–San Joaquin Delta, northern California, fall 2016. See table 1 for station information.

In addition to the northern Delta HF nutrient-monitoring network, the USGS CAWSC also operates a station on the San Joaquin River at Vernalis, the southern inflow to the Delta (fig. 2). The USGS has measured river discharge at this station since 1923 and suspended sediments since 1956.

High-Frequency Measurements

The existing USGS HF nutrient-monitoring program strives to integrate with existing flow and turbidity monitoring, and includes HF measurements (15-minute sampling frequency) of temperature, conductance, pH, DO, nitrate-N (sum of nitrate plus nitrite; $NO_3 + NO_2$), chlorophyll-*a*, phycocyanin (a tracer for blue-green algae such as *Microcystis aeruginosa*), and fluorescent dissolved organic matter (fDOM, a proxy for dissolved organic carbon concentration). Deployment of in situ phosphate analyzers at these stations occurs on a project or event basis, and in situ ammonium analyzers are under development. The HF monitoring program supplements monthly discrete sampling by the USGS and others with real-time water-quality and environmental data. The USGS HF nutrient-monitoring program has been in operation since 2013.

Description of Study Area

As of fall 2016, a total of 11 HF monitoring stations are established in the northern Delta region (table 1, fig. 2). Two stations—Freeport (FPT) and Walnut Grove (WGA)—are located on the Sacramento River upstream of the Cache Slough Complex, and three stations—Decker Island (DEC), Jersey Point (JPT), and Confluence (CFL)—are located downstream of the Cache Slough Complex. Four stations are located in the Cache Slough Complex of the northern Delta: (1) Toe Drain (TOE), (2) Liberty Cut (LCT), (3) Liberty Island (LIB), and (4) Cache Slough at Ryer Island (CCH). One station is located in the Sacramento Deep Water Shipping Channel (DWS). An 11th station adds nitrate measurements to the existing California Department of Water Resources monitoring station on the San Joaquin River near Vernalis (SJV; table 1, fig. 2). The Jersey Point and Confluence stations were established in September 2016; thus, data from those stations were not yet available for this report and are not discussed further. Two additional stations planned for Suisun Bay are expected to be installed by December 2017.

Attributes of a High-Frequency, Nutrient Monitoring Network for the Delta

Deployment of monitoring buoy from which multi-parameter water-quality sondes are suspended. Photograph by Bryan Downing, U.S. Geological Survey. September 9, 2014.

High frequency (HF): In tidal systems, measurements are made at least once every 15–20 minutes.

Continuous: Data are collected continuously over an extended period (months–years) of time.

Real time: Data are delivered to users in real time, facilitating decision making by managers, improving data quality, and acting as a trigger for additional data collection efforts. Data collected in the Delta are available at https://waterdata.usgs.gov/nwis.

Flux-based: Simultaneous collection of flow data permits calculation of mass fluxes and loads. Most existing nutrient stations in the Delta are co-located with the Delta flow-station network (Burau and others, 2016; https://doi.org/10.3133/fs20153061).

Multi-parameter: Simultaneous collection of related water quality parameters improves understanding of nutrient sources, sinks, processing, and effects. In the Delta, stations that are equipped with nitrate sensors also measure temperature, pH, conductivity, dissolved oxygen, turbidity, and fluorescence of dissolved organic matter, chlorophyll-*a*, and blue-green algae.

Network: Stations are spatially distributed so that sources, transport, and fate of nutrients can be tracked and their effects on Delta habitats can be assessed at multiple spatial scales.

Table 1. Station information for high-frequency water-quality monitoring stations equipped with in situ nitrate analyzer, Sacramento–San Joaquin Delta, northern California, fall 2016.

[High-frequency water-quality monitoring stations operated by U.S. Geological Survey (USGS) California Water Science Center. All stations are currently equipped with a SUNA nitrate analyzer and YSI EXO2, with the exception of the station at Vernalis (SJV), where an EXO sonde is operated separately by the California Department of Water Resources. All EXO2 sondes are equipped to measure temperature, specific conductance, pH, dissolved oxygen, turbidity, chlorophyll-*a* fluorescence, phycocyanin fluorescence (a tracer for blue-green algae such as *Microcystis*), and dissolved organic matter fluorescence (fDOM, a proxy for dissolved organic carbon concentration). Station data are available in real time on the USGS National Water Information System (NWIS; https://waterdata.usgs.gov/nwis). Deployment of in situ phosphate analyzers at these stations occurs periodically based on project needs or for specific events, and in situ ammonium analyzers are under development. Other abbreviations: No., number; NAD 83, North American Datum of 1983 (horizontal datum). Dates specified as month-day-year]

Official station name	Short station name	Station abbreviation	NWIS station No.	Date established	Latitude (NAD 83)	Longitude (NAD 83)
Sacramento River at Freeport	Freeport	FPT	11447650	08-30-13	38°27'22"	121°30'01"
Sacramento River above Delta Cross Channel	Walnut Grove	WGA	11447890	08-21-13	38°15'28"	121°31'02"
Toe Drain at Mallard Road, near Courtland	Toe Drain	TOE	11455139	08-19-14	38°21'54.50"	121°38'15.87"
Liberty Cut at Little Holland Tract, near Courtland	Liberty Cut	LCT	11455146	01-31-14	38°19'43.86"	121°40'03.11"
Sacramento River Deep Water Ship Channel near Rio Vista	Deep Water Shipping Channel	DWS	11455142	04-11-14	38°20'30"	121°38'38"
Cache Slough at Ryer Island	Cache Slough	CCH	11455350	02-01-13	38°12'46"	121°40'09"
Cache Slough at South Liberty Island, near Rio Vista	Liberty Island	LIB	11455315	07-15-13	38°14'32"	121°41'10"
Sacramento River at Decker Island, near Rio Vista	Decker Island	DEC	11455478	01-24-13	38°05'36"	121°44'10"
San Joaquin River at Jersey Point	Jersey Point	JPT	11337190	09-12-16	38°03'08"	121°41'16"
Suisun Bay at van Sickle Island, near Pittsburg	Confluence	CFL	11455508	09-12-16	38°02'58.31"	121°53'15.18"
San Joaquin River near Vernalis	Vernalis	SJV	11303500	01-21-15	37°40'34"	121°15'55"

The monitoring objectives in the upper Sacramento River are to: (1) determine mass fluxes of nitrate and phytoplankton (as chlorophyll-*a* fluorescence) entering the Delta from the Sacramento River, (2) improve understanding of the dynamics between nutrients (especially nitrate and ammonium) and phytoplankton, and (3) elucidate effects of wastewater effluent on food web dynamics. The lower Sacramento River station at Decker Island is intended primarily to determine mass fluxes from the northern Delta/Cache Slough Complex and linkages to delta smelt migration through the Sacramento River corridor.

Monitoring objectives in the Cache Slough Complex region (21,000 ha; about 52,000 acres) are related to tidal wetland restoration as suitable habitat for endangered fish species. This area has been identified as an area with high potential to meet tidal restoration requirements because of suitable habitat properties, such as turbidity, primary and secondary productivity, and use by endangered native fishes, such as the delta smelt. The Cache Slough Complex is bounded hydrologically by the Sacramento River on the south, Shag Slough on the west, the Yolo Bypass Toe Drain on the east, historical agricultural levees in the north, and Liberty Cut, a drainage oriented north-south on the eastern side of Liberty Island (fig. 2). Two distinct tidal wetlands are contained within the Cache Slough Complex: Liberty Island (2,100 ha; about 5,200 acres) and Little Holland Tract (570 ha; about 1,400 acres). Both wetlands once were diked and drained for agricultural use, but later became permanently flooded owing to unintentional levee breaches that were not repaired. The region is geographically and hydrodynamically complex, containing areas of emergent vegetation, shoals, and sloughs, with tidal currents that mix and transport organisms and nutrients.

Tides in the Delta can be mixed, composed of diurnal (only one high and low tide each day) to semidiurnal tides (two nearly equal high and low tides each day), with a maximum spring tidal range of 1.5 m and a minimum neap tidal range of 0.5 m. Tidal forcing in the Delta brings a mixture of seawater and freshwater (brackish water) ranging in salinity from about 0 to about 5 psu, and changes daily depending on tidal stage, weather, or other factors, such as geomorphology of channels. Strong winds in the Delta result in wind-wave induced resuspension of sediments and chlorophyll-*a* (Schoellhamer and others, 2012).

Data Availability and Quality Assurance

USGS HF nutrient measurements are available to the public and other researchers on the Web, and in daily reports by subscription. Data from the sensor stations in the HF monitoring network are available in real time through the USGS National Water Information System (NWIS) Web portal page for California (https://waterdata.usgs.gov/ca/nwis). This effort supports several specific targeted scientific objectives, all related to quantitative assessment of locations and rates of biogeochemical processes in the Delta. Data are corrected to quality standards and guidelines according to USGS national standards and guidelines (Wagner and others, 2006; U.S. Geological Survey [various dates]). Nitrate measurements and corrections follow protocols described by Pellerin and others (2013).

Station Locations and Descriptions

All USGS HF nutrient and water quality monitoring stations collect HF measurements (every 15 minutes) of nitrate, temperature, specific conductance, pH, DO, turbidity, chlorophyll-*a* fluorescence, phycocyanin fluorescence, and dissolved organic matter fluorescence (table 2). Sensors are located about 1 m below Mean Lower Low Water. Stations have been built with the capacity to install additional sensors (for example, phosphate, ammonium) as they become available. Physical descriptions of each station are available at https://waterdata.usgs.gov/ca/nwis. Station locations are shown in figure 2.

Sacramento River at Freeport (FPT).—The Sacramento River drains the northern Central Valley of California and supplies most nutrients (nitrogen [N] and phosphorus [P]) to the northern Delta (fig. 1). This station, located on the Freeport Bridge just upstream of the discharge location for the Sacramento Regional WWTP, was established in August 2013. This station provides information about water-quality conditions in the river immediately upstream of wastewater inputs. This station was established (1) to improve understanding of the linkages between nitrogen and phytoplankton dynamics in the Sacramento River, and (2) through comparison to downstream conditions, to help elucidate effects of effluent on nutrient concentrations and food web dynamics.

Table 2. Parameters measured at the U.S. Geological Survey high-frequency water-quality monitoring stations and information they provide.

Parameter	Information provided
Nitrate	Measurement of nitrate concentration, information about nitrate production and consumption. **Note:** The SUNA instrument measures “nitrate plus nitrite” and is reported in units of milligrams per liter as nitrogen.
Temperature	Temperature affects both abiotic and biotic processes, information about vertical and horizontal river mixing/stratification, indicator of water source.
Specific conductance	Information about water sources and about vertical and horizontal mixing/stratification.
pH	pH affects biogeochemical reactions; generally higher pH indicates photosynthesis, lower pH indicates decomposition or wastewater water treatment plant inflow.
Dissolved oxygen (DO)	DO generally indicates balance between oxygen production during photosynthesis and consumption during respiration.
Turbidity	Provides information about total particulate concentrations, insight into river mixing, water source, and the light field.
Chlorophyll-*a* fluorescence (fCHLA)	Proxy for phytoplankton biomass.
Phycocyanin fluorescence (fBGA)	Proxy for cyanobacteria biomass.
Dissolved organic matter fluorescence (ex 370/em 460) (fDOM)	Proxy for dissolved organic carbon concentration, information about carbon production and consumption, tracer of water source.

Sacramento River above Delta Cross Channel (WGA).—This station was established in August 2013 and is located just upstream of the Delta Cross Channel, about 18 mi (29 km) downstream of Freeport. It thus integrates the upstream inputs from the Sacramento River watershed with wastewater inputs from the regional WWTP. The station was established to improve understanding of the linkages between nitrogen and phytoplankton dynamics in the Sacramento River, to evaluate effluent effects on food web dynamics, and to better quantify nutrient inputs and transformation rates.

Cache Slough at Ryer Island (CCH).—Lower Cache Slough links the lower Sacramento River to the northern Delta, and acts as an advective and dispersive conveyance. This station, established in February 2013, provides information to assess exports from the Cache Slough Complex to the lower Sacramento River and San Francisco Estuary. The specific site was selected because of the presence of a flow monitoring station at Rio Vista and its location within a single tidal excursion from Liberty Island. For example, a water parcel residing on Liberty Island (LIB) at high tide can end up downstream of the Rio Vista Bridge (8–9 mi down estuary) in 6 hours with an outgoing tide (Burau and others, 2016).

Cache Slough at South Liberty Island, near Rio Vista (LIB).—Liberty Island is a 2,100-ha (about 5,200-acre) flooded wetland, breached in 1998 and recently designated as an ecological reserve to protect emergent wetlands and special status fish species. Liberty Island has been identified as a model for habitat restoration, to support delta smelt spawning and rearing in the northern Delta. This station, referred to as Liberty Island (LIB), is located near the downstream mouth of the flooded region and was selected as a pilot site for initial HF monitoring evaluation (table 1). The LIB station was established in July 2013. The location at the mouth of Liberty Island was selected because of the pre-existing flow monitoring station, necessary for flux-based measurements of nutrients and phytoplankton productivity. The station is deployed on a buoy. The buoy was necessary as there is no infrastructure (for example, piling, channel marker, dolphin, etc.) available to mount instrumentation.

Toe Drain at Mallard Road, near Courtland (TOE).—The Toe Drain is a tidal channel draining the eastern side of the Yolo Bypass. The Yolo Bypass is a 24,000-ha (about 59,000-acre) floodplain, about 41 mi long and ranging from 1 to 3 mi wide. The Toe Drain receives water from upstream drainage systems as well as the Yolo Bypass Wildlife Area, rice, and other agricultural fields within the bypass. The Toe Drain station was established in August 2014 and is located in the Toe Drain just upstream of the Cache Slough Complex to monitor inputs from these northern, upstream sources entering Liberty Island and to examine connections between Toe Drain inputs and productivity in the northern Delta.

Liberty Cut at Little Holland Tract, near Courtland (LCT).—This station in Liberty Cut was established in January 2014 to help assess effects of wetland restoration activities in the Yolo Bypass region of the Delta. The station was established to help identify and characterize timescales and modes of variability in habitat quality and to identify the hydrologic and biogeochemical conditions that drive habitat quality and ecosystem change.

Sacramento River Deep Water Shipping Channel near Courtland (DWS).—The Sacramento River Deep Water Shipping Channel is a 43.4-mi-long channel that is notable because it supports relatively high fish densities, including all life stages of the endangered delta smelt population. This station was established in April 2014 to better understand how water quality, nutrients, and phytoplankton abundance vary seasonally in this channel. Data from the station are used to inform and provide a baseline for experiments focused on increasing inputs of phytoplankton to the northern Delta.

Sacramento River at Decker Island, near Rio Vista (DEC).—The Decker Island station was established in January 2013 and is co-located with a pre-existing flow monitoring station. The station location was selected because of its location within the tidal excursion from flow monitoring at Rio Vista and at Cache Slough and because this site is well positioned to assess the advective and dispersive fluxes from the Sacramento River and northern Delta into the San Francisco Estuary as well as the dispersive fluxes from the estuary into the lower Sacramento River.

San Joaquin River near Vernalis (SJV).—The Vernalis station adds nitrate to the existing California Department of Water Resources monitoring station at this location.

Synthesis of Data from a Nutrient and Water-Quality High-Frequency Network

Timescales of Variability

Water quality in estuaries is affected by various processes that operate at multiple spatial and temporal scales. Numerous physical processes cause HF water-quality measurements in the Delta to vary over timescales ranging from seconds to years. Trends and loading estimates from monthly monitoring programs cannot account for processes, such as semidiurnal tides, diurnal tides, tidal harmonics, lower frequency tidal cycles (spring-neap), solar radiation, wind, and hydrodynamic conditions (for example, turbulence, instantaneous flow). Identification of these timescales is important and can be related, for example, to estimation of rates of nitrification, biological nutrient uptake, phytoplankton production, and other processes, all definitive goals of the HF monitoring approach. Identification of key hydrodynamic and biogeochemical drivers can help guide existing regional monitoring programs on when and where best to sample.

The primary benefits of HF monitoring are (1) to indicate patterns of important physical and biological processes and events at short temporal timescales, and (2) to allow for accurate calculation of fluxes and loads. Additionally, HF data also can be aggregated to assess long-term patterns on monthly, seasonal, and inter-annual timescales. Because these aggregated values are based on a large number of measurements, they are more accurate and precise than values based on one or two grab samples per month. Additionally, the aggregate values also have the important benefit of having measures of variability (standard deviations, percentiles, ranges) and can be used to assess the validity of monthly grab samples in different regions and locations.

In this section, we show the utility of HF monitoring by examining HF data for nitrate (mg/L as N), DO (mg/L), and chlorophyll-*a* (µg/L) concentrations collected at the USGS water quality stations in the Delta over two water years (WYs)—WY 2014 (October 1, 2013–September 30, 2014) and WY 2015 (October 1, 2014–September 30, 2015)—to identify important timescales of variability. We focused on these two water years because they include the greatest number of stations, allowing us to assess regional patterns. HF data collected outside this time period are available online (see table 1, and https://waterdata.usgs.gov/ca/nwis).

Seasonal, Inter-Annual, and Spatial Variability in Monthly Averages

To assess the seasonal water-quality patterns and related spatial patterns in the Delta, the HF data were aggregated for each station by month (figs. 3–6). Examination of the data in this way resulted in several general observations. For nitrate, concentrations generally were lower in the Sacramento River at Freeport (FPT), increasing down-estuary to the lower Sacramento River at Decker Island (DEC). By comparison, concentrations of nitrate generally are higher in the northern Delta stations (LIB, CCH, LCT, TOE), likely indicative of nitrification of wastewater-derived ammonium as well as inputs of nitrate from upstream sources during storm events (Kendall and others, 2015). Concentrations generally are greatest in winter in association with storm events and higher flows, but the timing of the peaks is different between stations; the highest concentrations at Freeport and Walnut Grove stations occur days or weeks earlier than the highest concentrations at the stations in the northern Delta and lower Sacramento River. The lowest concentrations occur in late summer, corresponding to the peak in the annual cycle of temperature (appendix A), which may be an indication of higher rates of biologically driven nutrient uptake and denitrification. These general trends are the same as those noted by Novick and others (2015), based on approximately monthly grab sample data collected at stations around the Delta. Examination of trends between stations shows some distinct differences. Elevated nitrate concentrations persist much longer at the northern Delta and lower Sacramento River (DEC) stations than at the Sacramento River stations (FPT, WGA), and DEC generally had lower seasonal variability.

Median nitrate concentrations in WYs 2014 and 2015 were highest in the lower Sacramento River at DEC (0.90 mg/L as N) during winter of WY 2014, and at TOE during spring of WY 2015 (1.0 mg/L as N). Nitrate enters Delta waters from point and non-point sources, and also is generated during transport due to nitrification of ammonium (O'Donnell, 2014; Kendall and others, 2015) as well as from decomposition of organic matter and release from the benthos (Novick and others, 2015). Nitrate concentrations measured at DEC station were higher than those measured at other stations because of increased flux of nitrate (and ammonium, which is subsequently nitrified) from the upper Sacramento River (FPT, WGA) and northern Delta sources (LIB, CCH), in response to precipitation and conceivably from unaccounted for cross-channel flows from the San Joaquin River and (or) Central Delta through Threemile Slough or downstream of the confluence. Winter and spring precipitation events (about 0.5–3 mm) in WYs 2014 and 2015 increased nitrate by a factor of about 2–3 at the DEC and TOE stations. High nitrate concentrations at TOE station in WY 2015 were concurrent with high seaward flows in the Toe Drain (2,000–3,700 ft^3/s). Nitrate concentrations in WYs 2014 and 2015 were low in late summer through fall. Accordingly, annual variability in nitrate concentration measured at all stations were highest in winter through spring, with low concentrations and variability beginning in late spring and extending to late summer/early fall.

Chlorophyll-*a* fluorescence and DO also showed seasonal, inter-site, and inter-annual variability (figs. 3–6). Chlorophyll-*a* concentrations tended to be higher in the winter and early spring than in other seasons in the upper Sacramento River (FPT, WGA) and the far northern Delta stations (TOE, LIB). The large channel stations—CCH and DEC—generally had lower chlorophyll-*a* concentrations than other stations. Within-month range in concentrations were substantial at most stations, indicating that monthly sampling has limited validity. Higher nitrate concentrations in the study area are not always associated with higher chlorophyll-*a* concentrations. For example, median nitrate concentrations of about 1.0 mg/L as N measured at DEC station in spring of WY 2014 were associated with chlorophyll-*a* concentrations of about 5 µg/L, compared to 1.0 mg/L as N measured at TOE in winter of WY 2015, which was associated with chlorophyll-*a* concentrations ranging from 10 to 20 µg/L. However, the relationship between nitrate and chlorophyll-*a* is interrelated because, whereas phytoplankton require N for primary production, they also draw down the nitrate concentration. Because of the complex hydrodynamics in the Delta, variability in grazing rates by zooplankton and other herbivores, and other factors, a predictable pattern of high nitrate followed by high chlorophyll-*a* and nitrate drawdown was not consistently apparent.

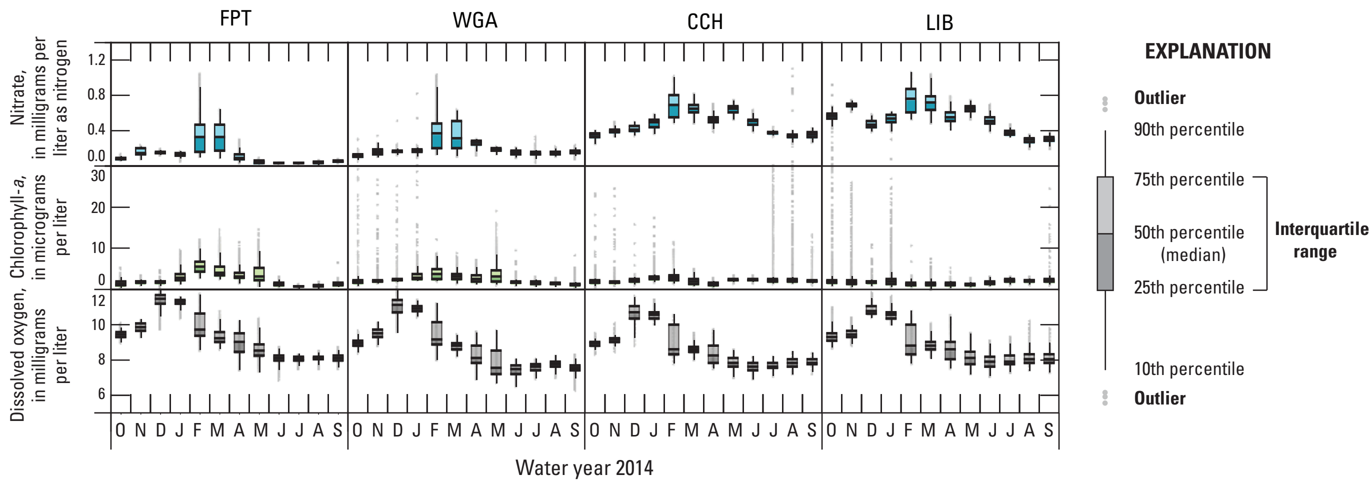


Figure 3. Boxplots of nitrate, chlorophyll-*a*, and dissolved oxygen at Freeport (FPT), Walnut Grove (WGA), Cache Slough (CCH), and Liberty Island (LIB) high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2014. See table 1 for station information and figure 2 for station locations.

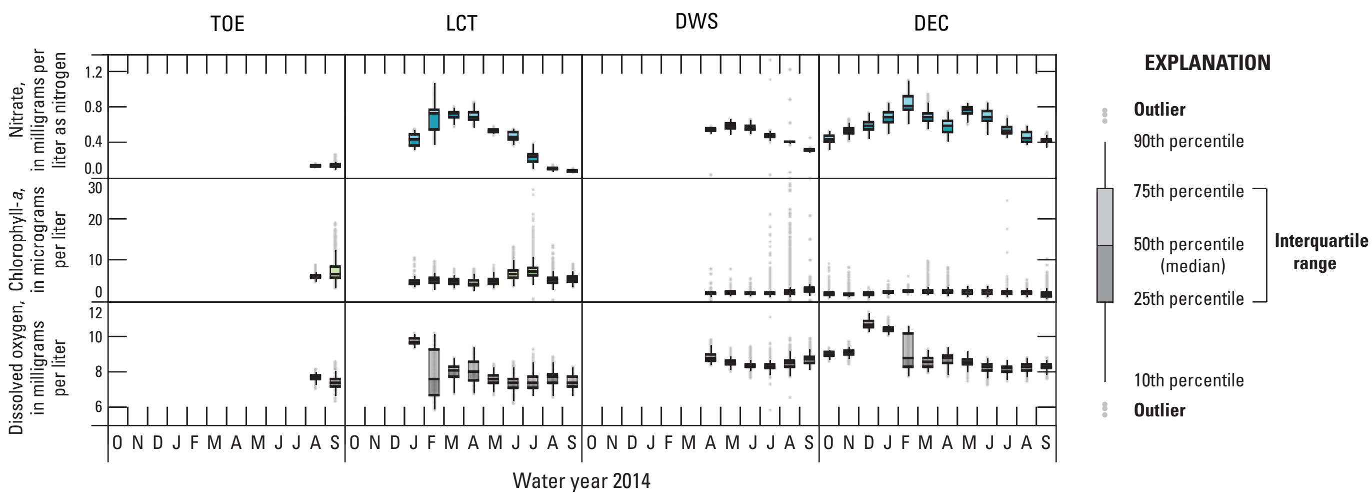


Figure 4. Boxplots of nitrate, chlorophyll-*a*, and dissolved oxygen at the Toe Drain (TOE), Liberty Cut (LCT), Sacramento River Deep Water Shipping Channel (DWS), and Decker Island (DEC) high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2014. See table 1 for station information and figure 2 for station locations.

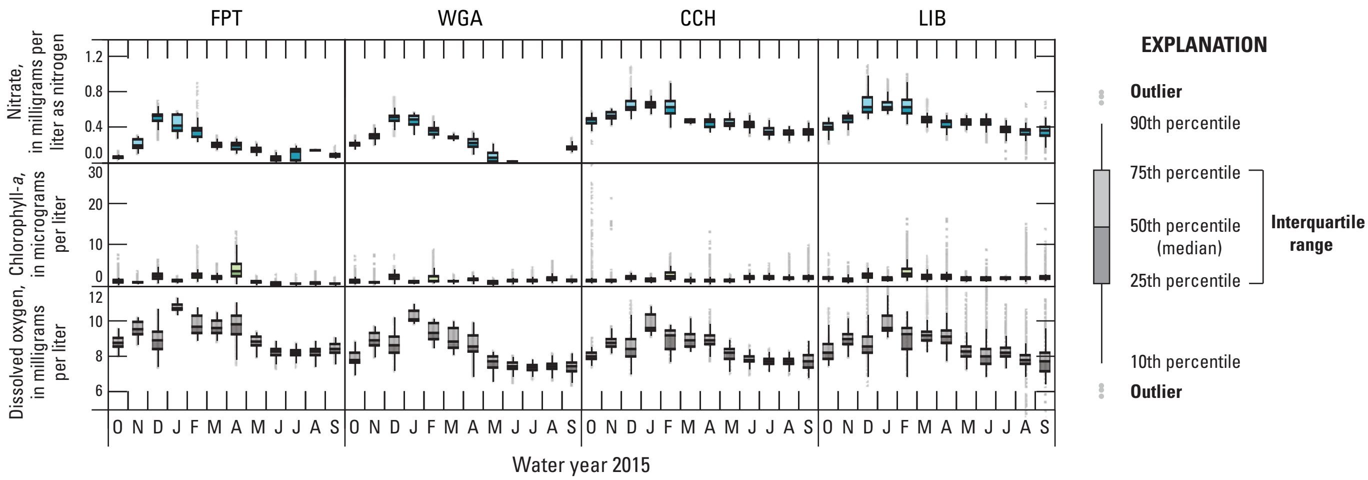


Figure 5. Boxplots of nitrate, chlorophyll-*a*, and dissolved oxygen at the Freeport (FPT), Walnut Grove (WGA), Cache Slough (CCH), and Liberty Island (LIB) high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2015. See table 1 for station information and figure 2 for station locations.

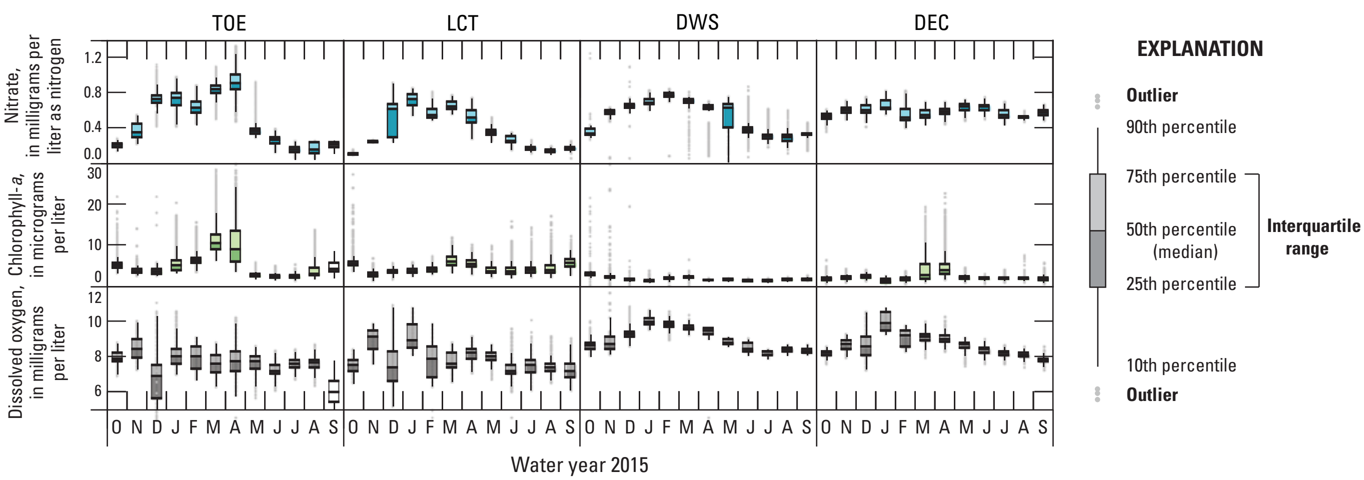


Figure 6. Boxplots of nitrate, chlorophyll-*a*, and dissolved oxygen at the Toe Drain (TOE), Liberty Cut (LCT), Sacramento River Deep Water Shipping Channel (DWS), and Decker Island (DEC) high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2015. See table 1 for station information and figure 2 for station locations.

For DO, there was clearly a seasonal component in the annual trends in concentration, owing to the temperature-dependent solubility of oxygen (that is, oxygen is more soluble at colder temperatures; see appendix A for temperature graphs), seasonal biological processes, and hydrodynamic changes. DO concentrations decrease from about 10 mg/L during winter and spring to a summer pattern of about 8.0 mg/L. However, some stations showed marked deviation from this seasonal pattern, evident even at the monthly time step. This suggests that other processes that produce oxygen (photosynthesis) or that consume oxygen (respiration, decomposition, nitrification) are dominant controls on DO concentrations at these stations. Concentrations at stations in the northern Delta (LCT, TOE) were lower than the seasonal change would suggest, indicating that DO was depressed for months at a time. These DO decreases are interesting in that these events may indicate seasonal changes in water residence time associated with low flow in the northern Cache Slough Complex, specifically in the stair-step levee region (fig. 2). Conversely, DO concentrations at LIB, CCH and DEC generally were greater in winter relative to summer, suggesting increased net primary production (figs. 3–6).

It is useful to examine the variability of the HF measurements in individual months to assess the extent to which historical monthly grab samples may have yielded uncertain estimates of mean values. Given that most monitoring assessments attempt to identify trends in concentration over time, we examined the total variation in measured concentration in comparison to the monthly mean (figs. 7 and 8)—that is, as the standard deviation in the HF measurement values as a fraction of the mean (that is, coefficient of variation). This analysis indicated that HF measurements for nitrate are particularly susceptible to variation at locations where concentrations tend to be low, as the deviation from the mean is comparatively large, such as at FPT and WGA stations. At these stations, monthly grab samples are more likely to deliver inaccurate results. At stations with higher mean monthly nitrate concentrations, the deviation about the mean tended to be lower, and thus monthly grab sample concentrations were more likely to be accurate and trends could more easily be detected.

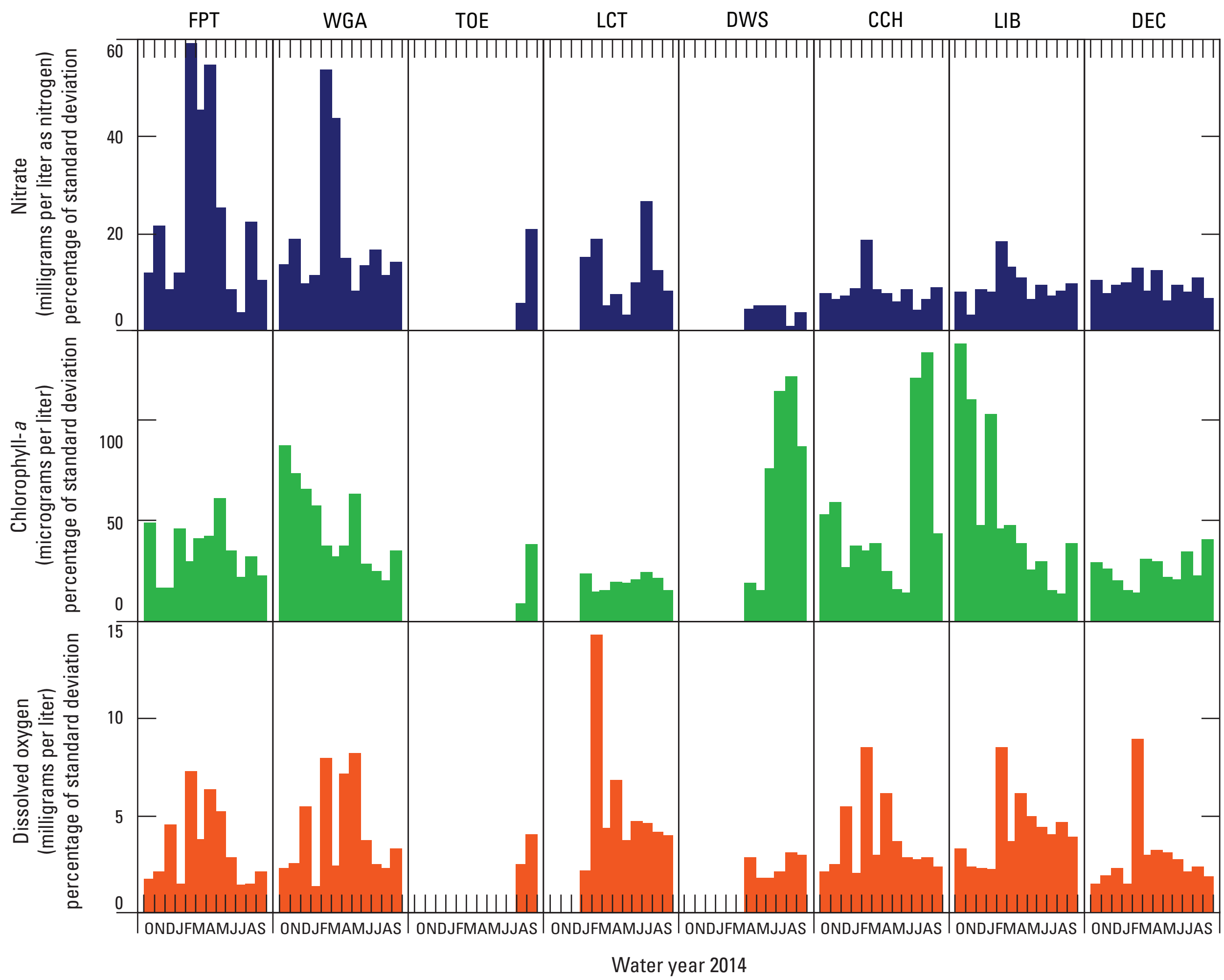


Figure 7. Percentage of standard deviation (coefficient of variation) for monthly mean concentrations of nitrate, chlorophyll-*a*, and dissolved oxygen at eight high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2014. Stations: Freeport (FPT); Walnut Grove (WGA); Toe Drain (TOE); Liberty Cut (LCT); Sacramento Deep Water Shipping Channel (DWS), Cache Slough (CCH); Liberty Island (LIB); and Decker Island (DEC). See table 1 for station information and figure 2 for station locations.

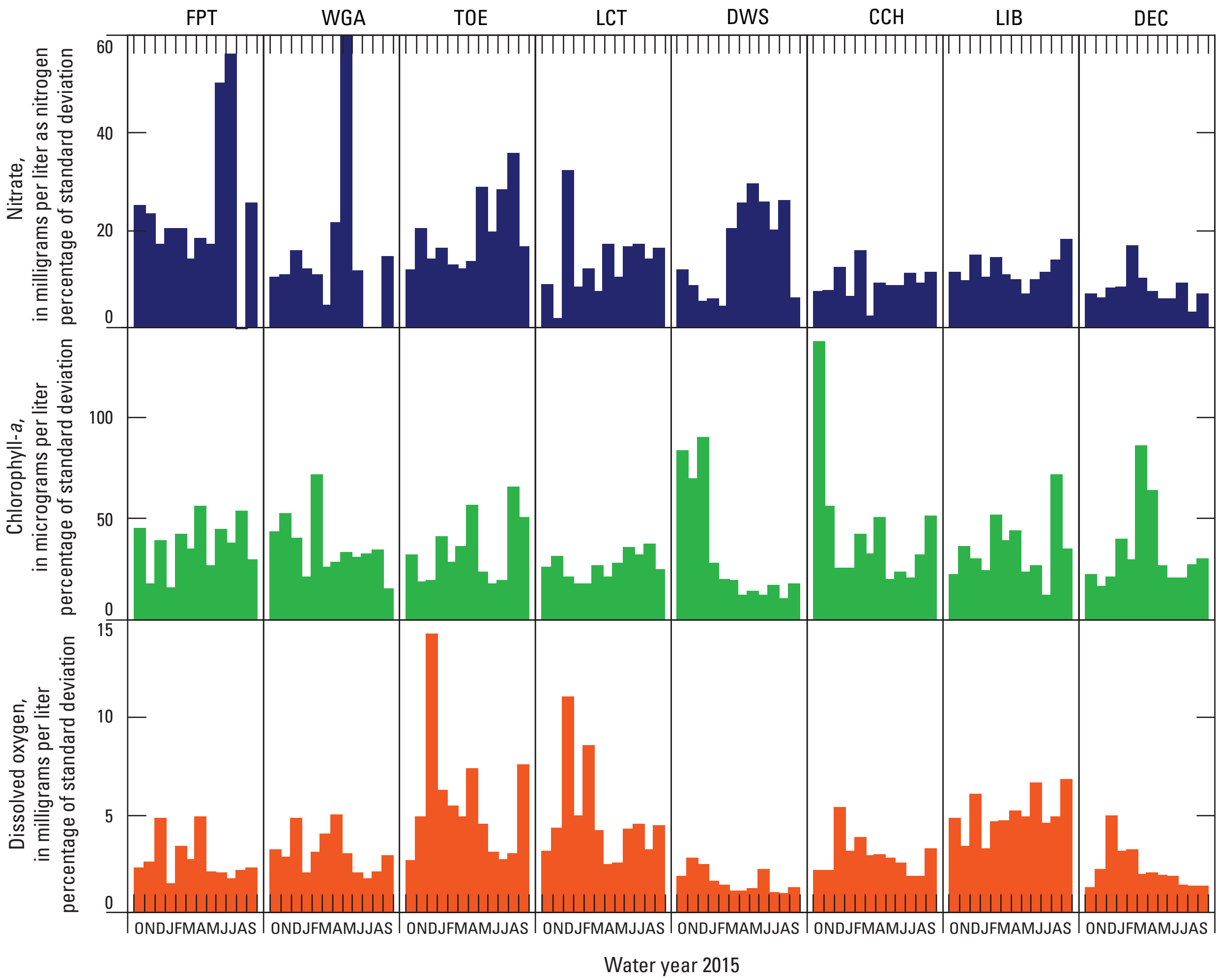


Figure 8. Percentage of standard deviation (coefficient of variation) for monthly mean concentrations of nitrate, chlorophyll-*a*, and dissolved oxygen at eight high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2015. Stations: Freeport (FPT); Walnut Grove (WGA); Toe Drain (TOE); Liberty Cut (LCT); Sacramento Deep Water Shipping Channel (DWS), Cache Slough (CCH); Liberty Island (LIB); and Decker Island (DEC). See table 1 for station information and figure 2 for station locations.

Seasonal, Inter-Annual, and Spatial Variability in High-Frequency Time Series

Substantial abrupt changes in response to external drivers are another reason for the inadequacy of monthly grab samples to accurately represent monthly means and trends. Examination of the HF time series for nitrate shows the high level of variability in the riverine and estuarine environments monitored. The individual HF time series (figs. 9–12) show how highly resolved time series are critical to accurately quantifying the rate and magnitude of changes in nitrate concentration due to storms and other drivers of rapid change. For example, nitrate concentration rapidly shifted during winter and spring precipitation events at all stations in WYs 2014 and 2015; peak concentrations in the continuous nitrate data are not evident in the monthly aggregated data (figs. 3–6) and were not captured in the grab sample-based monitoring. For example, a peak NO_3 concentration of 1.12 mg/L as N captured by continuous monitoring on February 14, 2014, at FPT station was substantially higher than the grab samples collected at FPT station on February 6, 2014 (NO_3= 0.09 mg/L as N), and March 14, 2014 (NO_3= 0.28 mg/L as N). Identification of the peak concentration is important for resolving sources, assessing effects, managing water quality, and meeting targets or regulations.

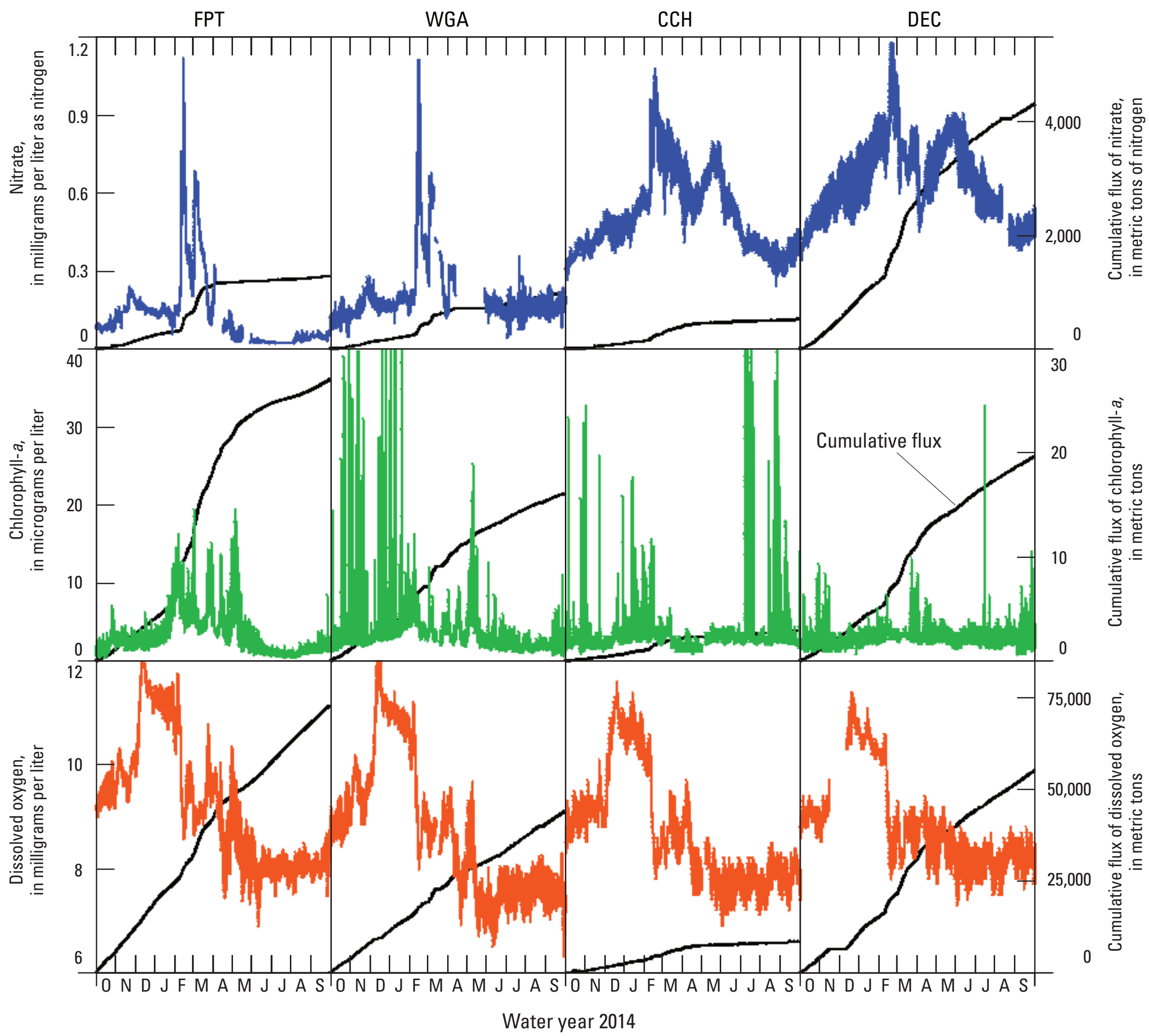


Figure 9. Cumulative fluxes and associated concentration data for nitrate, chlorophyll-*a*, and dissolved oxygen calculated for water year 2014 at Freeport (FPT), Walnut Grove (WGA), Cache Slough (CCH), and Decker Island (DEC) high-frequency, water-quality monitoring stations, when data available, Sacramento–San Joaquin Delta, northern California. See table 1 for station information and figure 2 for station locations.

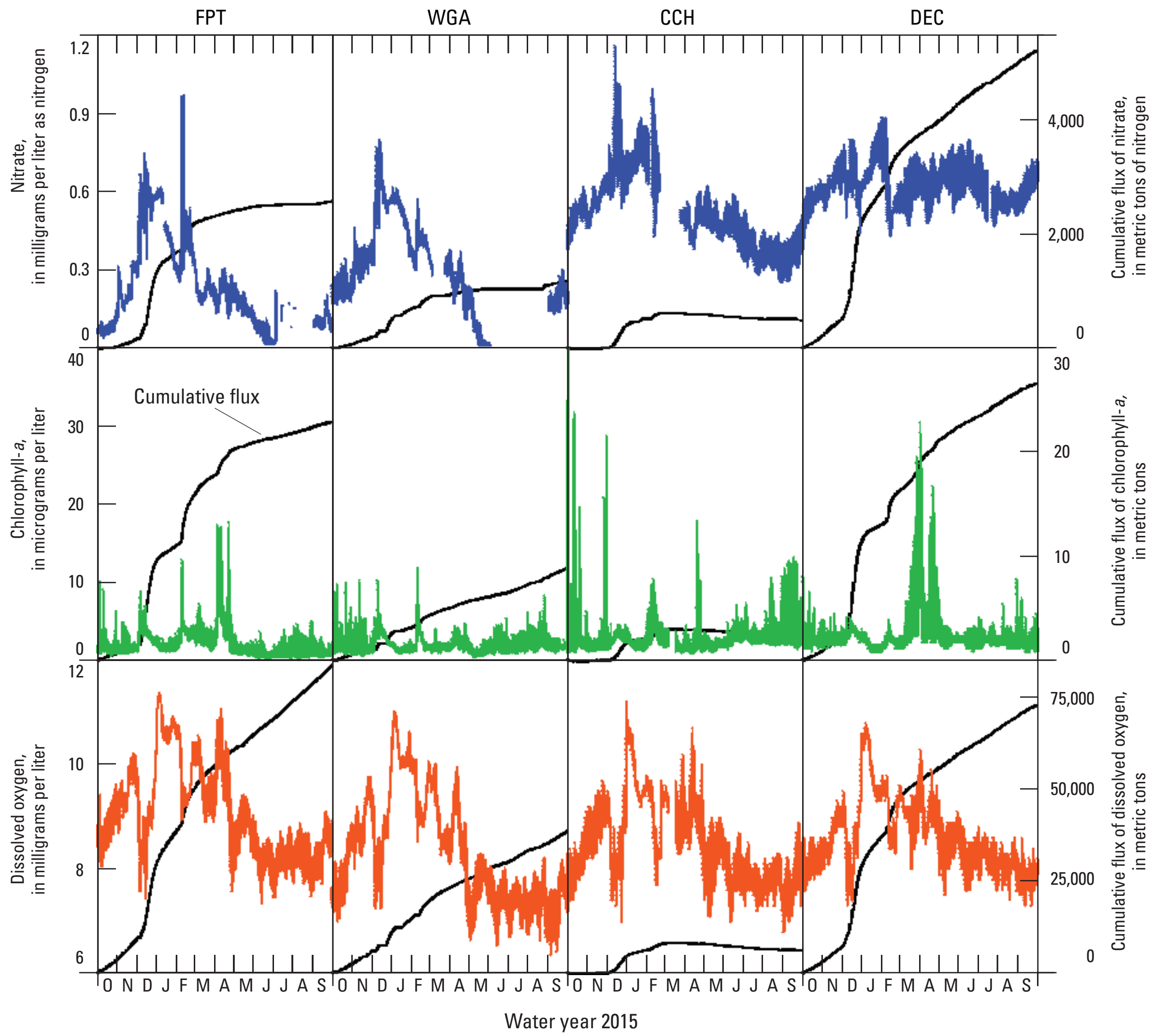


Figure 10. Cumulative fluxes and associated concentrations of nitrate, chlorophyll-*a*, and dissolved oxygen calculated for water year 2015 at Freeport (FPT), Walnut Grove (WGA), Cache Slough (CCH), and Decker Island (DEC) high-frequency, water-quality monitoring stations, when data available, Sacramento–San Joaquin Delta, northern California. See table 1 for station information and figure 2 for station locations.

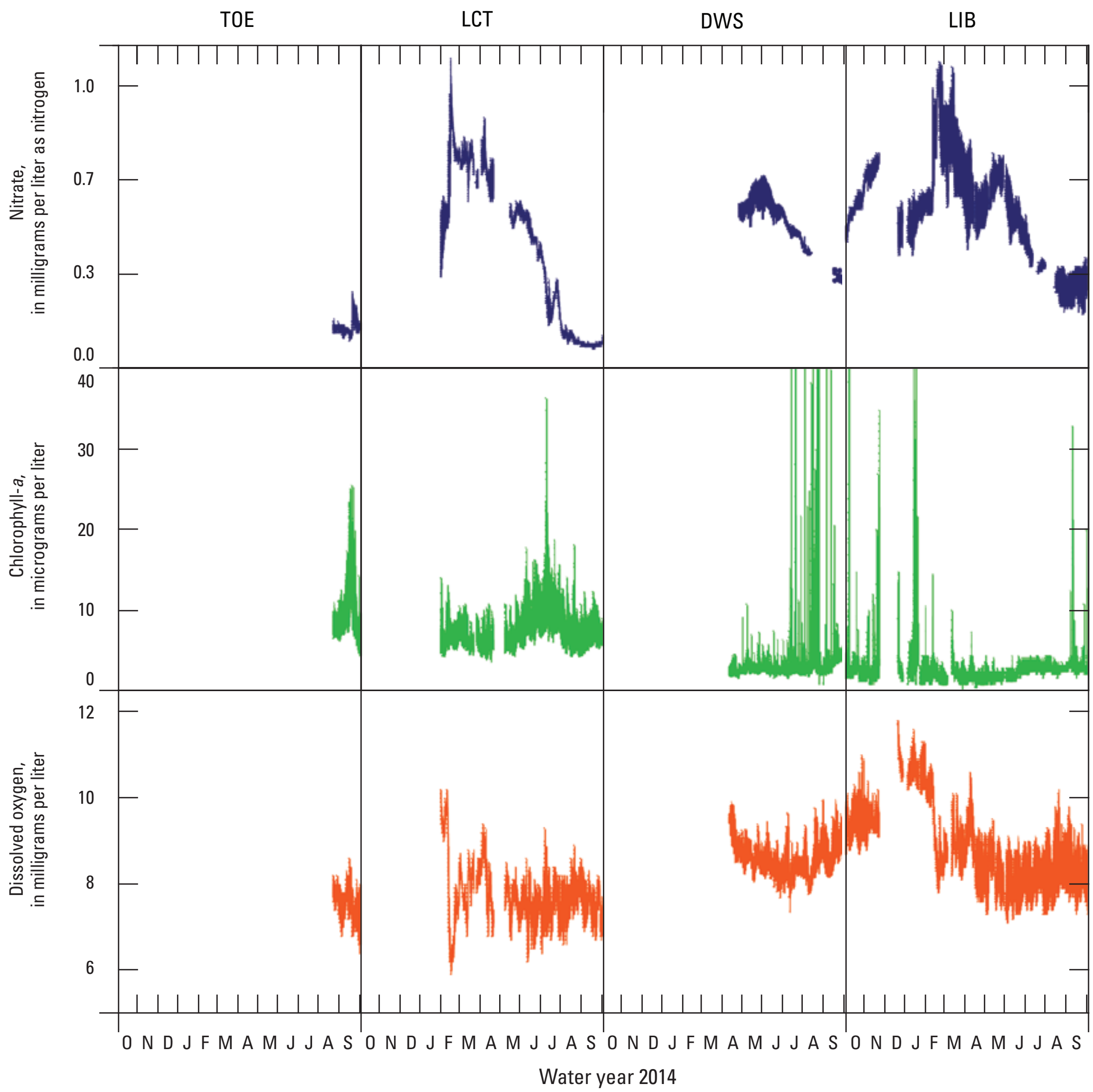


Figure 11. Concentrations of nitrate, chlorophyll-*a*, and dissolved oxygen measured at Toe Drain (TOE), Liberty Cut (LCT), Sacramento River Deep Water Shipping Channel (DWS), and Liberty Island (LIB) high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2014. See table 1 for station information and figure 2 for station locations.

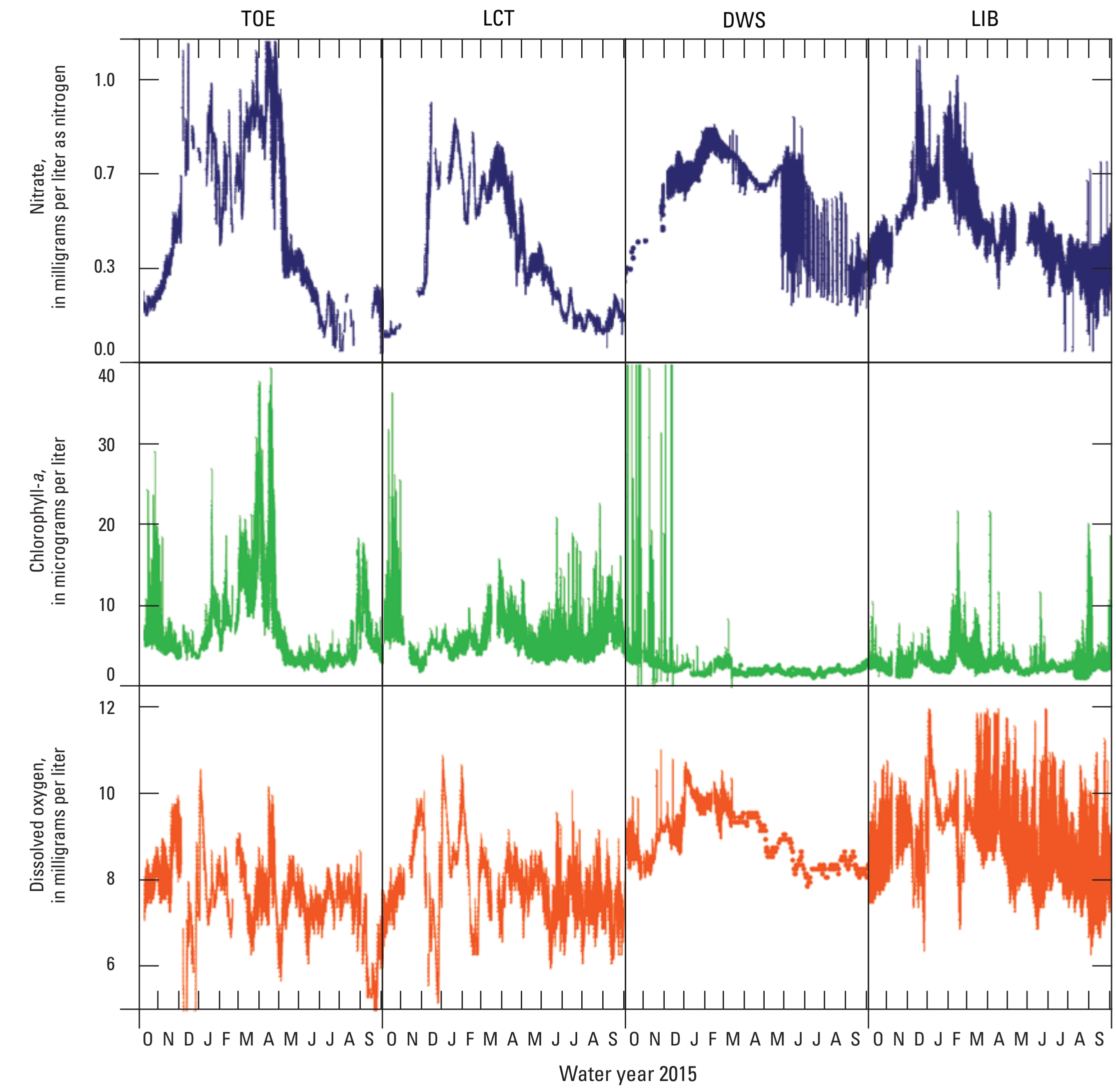


Figure 12. Concentrations of nitrate, chlorophyll-*a*, and dissolved oxygen measured at Toe Drain (TOE), Liberty Cut (LCT), Sacramento River Deep Water Shipping Channel (DWS), and Liberty Island (LIB), high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California, water year 2015. See table 1 for station information and figure 2 for station locations.

The response in nitrate concentration to storm activity is distinctly different between stations. For example, nitrate concentration at stations FPT and WGA show very steep changes in response to storms, while farther downstream at stations LIB and CCH, the response is attenuated because of tidal mixing. These differences highlight the benefits of having a network of stations. Furthermore, inspection of HF data over a single day, or over spring-neap tidal scales (about 14 days) indicates substantial periodic variability related to diurnal tides (for example, single high and single low tide per tidal day); semidiurnal tides (for example, two high and two low tides per tidal day); and diel (solar radiation 24-hour period) cycling. The effects of tides are different between stations; for example, stations DEC and CCH show high tidal variability in nitrate, whereas FPT shows comparatively low tidal variability in nitrate.

Annual Loads

To determine annual loads for nitrate-nitrogen, chlorophyll-*a*, and DO concentrations, we summed the product of the instantaneous discharge (*Q*) and concentration (that is, flux data, measured every 15 minutes) continuously over a water year (Downing and others, 2009). Note that the cumulative flux is the continuous expression of the integrated flux over time as the year progresses, whereas the annual load is the value of the cumulative flux at the end of the year. The trend in the cumulative flux of nitrate-nitrogen can be positive, indicating that net export of the constituent is seaward, or negative, indicating that net movement of the constituent is landward. For WYs 2014 and 2015, annual nitrate-nitrogen loads calculated for all eight stations ranged from about 500 to 5,000 metric tons (t) (figs. 9 and 10).

Step increases in the cumulative flux are related to precipitation events and account for about 30–40 percent of the measured annual load. Annual loads were highest at station DEC compared to the other seven stations, especially considering the relatively low annual load at station CCH (which is about 1 tidal excursion upstream of DEC) in both water years; this will require further investigation. Because nitrification of ammonium cannot reasonably account for this increase, there may be unaccounted for inputs of nitrate from the San Joaquin River and (or) Central Delta through Threemile Slough or the confluence that serves as subsidy to the larger fluxes seen at Decker Island.

Annual loads of chlorophyll-*a* ranged from about 3 to 25 t; loads were highest at station FPT and lowest at station CCH in WYs 2014 and 2015 (figs. 9 and 10). Chlorophyll-*a* concentrations have decreased during transport down the Sacramento River for years; this is an on-going subject of the current investigation (for example, Foe and others, 2010; Kraus, Carpenter, and others, 2017). The annual chlorophyll-*a* load at station DEC also was high and, like nitrate-nitrogen, may be the result of unaccounted for inputs from Threemile Slough or the confluence. Annual loads of DO ranged from about 8 to 80 t; loads were highest at station FPT and lowest at station CCH in WYs 2014 and 2015.

Advective and Dispersive Fluxes

One benefit of HF time series data is that it is possible to examine the difference between the advective flux—the constituent flux driven by movement of water in one direction, such as in a river—and the dispersive flux—the flux driven by mixing of water with different constituent concentrations. Advective fluxes typically are seaward, driven by river discharge, but they also can be landward, driven by water withdrawals. Landward advective discharge and fluxes are common in the summer and fall in Cache Slough (CCH) and the Toe Drain (TOE), when water withdrawals are high and runoff and precipitation are low. Traditional methods for calculating constituent fluxes typically use a monthly or flow-weighted median concentration value, which only accounts for the advective flux.

Dispersive flux is always in the direction of higher to lower concentration, which at stations such as DEC, LIB, and CCH is highly variable; at times, the water flowing landward during flood tides has the higher concentration and, at times, the water flowing seaward during ebb tides has the higher concentration. Thus, the dispersive flux direction can be variable and can change rapidly as conditions change. The magnitude of the dispersive flux is directly related to the difference in concentration. The dispersive part of the flux is most often a relatively small component of the total flux, but in estuaries, it can be quite large, sometimes forming the dominant part of the flux, as it does in tidal wetlands (Downing and others, 2009).

Separating the advective flux from the total flux past the Cache Slough (CCH) station indicates that the advective flux of nitrate is only about 70 percent of the total nitrate flux, meaning that traditional methods would underestimate the total by about 30 percent (fig. 13). This separation also shows how this station mediates nutrient transport from the Sacramento River to the Cache Slough area. Without continuous HF measurements, accurate calculation of the flux could not have been accomplished.

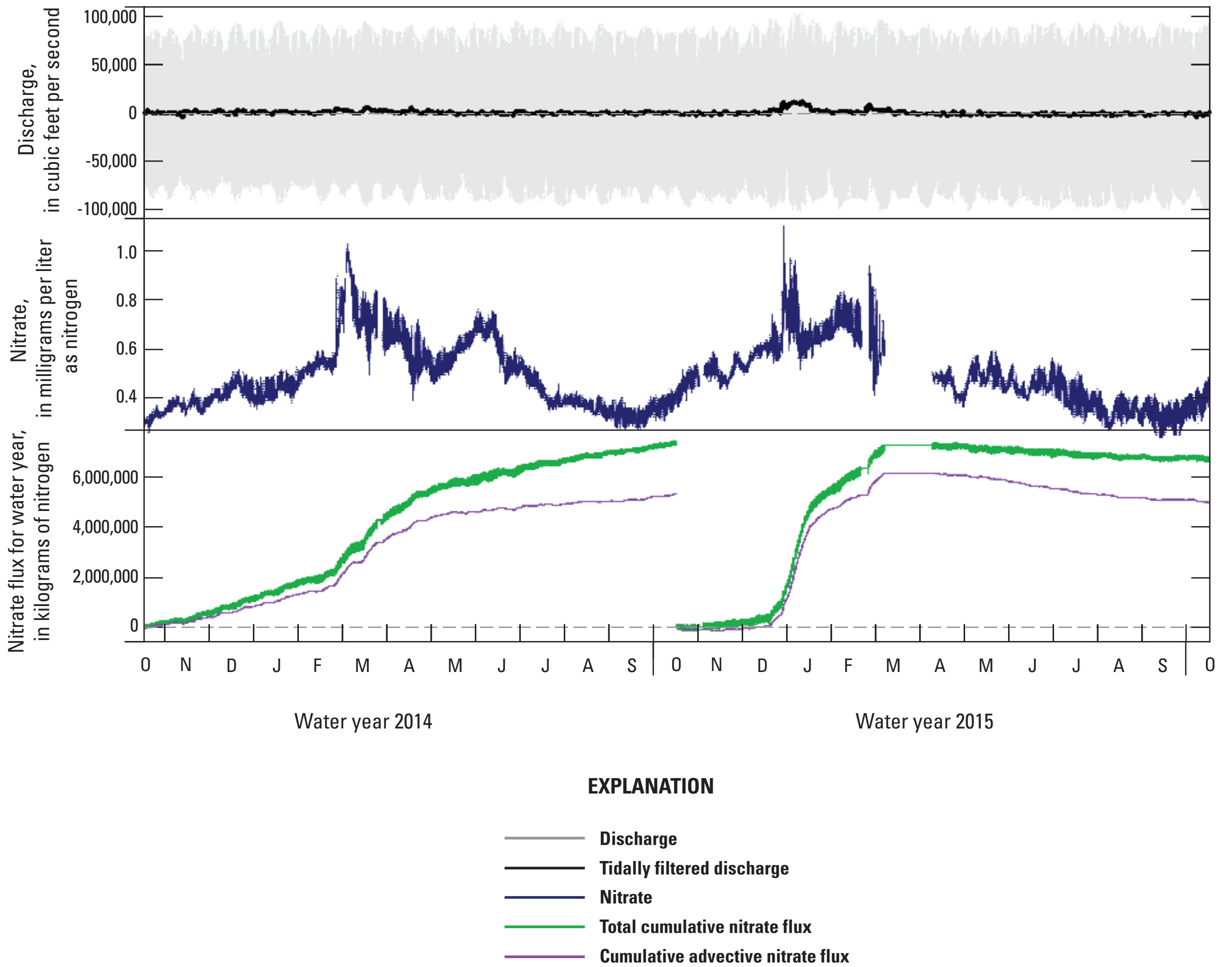


Figure 13. Time series from top to bottom of measured discharge, tidally filtered discharge, nitrate concentration, and calculated total cumulative and cumulative advective fluxes at Cache Slough (CCH) high-frequency, water-quality monitoring station, Sacramento–San Joaquin Delta, northern California, water years 2014 and 2015. See table 1 for station information and figure 2 for station location.

Time Series Analysis

As discussed above, HF monitoring is essential in tidal systems to address the multiscale variability of physical and chemical parameters. Time series analysis is a useful tool to identify the different periods of time over which cyclical variability is observed, and to relate these period scales to physical (for example, tides, both diurnal and lunar) and biological (for example, primary production, typically daily) drivers.

The goal of time series analysis, therefore, is to identify important periods of variation (frequencies) in the continuous monitoring data (time series data). This often is displayed as a periodogram, which diagrams the relative importance of the frequency values best explaining cyclic patterns in the time series data, reported here in days (d^{-1}). Because it is nearly impossible to collect perfectly continuous HF data without gaps (irregular data), we used the Lomb-Scargle approach (Lomb, 1976; Scargle, 1982), which uses a least-squares method to fill missing data.

High-frequency periodicities are discernible in the periodograms, representing quarter daily tides and high-frequency subharmonics of the tides (fig. 14; diel periods at 0.98–1.02 per day, daily tidal maximum/minimum at 0.91–0.97 per day, and semi-daily tides [twice daily tides] at 1.90–1.99 per day). Low frequency periodicities (days or months) may be related to meteorological conditions over the measurement period (<1.0 per day).

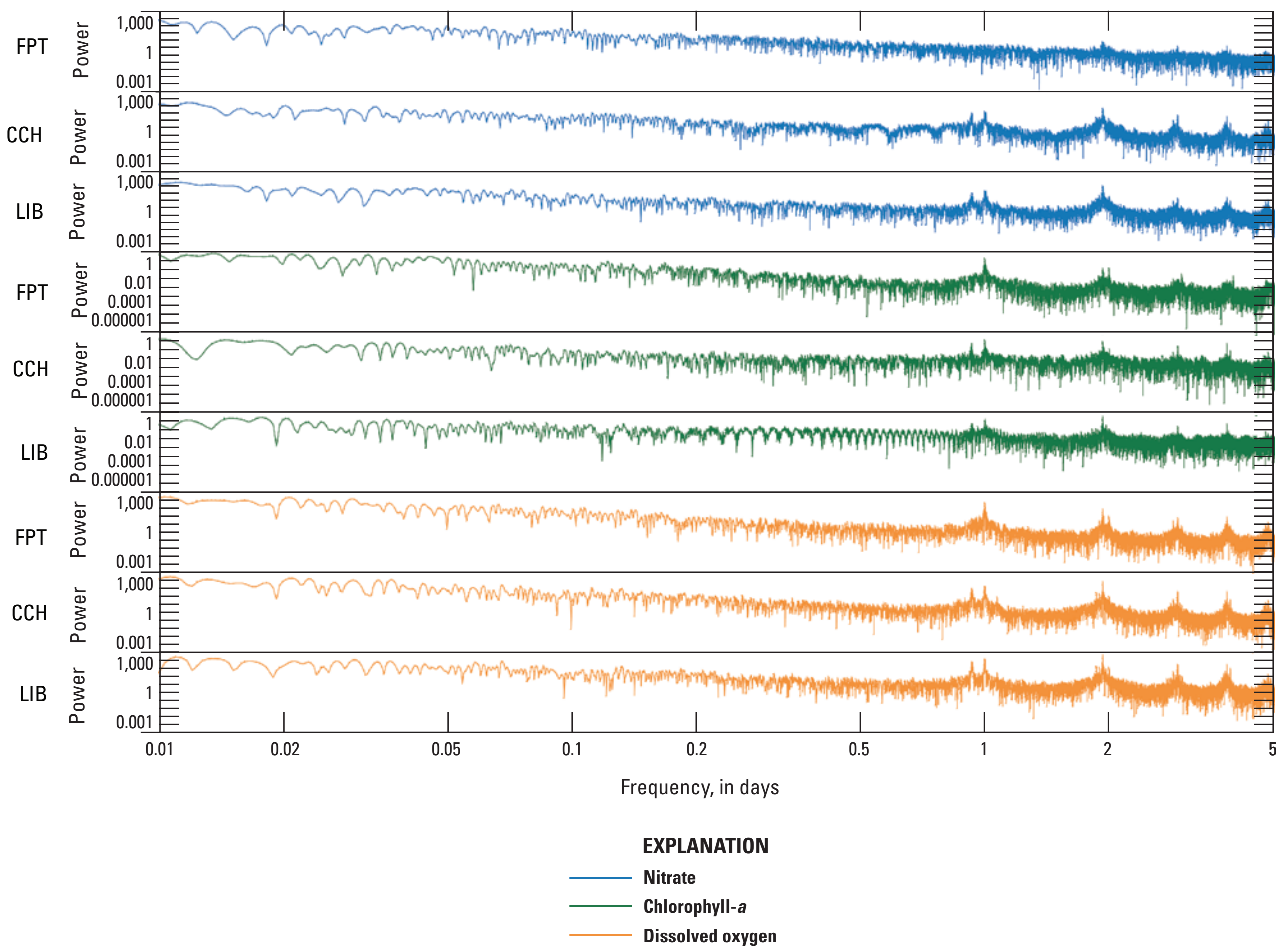


Figure 14. Log-log plots of periodograms for nitrate, chlorophyll-*a*, and dissolved oxygen at Freeport (FPT), Cache Slough (CCH), and Liberty Island (LIB) high-frequency, water-quality monitoring stations, Sacramento–San Joaquin Delta, northern California. Periodograms show the periodicities (x-axis) and spectral power density (y-axis) associated with diel periods (0.98–1.02 per day), daily tidal maximum/minimum (0.91–0.97 per day), and semi-daily tides (twice daily tides; 1.90–1.99 per day). See table 1 for station information and figure 2 for station locations.

We computed and compared periodograms for three different stations from the monitoring network (FPT, CCH, and LIB) using the full time series over WYs 2014 and 2015. Periodograms of nitrate, chlorophyll-*a*, and DO time series data are shown in log-log plots (fig. 14). The periodograms show a range of high frequency (that is, >1.0 per day, indicating subtidal harmonics and noise) to low frequency (for example, <1.0 per day, indicating patterns across days to months) representing large aperiodic variability in the data, possibly due to wind and other meteorological conditions. Low-frequency periodicities beyond 1 day such as spring-neap periods (about 14 days or a periodicity of about 0.7 per day) were not observed in the periodograms. Diel and tidal periodicities (diel = 24 hours, daily = 24.83 hours, semi-daily = 12.5 hours) were observed at all three stations. The influence of tides on nitrate, chlorophyll-*a*, and DO is highest at stations LIB and CCH, as evidenced by the higher power for values between 1 and 2 . Power densities for nitrate, are about 100 times higher at station CCH compared to station LIB at daily and semi-daily timescales, indicating the greater influence of tides in shaping concentration at station CCH.

The differences in these signals and their relative power spectra identify the station location relative to fluctuations in flow, length of tidal excursion, and position of the tidal prism. For example, the absence of diel and daily tidal periodicities of nitrate at station FPT indicates that neither uptake by primary producers nor tides are controlling nitrate concentration at this station. Diel, daily, and semi-daily tidal power densities of chlorophyll-*a* at stations FPT, LIB, and CCH are all nearly equal at all three stations, with the exception of a missing daily tidal signal at station FPT (fig. 14), indicating that daily cycles in productivity (likely driven by temperature, light and [or] wind) are as strong as the tides in terms of controlling nitrate concentrations and primary production. Tidal signals at stations LIB and CCH point to active phytoplankton productivity in those locations, as supported by simultaneous tidal periodicities of DO at stations LIB and CCH. Dominance of the diel periodicity and absence of daily tidal periodicities for DO and chlorophyll-*a* at station FPT indicate that productivity occurs upstream and is primarily advected downstream.

Summary

The purpose of this report is primarily to make readers aware of the data available in real time from the U.S. Geological Survey high-frequency (HF) nutrient and water-quality monitoring station network, and the use of that data for active management and assessment of trends in, for example, nitrate concentrations in the northern Sacramento–San Joaquin Delta of northern California. We also showed how nutrient data may be related to other biogeochemical parameters to assess the persistence and effects of nutrients on aquatic ecosystems. We noted numerous timescales of variability and their importance and effects, as well as calculated and compared cumulative fluxes and annual loads at different points in the San Francisco Estuary. In doing so, we demonstrated how and why HF data are necessary for accurate determination of fluxes and loads, particularly when assessing the difference between the river-like advective flux and the tidally driven dispersive flux. Finally, we showed how time series of HF data can be used to understand how nutrient fate and effects are related to the periodic cycles occurring within the Delta. Future, more rigorous analysis of these data, including their use to build and validate a hydrodynamic-biogeochemical model, is needed to fully realize the value of these data. However, the data presently are useful for environmental monitoring, to inform special studies, as infill between grab samples, and to identify monitoring gaps.

Acknowledgments

The authors gratefully acknowledge the Bureau of Reclamation, which for years has supported our efforts to build, maintain, and improve a nutrient biogeochemical monitoring network in the northern Sacramento–San Joaquin Delta. Without their support, this report would not be possible. We would like to thank the Delta Regional Monitoring Program (RMP) and the San Francisco Estuary Institute for supporting preparation of this report series. Furthermore, we would like to express our appreciation to Scott Nagel, Katy O’Donnell, Thomas Johnston, Kyle Nakasutka, Ayelet Delascagigas, Angela Hansen, Elizabeth Stumpner, and Brian Pellerin at the U.S. Geological Survey, without whom we would not have completed this report. Finally, we would like to thank Phil Trowbridge, Thomas Jabusch, Meg Sedlak, Joe Domagalski, Stephen McCord, Anke Muller-Solger, and members of the Delta RMP Nutrient Technical Advisory Committee, whose feedback and comments have improved the quality of this report.

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Appendix A. Temperature, Specific Conductance, Turbidity, and pH Measured at Eight High-Frequency, Water-Quality Monitoring Stations, Sacramento–San Joaquin Delta, Northern California, Water Years 2014–15

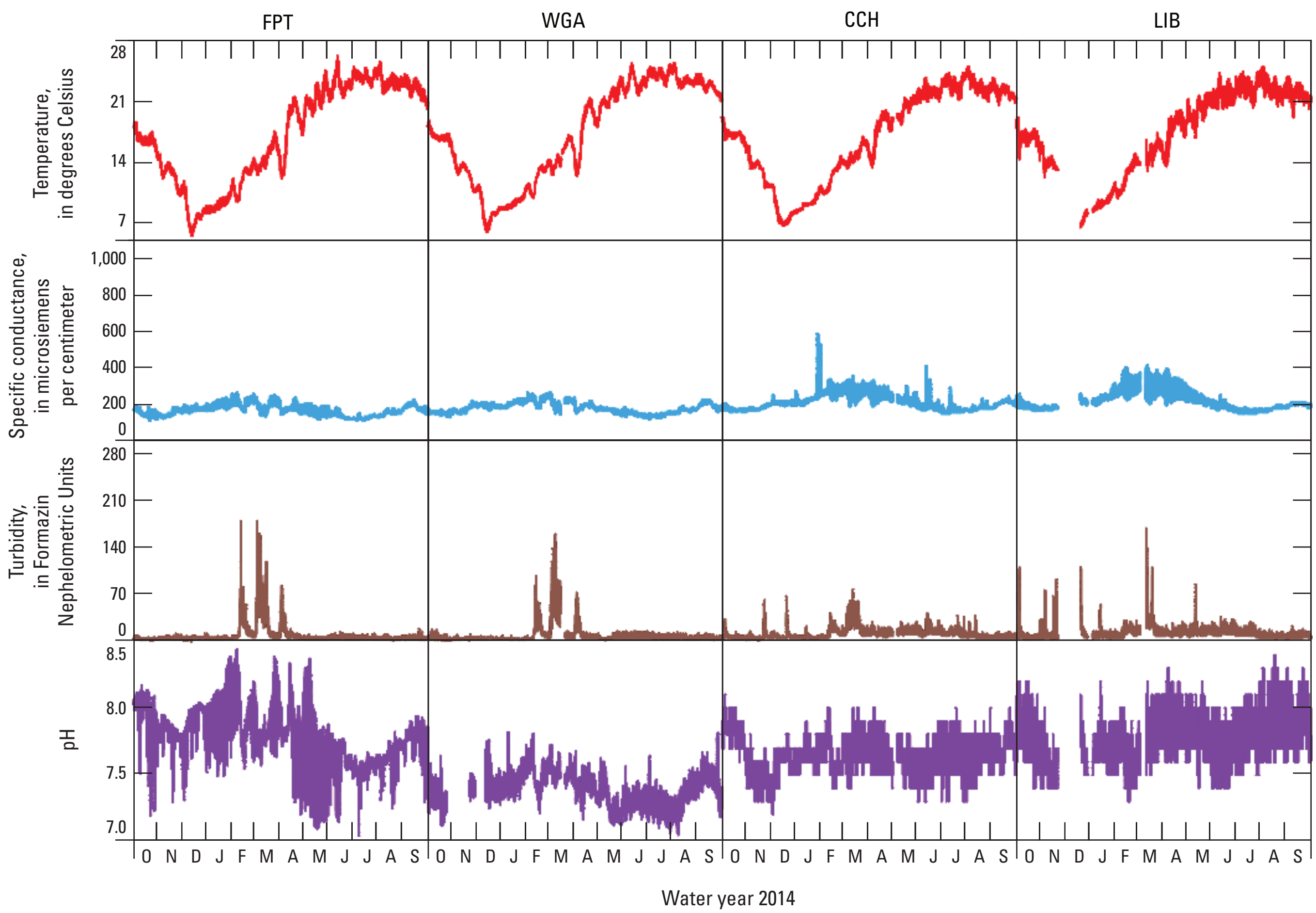

Figure A1A. Temperature, specific conductance, turbidity and pH data measured at Freeport Bridge (FPT), Walnut Grove (WGA), Cache Slough (CCH), and Liberty Island (LIB) high-frequency, water-quality monitoring stations, when data available, Sacramento–San Joaquin Delta, northern California, water year 2014. See table 1 for station information and figure 2 for station locations. Data are available at https://waterdata.usgs.gov/nwis.

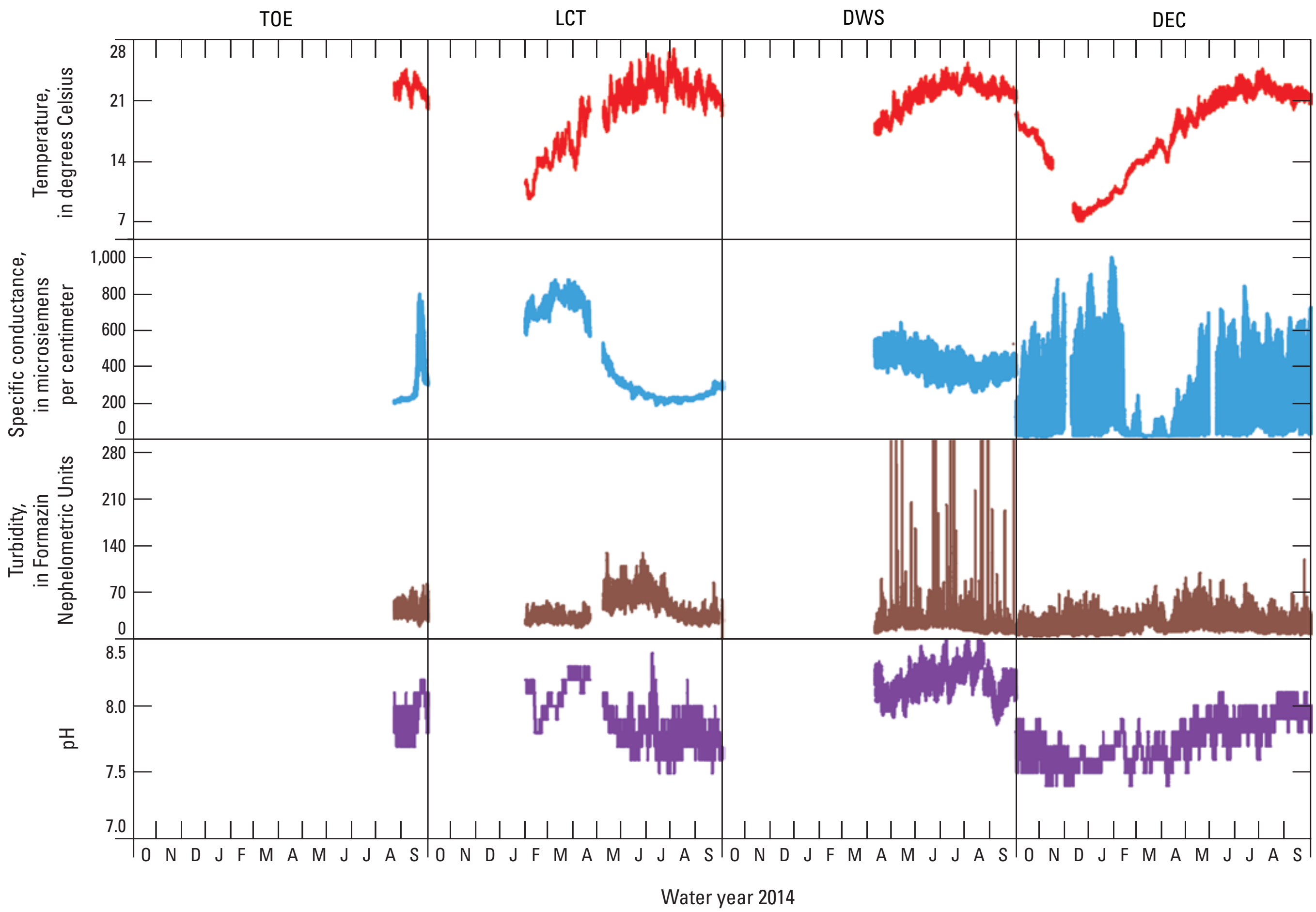

Figure A1B. Temperature, specific conductance, turbidity and pH data measured at Toe Drain (TOE), Liberty Cut (LCT), Sacramento Deep Water Shipping Channel (DWS), and Decker Island (DEC) high-frequency, water-quality monitoring stations, when data available, Sacramento–San Joaquin Delta, northern California, water year 2014. See table 1 for station information and figure 2 for station locations. Data are available at https://waterdata.usgs.gov/nwis.

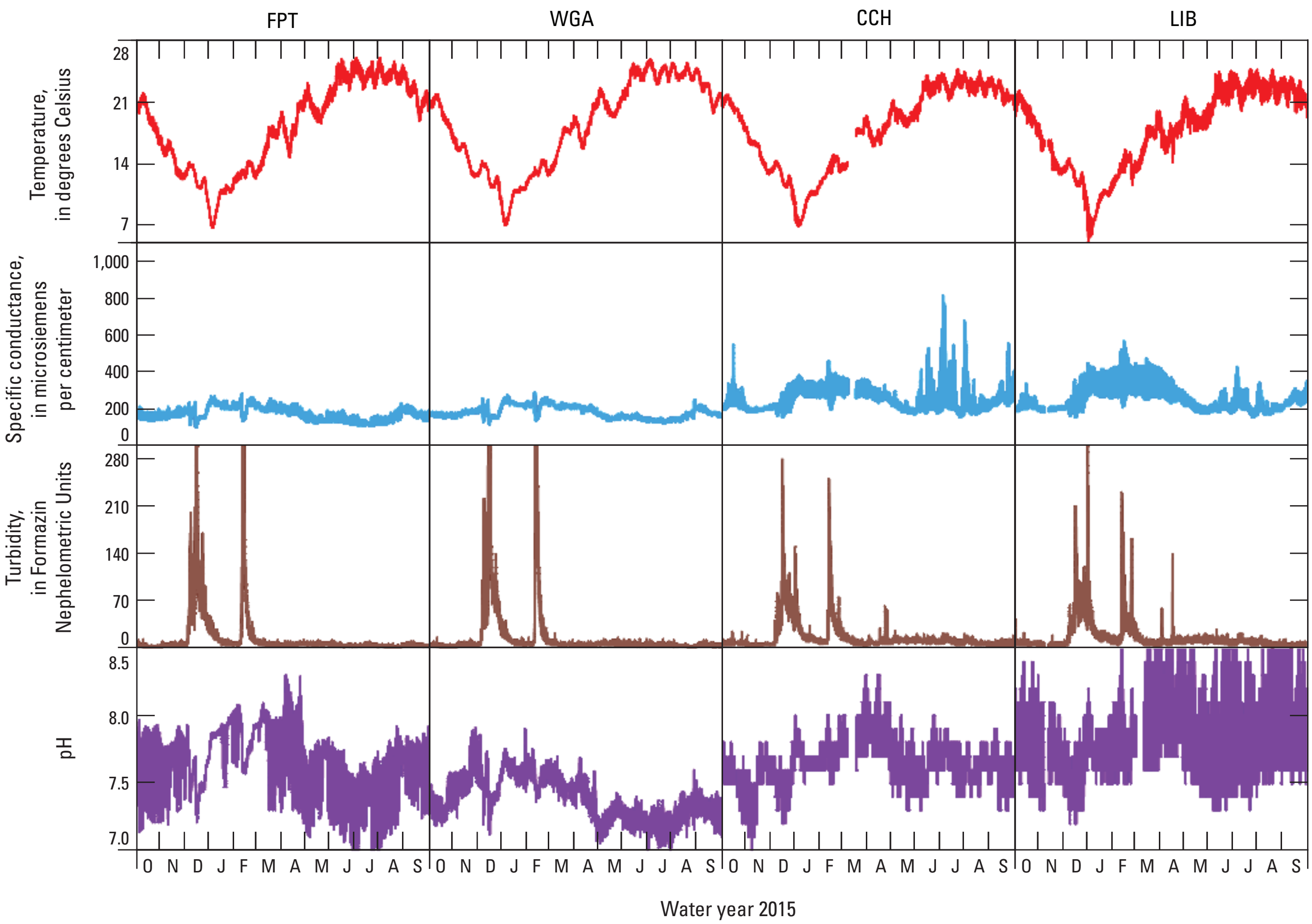

Figure A2A. Temperature, specific conductance, turbidity, and pH data measured at Freeport Bridge (FPT), Walnut Grove (WGA), Cache Slough (CCH), and Liberty Island (LIB) high-frequency, water-quality monitoring stations, when data available, Sacramento–San Joaquin Delta, northern California, water year 2015. See table 1 for station information and figure 2 for station locations. Data are available at https://waterdata.usgs.gov/nwis.

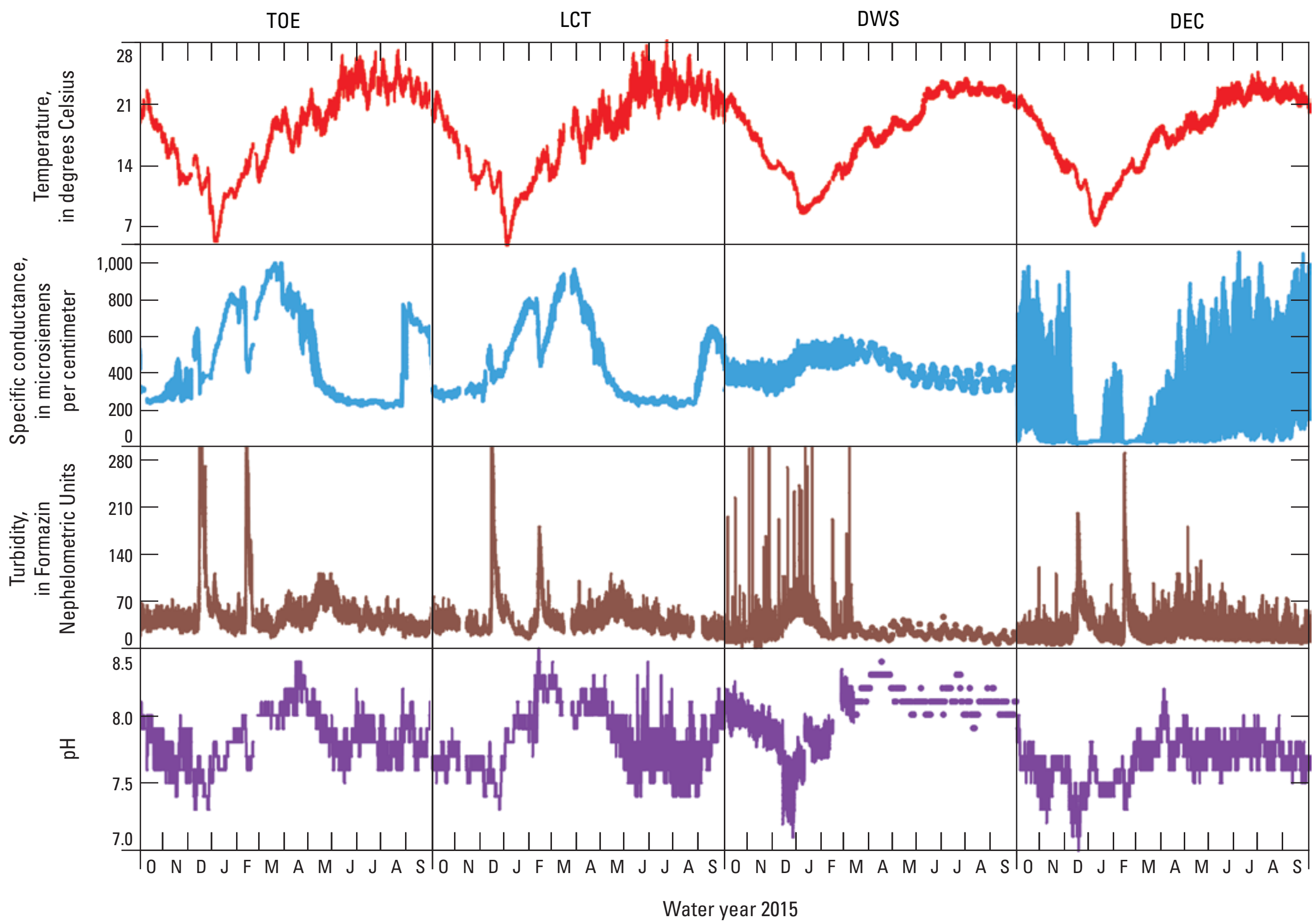

Figure A2B. Graphs showing tTemperature, specific conductance, turbidity, and pH data measured at the Toe Drain (TOE), Liberty Cut (LCT), Sacramento Deep Water Shipping Channel (DWS), and Decker Island (DEC) high- frequency, water-quality monitoring stations, when data available, Sacramento–San Joaquin Delta, northern California, water year 2015. See table 1 for station information and figure 2 for station locations. Data are available at https://waterdata.usgs.gov/nwis.

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