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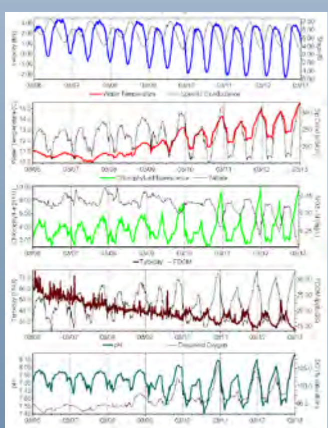
An Introduction to High-Frequency Nutrient and Biogeochemical Monitoring for the Sacramento–San Joaquin Delta, Northern California



Scientific Investigations Report 2017–5071

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

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.

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

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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

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
micrometer (µm)	3.93701×10^{-5}	inch (in.)
kilometer (km)	0.6214	mile (mi)
	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)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
	Mass	
milligram (mg)	3.5274×10^{-5}	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

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

$$°F = (1.8 \times °C) + 32.$$

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
liter (L)	0.2642	gallon (gal)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

Delta	Sacramento–San Joaquin Delta
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
DOC	dissolved organic carbon
HABs	harmful algal blooms
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

An Introduction to High-Frequency Nutrient and Biogeochemical Monitoring for the Sacramento–San Joaquin Delta, Northern California

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

Executive Summary

This report is the first 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). This first report provides an introduction to the reasons for and fundamental concepts behind collecting HF measurements, and describes the benefits associated with a real-time, continuous, HF, multi-parameter water quality monitoring station network that is co-located with flow stations. It then provides examples of how HF nutrient measurements have improved our understating of nutrient sources and cycling in aquatic systems worldwide, followed by specific examples from the Delta. These examples describe the ways in which HF instrumentation may be used for both fixed-station and spatial assessments. The overall intent of this document is to describe how HF measurements currently (2017) are being used in the Delta to examine the relationship between nutrient concentrations, nutrient cycling, and aquatic habitat conditions.

The second report in the series (Downing and others, 2017) summarizes information about HF nutrient and associated biogeochemical monitoring in the northern Delta. The report synthesizes data available from the nutrient and water quality monitoring network currently operated by the U.S. Geological Survey in this ecologically important region of the Delta. In the report, we 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 (for example, storms, reservoir releases, phytoplankton blooms) timescales. As expected, we determined that there is substantial variability in nitrate concentrations at short timescales within hours, but also significant variability at longer timescales such as months or years. This multi-scale, high variability affects calculation of fluxes and loads, indicating that HF monitoring is necessary for understanding and assessing flux-based processes and outcomes in tidal environments, such as the Delta.

The third report in the series (Bergamaschi and others, 2017) provides information about how to design HF nutrient and biogeochemical monitoring for assessment of nutrient inputs and dynamics in the Delta. The report provides background, principles, and considerations for designing an HF nutrient-monitoring network for the Sacramento–San Joaquin Delta to address high-priority, nutrient-management questions. The report starts with high-priority management questions to be addressed, continues with 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. For the three example networks, we assess how they would 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.

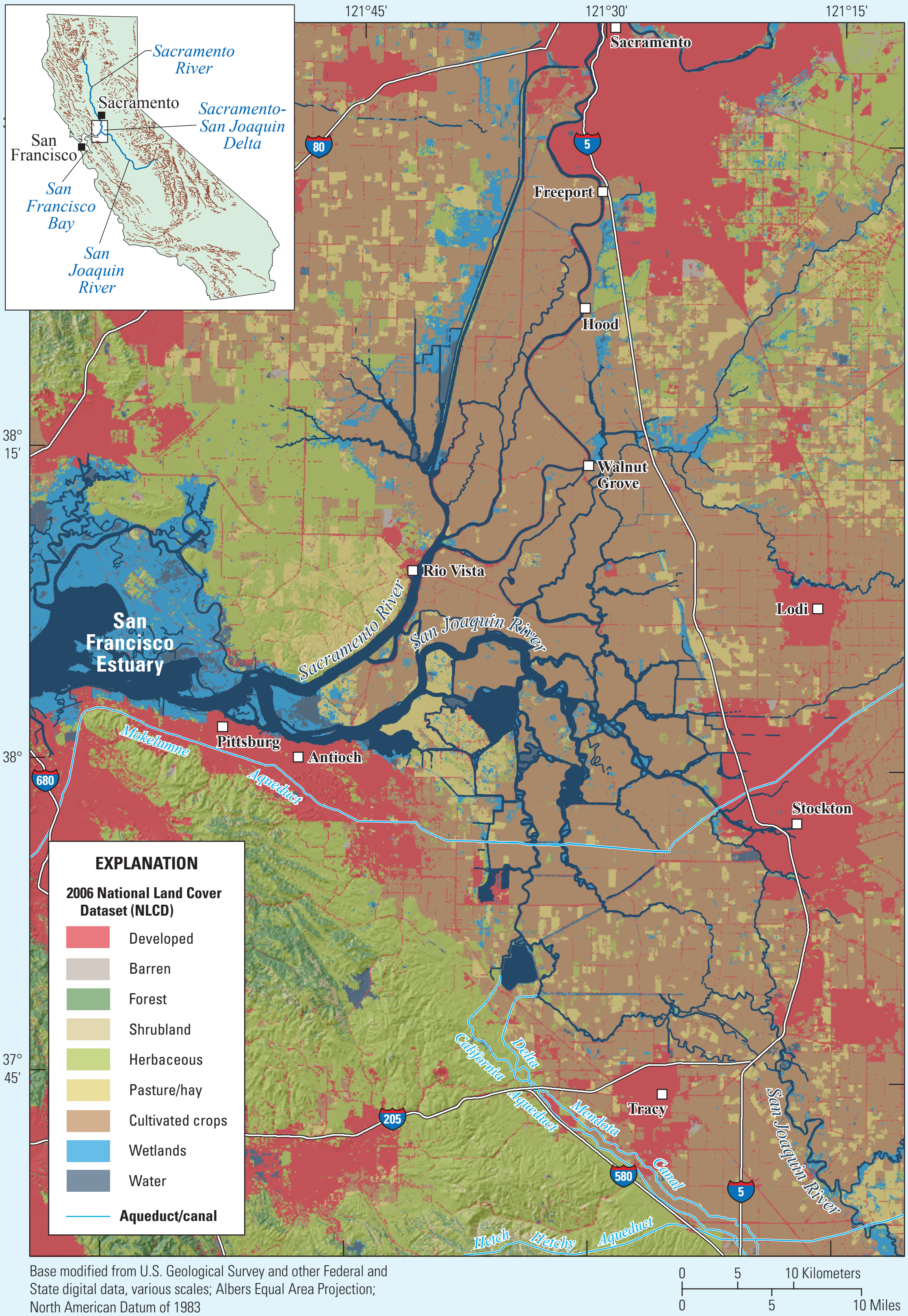

Figure 1. Sacramento–San Joaquin Delta, northern California.

Background

The nutrients nitrogen (N) and phosphorus (P) comprise essential constituents of all living organisms and, thus, are critical to aquatic and terrestrial ecosystems alike. However, worldwide, rivers and estuaries support large human populations and consequently receive elevated nutrient inputs from agriculture, wastewater treatment plants (WWTPs), and urban runoff. Excessive nutrient concentrations can have deleterious effects, including drinking water contamination and eutrophication—a process by which water bodies become enriched in organic matter largely due to overproduction of algae, often leading to hypoxia during the subsequent degradation of that organic matter (Cloern, 2001). In addition to supporting nuisance algal blooms, high nutrient concentrations can lead to harmful algal blooms (HABs), which can produce toxins that further contaminate drinking water and imperil wildlife, pets, and humans (Heisler and others, 2008; Erisman and others, 2013; Paerl and Otten, 2016). Additionally, some studies suggest that high concentrations of ammonium or an imbalance between nitrogen and phosphorus concentrations can inhibit phytoplankton growth and alter species composition (Dugdale and others, 2007; Van Nieuwenhuyse, 2007; Paerl and others, 2014; Lehman and others, 2015; Glibert and others, 2016), with consequent effects on the larger food web.

Increasing nutrient availability, including ammonium from WWTPs, may be linked to the spread of invasive aquatic weeds, which can have detrimental effects on native organisms and can interfere in commercial and recreational activities (Luoma and others, 2015; Dahm and others, 2016). There is some evidence that high concentrations of ammonium can exert chronic toxicity on zooplankton (Senn and Novick, 2014), and at particularly high concentrations, un-ionized ammonium (ammonia, NH_3) can have toxic effects on many aquatic organisms (Constable and others, 2003). For these and other reasons, accurate and timely information on nutrient concentrations, loads, and processing is integral to strategies designed to manage the underlying drivers of water quality impairment and minimize risk to aquatic organisms.

In many aquatic systems, increases in nutrient inputs often coincide with many other changes that have led to worldwide degradation of these systems (Lotze and others, 2006). These changes include, for example, the loss of riparian vegetation and connected wetlands that could mitigate negative effects of nutrient inputs through processes such as uptake, denitrification, and burial. Because of the many aquatic processes affected by nutrients (fig. 2), this combination of events has substantially altered and continues to shape aquatic environments, contributing to considerable economic and ecological loss (Richardson and Jørgensen, 1996). Despite major local, State, and Federal efforts to manage N and P inputs to aquatic systems (for example, phosphate detergent ban, improved agricultural practices, controls on industry, and WWTP upgrades), nutrient concentrations in many rivers across the Nation have remained elevated since the early 1990s (Dubrovsky and others, 2010). Recently, an estimated 14,000 water bodies nationwide were identified as affected by excess nutrients (Pellerin and others, 2016). Furthermore, 65 percent of the major estuaries in the Nation have moderate to high nutrient contamination (Bricker and others, 2008), and coastal eutrophication continues to increase (Cloern, 2001). A recent study by Sobota and others (2013) estimated the economic effects of nitrogen contamination on U.S. aquatic systems at $210 billion per year when considering both the human health and environmental impacts, with approximately 10 percent of the costs related to drinking water and approximately 40 percent related to effects on freshwater ecosystems.

There are also costs associated with developing and implementing nutrient-reduction plans to restore or maintain water quality. For example, in the Chesapeake Bay watershed, the cost of implementing best management practices (BMPs) to comply with total maximum daily loads is estimated at about $900 million per year for full implementation (Kaufman and others, 2014). Upgrades to wastewater and drinking water treatment plants to meet more stringent nutrient concentration limits can cost tens or hundreds of millions of dollars.

Water quality monitoring programs often are explicitly designed to understand current conditions and meet existing regulatory and management needs. For longer range planning, they also need to capture trends occurring over time and help managers predict how the system will respond to future changes—regardless of whether those changes are a result of natural events or human action. Because nutrient concentrations often vary over short temporal and spatial scales, there is increasing recognition that traditional monitoring approaches, such as grab sample collection—whereby discrete samples are collected manually from individual sites at weekly to monthly intervals followed by days to weeks until laboratory analyses are completed and data become available—may not provide adequate data resolution or timely information to identify specific sources, understand drivers, assess effects, and develop effective responses (Blaen and others, 2016; Pellerin and others, 2016; Rode and others, 2016). Recent technological advances have made new approaches increasingly feasible, accurate, cost-effective, and reliable for collecting in situ, high-frequency (HF) nutrient measurements that are available in real time. As the collection, interpretation, and publication of these HF data grow, appreciation of the value that these data provide also is growing. In view of these and other benefits of HF monitoring described in this report, the U.S. Geological Survey (USGS), with support from the Bureau of Reclamation as well as the Sacramento County Regional Sanitation District and the State and Federal Water Contractors, has implemented a program of measurements and monitoring in the Delta that currently (2017) has expanded to examine the relations among nutrient concentrations, nutrient cycling, and aquatic habitat conditions. This report, along with the other two reports of this

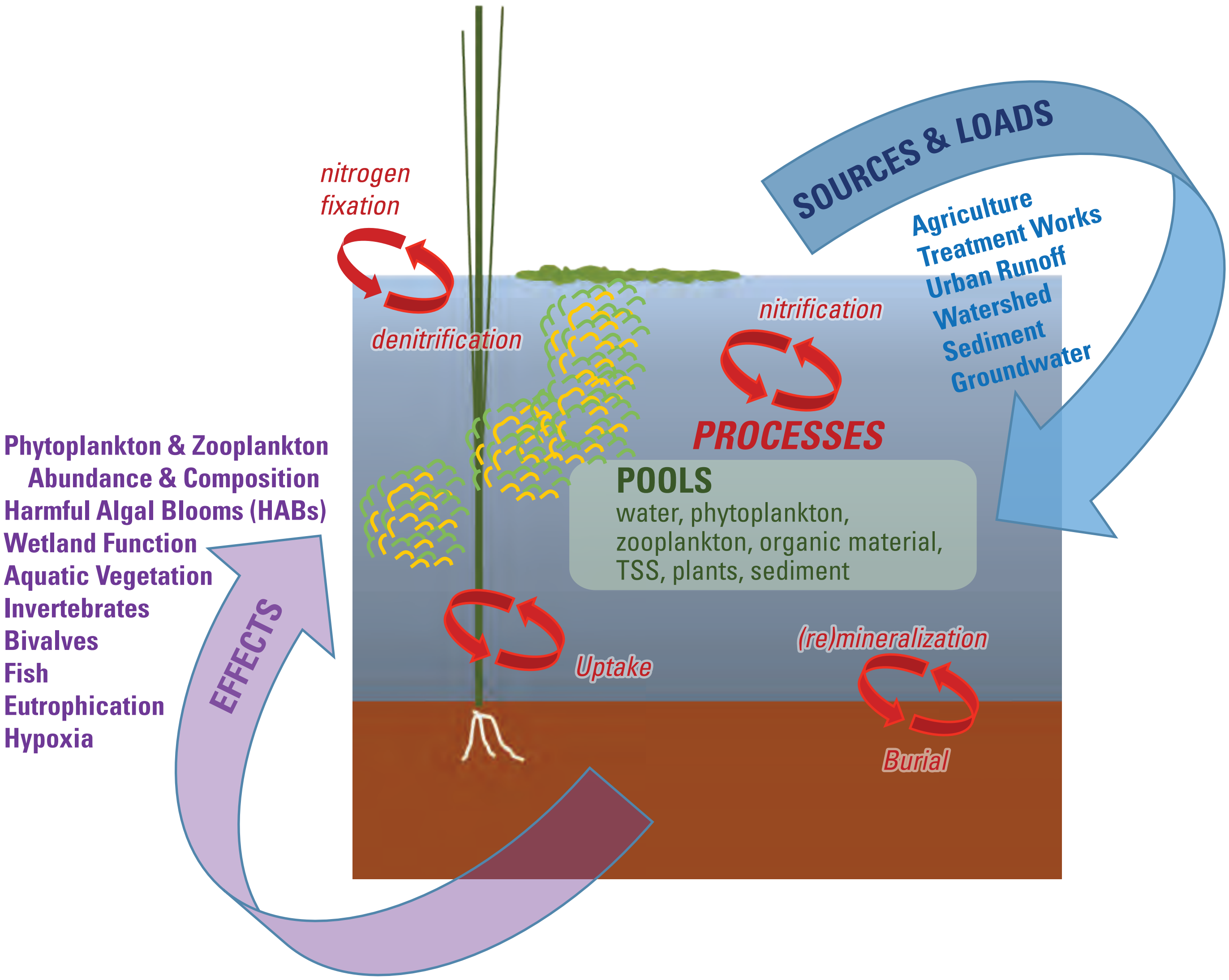

Figure 2. Nutrient sources, pools, processes, and effects.

series (Bergamaschi and others, 2017; Downing 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.

There have been numerous publications on the state of the Delta highlighting the competing demands on this freshwater resource and the need to understand drivers of ecosystem health, including the role of nutrients (for example, Sommer and others, 2007; Lund and others, 2010; Cloern and others, 2011, 2012; Luoma and others, 2015; Dahm and others, 2016). Many factors interact to shape the Delta environment, including tides, river inflows, exports, salinity gradients, nutrients, suspended sediments, temperature, contaminants, invasive species, harmful algal blooms, channel geometry, island drainage, and other factors affecting physical and biological processes. In terms of annual loads, Central Valley watersheds are the largest contributor of nutrients to the Delta (Domagalski and Saleh, 2015; Saleh and Domagalski, 2015; Schlegel and Domagalski, 2015). Urban inputs from publicly owned treatment works (POTWs, commonly referred to as WWTPs) also are a major source of nutrients. Moreover, WWTP inputs not only are important because of their contribution to total annual loads, but also because nutrients from WWTPs enter the system continuously; this is a key factor when compared to storm events and agricultural inputs that can be diffuse, episodic and often are associated with high-flow events that result in rapid nutrient transit through the system. The concentrations, forms, total loading, and timing of nutrients discharged from WWTPs are controlled by the quality of water entering the treatment plant in combination with its specific treatment processes. For example, some treatment plants release N primarily in the form of ammonium, whereas others employ nitrification and denitrification steps and thus release N primarily in the form of nitrate (NO_3).

Whereas nutrient loads from point sources like WWTPs may vary gradually over time, the extent to which these inputs are diluted when they enter the Delta and how fast and how far they are transported can vary greatly depending on river flows, particularly in tidally affected regions. For example, wastewater discharge from the Sacramento Regional WWTP can make up anywhere from 0 to 7 percent of Sacramento River flows, which can result in a greater than 10-fold difference in riverine N and P concentrations over a single tidal cycle (O’Donnell, 2014). Additionally, hydrologic conditions will determine where in the Delta the nutrients are transported and the residence time of those inputs. Water residence time is a master driver of biogeochemical processes, determining to what extent nutrients will be retained and recycled within aquatic systems (Downing and others, 2016). When Sacramento River flows are at 8,000 ft^3/s at Freeport, it takes an estimated 18 days for water to travel down the Sacramento River to Suisun Bay. In contrast, during winter storm periods, flows commonly are greater than 20,000 ft^3/s and water travels the same distance over a matter of a few days.

New Technologies that Permit High-Frequency Measurement of Nutrients and Related Parameters

The ability to make HF water quality measurements has expanded rapidly over the last few decades because of advancements in both sensor and data management technologies (Blaen and others, 2016; Pellerin and others, 2016; Rode and others, 2016). Although the commercial availability of HF sensors—particularly optical sensors—for nutrients is relatively recent, there is a wealth of information about the collection of HF data for other water quality parameters such as temperature, pH, specific conductance, dissolved oxygen (DO), turbidity, chlorophyll fluorescence, and others (for example, Johnson and others, 2007; Pellerin and others, 2016). The advantages offered by optical sensors over other in situ approaches (ion selective electrodes and wet chemical sensors) are many—rapid sampling rates, low detection limits, low power consumption, no chemicals, easy

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.

field servicing, and long-term deployment capability. To date, most focus has been on the development of HF nitrate sensors, given that nitrate is a concern for surface-water and groundwater quality, and because it is optically reactive and thus amenable to optical sensor technology (see reviews by Blaen and others, 2016; Pellerin and others, 2016; Rode and others, 2016). However, a sensor using wet chemistry followed by an optical measurement is now commercially available for phosphate, and a similar approach for ammonium is promising. There also have been improvements in the equipment needed to support HF monitoring stations such as telemetry, batteries, wipers to prevent fouling, housing materials and design, availability of commercially available standards, and others.

Worldwide, sensors that collect nutrient data in situ at HF are becoming essential tools for water supply, water quality, and aquatic habitat evaluation (for example, Kirchner and others, 2004; Johnson and others, 2007; Pellerin and others, 2016). Not only have these tools become more affordable, but they also have become easier to use, more accurate, and more reliable. In 2016 the USGS alone operated about 100 in situ HF nitrate sensors in 24 States (Pellerin and others, 2016) and about 10 orthophosphate sensors (Brian Pellerin, U.S. Geological Survey, oral commun., 2016; https://waterwatch.usgs.gov/wqwatch/?pcode=00630), with most of these data streamed in real time where they are publicly available (https://waterdata.usgs.gov/usa/nwis). Other State, local, and private entities in the United States and internationally also are adopting these technologies in monitoring programs and targeted studies (Blaen and others, 2016; Pellerin and others, 2016). Typically, the nutrient sensors are deployed with other HF sensors such as temperature, pH, DO, specific conductance, turbidity, and (or) chlorophyll, and are co-located with stations measuring streamflow to gain a broader understanding of ecosystem processes and nutrient effects.

A development of equal importance to the recent advances in sensor technology is the emerging capability to store, manage, integrate, share, and make best use of the large datasets generated by these HF sensors. This capability includes improved visualization and modeling tools.

Attributes of a High-Frequency, Nutrient Monitoring Network

Today, the term "high-frequency (HF) monitoring" is most commonly used when referring to data collection efforts that gather information at frequencies on the order of seconds to hours, and are maintained continuously for at least several days if not over weeks or months. Although obtaining nutrient data in aquatic systems at 15-minute or hourly rates can certainly be attained using traditional water sampling techniques (that is, with a person or auto-sampler collecting individual samples and making measurements either in the field or on discrete samples transported to a laboratory), the analytical costs for that type of data collection are overwhelmingly prohibitive. For the purposes of this report, the term HF monitoring refers to sensors that can be deployed in situ in aquatic environments and that can collect individual measurements on the order of once per second to once per hour, and that have the capacity to remain deployed in situ for several weeks before requiring service. In addition, the idea of spatially HF monitoring (that is, for mapping) is discussed, as exemplified by deployment of these instruments during boat-based data collection campaigns.

In the following sections, six key attributes that characterize a modern HF monitoring system for the Delta are described—high frequency, continuous, real time, flux based, multi-parameter, network.

High Frequency

The field of statistics informs us that for data to be representative, they must be collected in a way that either captures or integrates the variability of a system. In the Delta, collection of monitoring data at an appropriate temporal frequency is especially important because of the multiple timescales of variability in this highly dynamic system. These include the timescales of tidal currents (daily and lunar), diurnal cycles (photosynthesis), seasonal cycles (temperature, precipitation, snowmelt runoff), annual changes (wet and dry years) and long-term changes (land use, population). There are also less predictable cycles in agricultural activity, water diversion, economic development, and recreational use, and irregular factors that affect water quality such as reservoir discharges, water transfers, emplacement of temporary barriers, droughts and floods, levee failures, atmospheric pressure changes, and storms. Quantifying the effects of these interacting drivers and understanding the consequences of management actions requires that monitoring be at a frequency sufficient to capture and resolve these different timescales of change.

Retrospective analyses of data from the Delta and elsewhere have shown that if HF variability is not taken into account, trends observed in the magnitude and timing of any observed change (for example, concentration, load), as well as values of any time-period average quantities (for example, weekly, monthly, seasonal, and yearly averages typically used in regulatory frameworks), can be misleading (Schoellhamer and others, 2007; Pellerin and others, 2008, 2014). This is because sampling theory states that to accurately resolve any change, sampling must occur often enough to capture the most rapidly varying component in the data (Johnson and others, 2007). The problem with sampling at frequencies below this rate is that it often leads to erroneous results, a phenomenon called "aliasing" (fig. 3). It is important to recognize that sampling at intervals less than this critical frequency—the Nyquist frequency—can lead to errors in the assessment of the magnitude and timing of the underlying trends.

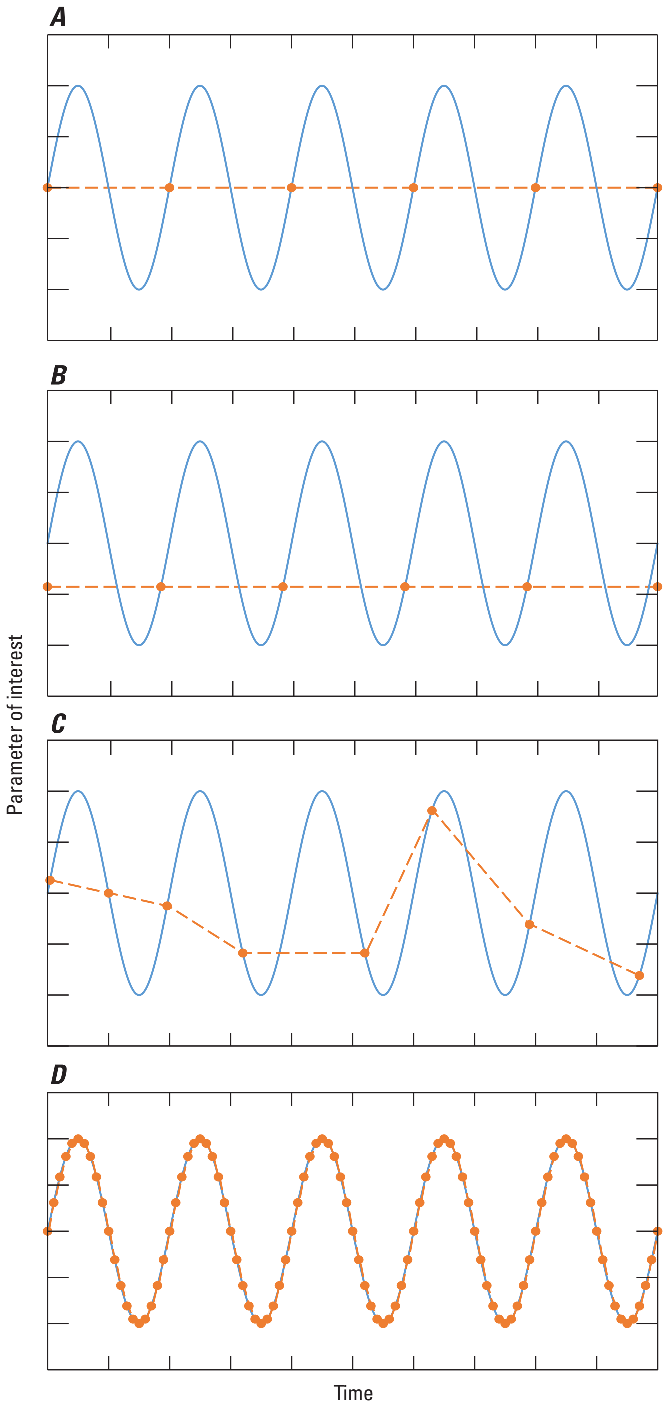

Figure 3. Discrete sample collection at lower frequency (*A*–*C*) can misrepresent water quality constituent dynamics in a system, a phenomenon referred to as "aliasing." High-frequency in situ measurements (*D*) provide a more accurate depiction of the system.

"Spatial sampling approaches . . .can supplement and benefit from fixed-station time-series data (streams and rivers), depth profiles (lakes), and other standard aquatic data sets. Integration of these multiple approaches will likely yield new insights and breakthroughs in the study of freshwater ecosystems, but their assimilation will likely be ecosystem- and question-specific. The goal should not be to eliminate fixed-sensor installations or long-term sampling schemes, but rather to supplement those with spatial snapshots."

—Crawford and others (2015, p. 449)

In complex systems like the Delta, we often do not know the magnitude of variability, regardless of whether it is over the short term (tidal), the long term (wet compared to dry years, landscape-scale changes, hydrologic modifications), or during events (storms, spills, levee breaks). Thus, one aim of HF monitoring is to characterize this variability to inform future sampling frequency. As a practical matter, by assuming that tidal-timescale drivers account for the highest-frequency variability in the Delta, sampling should occur about every 15 minutes. Although higher frequencies of variability in nutrients occasionally have been observed, and many instruments are capable of sampling more frequently (for example, every second), there are data management costs associated with oversampling and, thus, there are reasons to avoid redundant and unnecessary data collection (Blaen and others, 2016).

Hydrologically complex, tidal systems like the Delta are characterized by high temporal variability in constituent concentrations, but there also is extremely high spatial variability. A substantial limitation of fixed station-based HF monitoring is that the total number of stations that can be feasibly deployed is limited; thus, stations typically are placed in major channels and at well-mixed junctions that are broadly representative of system conditions. However, fixed-station data often may not adequately capture conditions in areas that are not well mixed or are poorly connected with major channels. In the Delta, this includes backwater sloughs, flooded islands, and tidal wetlands. Therefore, it often is beneficial to complement fixed-station monitoring with spatially dense data collected (for example, on moving boats) using HF sensors (Crawford and others, 2015; Downing and others, 2016; Fichot and others, 2016). Mapping with HF sensors can spatially resolve, for example, different sources and sinks for nutrients and organic matter such as agricultural drains, wastewater outfalls or seeps, and wetlands. Through repeated mapping excursions made under different conditions, we can track how these properties change over time and space, and also can document how environmental processing affects or is affected by the distribution of nutrients. Recently developed approaches to collect and visualize this type of HF mapping data—using the same set of sensors that can be deployed at fixed stations, including nutrient sensors—have made this approach much more feasible.

In addition to informing current status and trends analyses, the data generated by HF monitoring is of tremendous value to modeling efforts. These large datasets can be used to build, calibrate, and validate complex hydrological and biogeochemical models. This applies to both HF fixed-station and mapping data. The ability to map nutrient concentrations along with other water quality parameters across a broad geographic area provides an unprecedented opportunity to test the validity of model results that incorporate not just the main, deeper channels of the Delta that typically are sampled, but also the smaller sloughs, backwater areas, and wetland habitats. Documenting gradients and abrupt changes in parameters can help modelers to understand relationships between nutrient inputs, channel geometry, hydrodynamics, and biogeochemical processes, and, thus, to build models that can assess how Delta systems will respond to various management actions and physical modifications.

Continuous

The collection of long-term, “continuous” datasets is essential for tracking changes that occur over time. Recognition of long-term trends and regime shifts in the Delta using approximately monthly data can be difficult because they occur against a background of short-term variability. Changes in a complex system like the Delta can be detected in a more timely and accurate way through long-term monitoring that includes concurrent assessments of short-term variability. Furthermore, scientific understanding has evolved to more fully recognize the multiplicity of environmental drivers and ecological responses, the complexity of the processes that connect them, the ever-changing nature of the estuary, and the importance of changes at multiple spatial and temporal scales (Cloern and Jassby, 2012; Interagency Ecological Program Management, Analysis, and Synthesis Team, 2015). HF, continuous measurements provide an essential database for interpreting environmental change against the background of long-term climatic and anthropogenic effects on the Delta.

> High-resolution data over both time and space can help build, calibrate, and validate coupled biogeochemical-hydrodynamic models for the Delta.

The other major advantage of continuous measurements is the collection of data during unanticipated events, particularly those that cause rapid changes in constituent concentrations. This includes storm events, phytoplankton blooms, agricultural releases, contaminant spills, levee failures, and operation of temporary barriers. Some of these events can be ephemeral, and in the absence of HF, continuous data, the occurrence and effects of these types of events too often go unnoticed and undocumented. Collection of in situ, HF, continuous data at locations that are difficult and time consuming to access, particularly during inclement weather, is sometimes the only feasible approach.

Real-Time

An additional benefit of modern, in situ, nutrient measurement technology is that the data can be made available in numerical and graphical form over the Internet in near real time. Real-time data dissemination provides an advantage over data associated with discrete samples that can take days if not months to be made available to project scientists—and longer to be made publicly available. Real-time data dissemination enables an early warning system for unanticipated, short-lived, or rapidly changing conditions such as those due to spills and harmful algal blooms, and water quality changes related to storms or levee breaches. Timely access to information also is useful for management. For example, drinking water treatment plants use real-time data to help anticipate changes in source water quality and to inform treatment plant operations (Carpenter and others, 2013). The network of flow and turbidity sensors now in place in the Delta is used by State and Federal water managers to make daily decisions about water export activities (Burau and others, 2016). Real-time data also can be used by Delta monitoring programs to trigger sampling for other parameters that require manual field sampling or to turn on automatic-samplers staged in the field for this purpose. For example, high nutrient concentrations combined with high chlorophyll-*a* and (or) dissolved oxygen (DO) concentrations could trigger manual sampling for the presence of toxins produced by harmful algae like *Microcystis* or, alternatively, low DO concentrations could trigger alerts to fisheries managers about potential threats to fish populations in the affected waters. Furthermore, real-time data access greatly improves data quality because it allows operators to monitor sensor performance, to trigger sensor maintenance visits, and to implement adaptive sampling to improve quality control (Bergamaschi and others, 2017).

Flux-Based

Linking continuous concentration measurements of constituents such as nutrients to discharge measurements allows fluxes and loads to be calculated. Constituent flux, sometimes referred to as instantaneous load, is calculated by multiplying instantaneous concentration data by instantaneous discharge data, and is reported as the amount of a constituent moving across a channel cross section per unit time (typically per second, minute, hour, or day). Loads, in turn, are calculated by summing flux data over a specified period of time such as a day, week, month, or, most commonly, over a year (annual loads). Loads often are reported in units of mass, but the time period over which the flux data were summed must be specified.

> ***"Accurate and timely information on nutrient concentrations and loads is integral to strategies designed to minimize risk to humans and manage the underlying drivers of water quality impairment."***
>
> —Pellerin and others (2016, p. 1).

Information about fluxes and loads permits identification and quantification of nutrient sources and sinks, and direct evaluation of the effects of upstream management actions or mitigation programs. In tidal systems like the Delta, HF data are necessary to quantify fluxes and loads because tidal flows are bi-directional and the net flux is the difference between the flux carried upstream by the in-coming tide and the flux going downstream by the outgoing tide. By pairing HF constituent concentration data with flow data collected simultaneously at the same (or near-by) station, we can more accurately calculate fluxes and loads. These calculated values, along with associated uncertainty, can be used to quantify the amount of a constituent exported from or retained in a specific region.

Terminology—FLUX and LOAD

FLUX: Constituent flux, sometimes referred to as instantaneous load, has units of mass per unit time. It is calculated as the product of concentration and discharge through a channel cross section; it typically is reported as the flux per second, but also can be reported per minute, hour, day, or other time period.

LOAD: Constituent load is calculated as the integrated flux over a specified period of time, and has units of mass. The time over which the flux is integrated must be specified. For example, an annual load is the flux integrated over a year, but other time periods may be chosen.

NOTE: As a general rule, the higher the temporal frequency (resolution) of the flux data, the more accurate the load calculation will be.

The importance and benefits of HF nutrient flux measurements have recently been demonstrated in the Mississippi River, which delivers large loads of nitrate to the Gulf of Mexico, resulting in periods of hypoxia (low DO concentrations). Historically, nitrate loads to the Gulf of Mexico have been modeled using a regression-based estimation technique that predicts nutrient concentrations through time from relatively infrequent (bi-weekly or monthly) discrete samples and HF discharge measurements. These models often are based on an important assumption that there is a predictable relationship between instantaneous nitrate concentration and instantaneous discharge (C-Q relationship); however, this relationship is not necessarily straightforward, even in large rivers like the Mississippi River (fig. 4). Pellerin and others (2014) collected HF nitrate data over a 2-year period (2011–2013), and compared load calculations using the HF data to loads estimated from three different regression-based load estimation models (LOADEST, the Composite Method, and WRTDS). Results from this study indicated substantial variability in concentration-discharge (C-Q) relationships led to model overestimates and underestimates (fig. 5). Although the total loads calculated were similar at the annual scale, differences between models were much larger at shorter, biologically relevant timescales of weeks or months, demonstrating that HF nitrate measurements can improve the accuracy and precision at timescales relevant to environmental management.

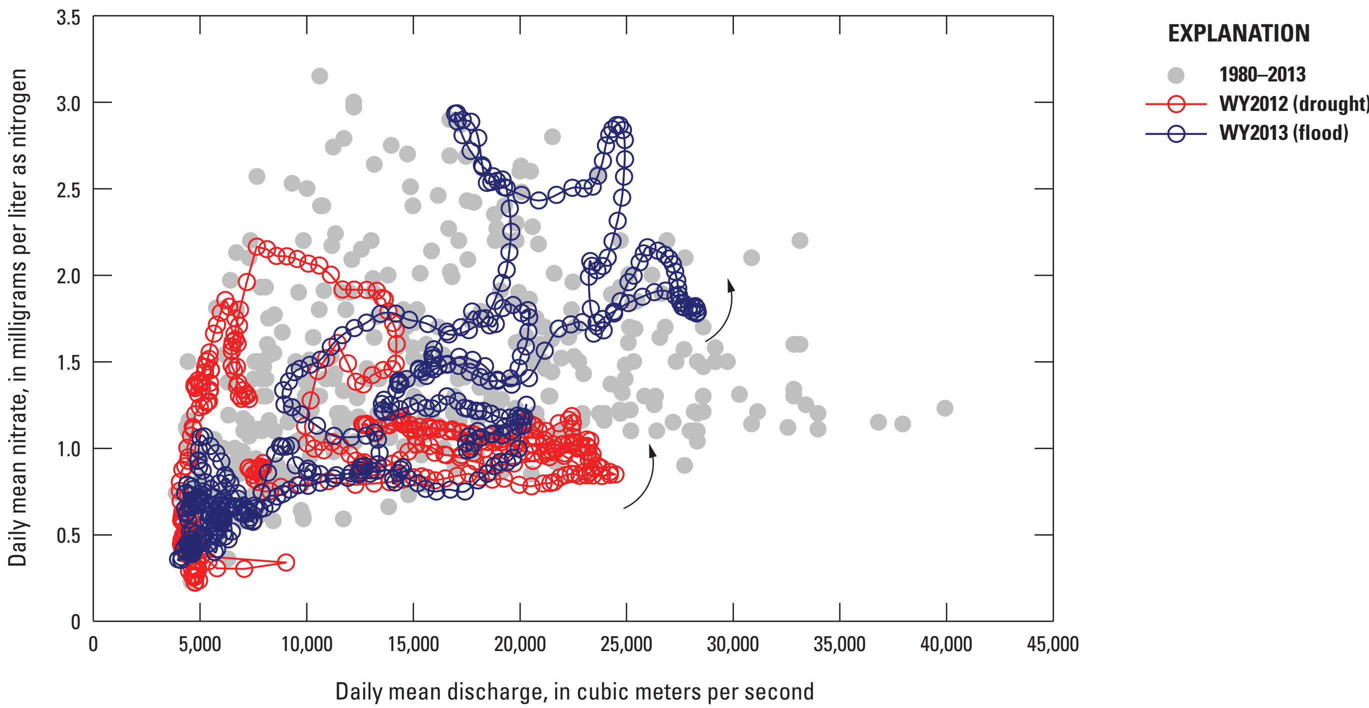

Figure 4. High-frequency discharge and nitrate concentration data from the Mississippi River collected in water years (WY) 2012 and 2013 compared to data collected from 1980 to 2013 using traditional discrete sampling methods, illustrating that there is not always a clear relation between daily mean discharge and daily mean nitrate concentration. Arrows show the dominant direction in the hysteresis (counterclockwise). (From Pellerin and others, 2014).

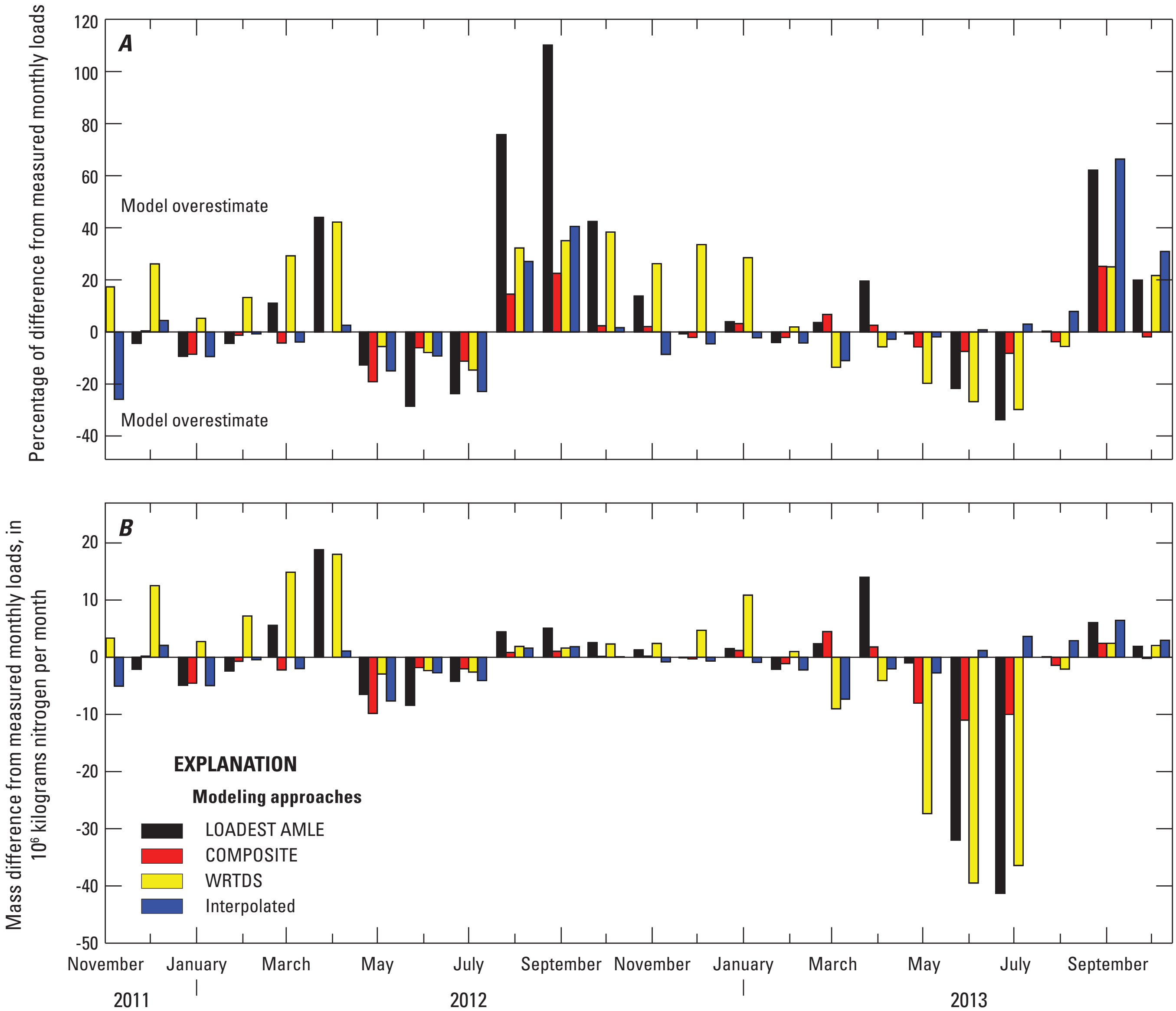

Figure 5. Percentage differences between nitrate-nitrogen (NO_3-N) loads calculated using four different modeling approaches (LOADEST AMLE, COMPOSITE, WRTDS, and interpolated) compared to high-frequency, in situ sensor-measured NO_3-N loads, expressed as (*A*) percentage of difference from measured monthly loads, and (*B*) mass deviation from measured monthly loads (in 10^6 kilograms nitrogen per month). (From Pellerin and others, 2014).

In the Delta, there is a well-established and extensive flow station network (Burau and others, 2016), and many of the existing flow stations are equipped with HF water quality sensors that have enabled flux-based monitoring of several important constituents, including suspended sediments. Flux-based monitoring has yielded important insights into estuarine processes across a range of scales, such as in South San Francisco Bay (Shellenbarger and others, 2013), the Delta (Wright and Schoellhamer, 2004), Cache Slough Complex (Morgan-King and Schoellhamer, 2013), and Browns Island (Bergamaschi and others, 2011, 2012). Flux-based monitoring also provides data to estimate internal reaction rates and to quantify the effects of episodic events and loads during, for example, high flows (Saraceno and others, 2009). By coupling constituent concentrations with flow data, we can determine not only where constituents are moving, but also the mechanics of why and how they are moving. In other words, temporally dense, flux-based monitoring allows us to obtain a much clearer and more mechanistic picture of important estuarine ecosystem processes and their effects.

Multi-Parameter

Aside from nutrients, there are numerous other parameters important to assessing the effects of nutrients and the health of aquatic ecosystems that also can be measured concurrently at high frequency, leveraging the investment in and scientific value of establishing, maintaining, and visiting each station. In fact, HF monitoring of water temperature and specific conductance have been implemented continuously for decades in many systems, including the Delta, and have laid the foundation for establishing multi-parameter monitoring stations. More recently, technological innovations, including the development of optical sensors, have improved our ability to measure turbidity, DO, chlorophyll-*a*, and fluorescence of dissolved organic matter. By embracing a multi-parameter approach, nutrient monitoring programs in the Delta and elsewhere can demonstrate that there are multiple factors that together affect water and habitat quality. Such an approach also can provide information about processes affecting nutrient sources, sinks, transformations, and fate, such as mineralization, assimilation, nitrification, denitrification, and burial (Novick and others, 2015), and can improve our understanding of how nutrients and other parameters may interact to affect primary production, harmful algal blooms, submerged and floating aquatic vegetation, and exotic species invasions, among other concerns.

“The value of these measurements will be maximized when collected in combination with other measurements (e.g., open-channel metabolism and denitrification, chamber and sediment core experiments) that can be used to test mechanistic hypotheses and strengthen inferences derived from high-frequency measurements. Conversely, high resolution measurements can be used to evaluate ecosystem-scale predictions that follow from mechanistic models and experiments. Such an integrated approach will be necessary to develop a process-specific understanding of large river N dynamics.”

—Heffernan and Cohen (2010, p. 687)

Network

There are times when monitoring a single location meets the goals of a monitoring program. However, a network of spatially distributed sensors is needed if the goal is not just to track nutrient concentration trends in one particular location, but to resolve both external sources and internal processes and interconnections across a large region such as the Delta. For example, comparing data between two points that are hydrologically connected sheds light into whether the region between the sensors is a source or sink for nutrients or other constituents being measured. This can provide information about how nutrient concentrations and forms change spatially and temporally as water moves through the Delta and interacts with specific habitats. A network of stations also provides information about the source and history of individual pulses of water. Without a distributed network of sensors, it is difficult to link water sources to observed environmental conditions.

Designing a High-Frequency Monitoring Network

An effective design for a specific HF monitoring network will depend on the objectives of the monitoring program; thus, not all the attributes of an HF monitoring network discussed above always will be required. For example, short-term deployment of a nitrate sensor in an urban drainage canal to document changes in nitrate concentrations during a 2-day storm event may meet one monitoring objective, whereas a long-term instrumentation package comprising nitrate, phosphate, DO, and chlorophyll-*a* sensors that transmits data in real-time to managers to inform daily operations might be required to meet another objective. The third report of this series (Bergamaschi and others, 2017), presents further discussion of factors to consider when designing an HF nutrient monitoring program.

In the broadest terms, the objective of high-frequency monitoring in the Delta is to provide timely, high-quality information to enable managers to more effectively manage the Delta as a functioning ecosystem and the primary water supply for more than 1 million hectares of agricultural land and more than 27 million Californians.

Insights from High-Frequency Nutrient Measurements Worldwide

Temporal Variability in Nutrient Concentrations and Loads

Collection of nutrient data at frequent intervals in aquatic systems has in almost all cases indicated much higher variability than was evident in less-frequent discrete sample collection (Pellerin and others, 2009, 2012, 2014; Bende-Michl and others, 2013; Wild-Allen and Rayner, 2014; Blaen and others, 2016). HF data of this type also revealed patterns in nutrient dynamics that occur at yearly, seasonal, diurnal, tidal, and episodic event timescales that are difficult, if not impossible, to detect using low-resolution data (Bowes and others, 2009; Pellerin and others, 2009, 2012, 2014; Cohen and others, 2012, 2013; Bende-Michl and others, 2013; Wild-Allen and Rayner, 2014). This is not only because of the higher temporal and spatial resolution that HF measurements make possible, but also because measurements can be collected during atypical, episodic, and sometimes previously unidentified conditions. Moreover, diel cycles may be clarified by HF observations collected during the night when discrete samples are rarely collected.

One fundamental consequence of finding higher than expected variability is that it highlights the need to evaluate classical techniques for calculating loads as a function of intermittent concentration data and continuous discharge data. Comparison of nutrient fluxes and loads calculated using concentration data from less frequent discrete samples to those calculated from HF data has shown that collection of data at more frequent intervals improves accuracy and precision, even in large rivers that are assumed to be buffered from short-term nutrient pulses (Rozemeijer and others, 2010; Cassidy and Jordan, 2011; Carey and others, 2014; Pellerin and others, 2014). The magnitude and direction of the mismatch between load calculations using low-frequency and HF data are variable and often dependent on the time period of interest. As mentioned above, this is related to the observation that the relationship between nutrient concentrations and discharge (C-Q relationship) has been observed to vary—sometimes unpredictably—between, for example, storm events and seasons (Rusjan and others, 2008; Saraceno and others, 2009; Stenback and others, 2011; Hirsch, 2014; Jiang and others, 2014; Pellerin and others, 2014).

HF data not only can improve load estimates, but also can provide novel insights into nutrient sources and cycling, and can improve our ability to quantify these processes. There are many examples of this in the water-quality literature. In a 2-year study, Bowes and others (2015) collected in situ nutrient measurements in a small rural river in southern England and determined that, although the main source of nitrate was from groundwater, phosphate appeared to come predominantly from wastewater effluent inputs. Further evaluation of the data indicated that WWTP-derived P from within channel bed sediments was remobilized into the water column, and differences in groundwater flow paths across storm events affected nitrate concentrations. They also identified diffuse agricultural inputs of nutrients during the first major storms of the winter period.

"If we 'make do' with weekly or monthly water quality sampling, then we are viewing the catchment's behavior through a blurry telescope that can only see its largest and most persistent features….Our point is not that there is anything wrong with either of these conventional sampling schemes, but that there is a lot to be learned if we take the time and trouble to monitor catchment hydrochemical behavior at high frequency over long spans of time.

"Imagine trying to understand a Beethoven symphony if one could only hear one note every minute or two! That is what we are trying to do when we infer the hydrochemical functioning of a catchment from weekly or monthly grab samples. Or imagine trying to understand a symphony from a high-fidelity recording of just one of its crashing crescendos. That is what we are trying to do when we analyze high-frequency samples of an individual storm event. Continuous high-frequency monitoring of catchment hydrochemistry will require significant resources and tenacity. In our view, however, what we stand to learn is well worth the effort. If we want to understand the full symphony of catchment hydrochemical behavior, then we need to be able to hear every note."

—Kirchner and others (2004, p. 1,359)

Data collection during both day and night provides information about photosynthetic controls on nutrients and helps differentiate biotic compared to abiotic processes, and the linkages between them (Cohen and others, 2013). This approach was used by Heffernan and Cohen (2010) to estimate N assimilation and denitrification rates in the Ichetucknee River in Florida. Additionally, they found these processes to be closely linked to primary productivity, suggesting that production of labile organic matter through photosynthesis plays a key role in fueling microbial processing and thus plays a role in the fate of N. Other studies have used HF data to identify periods where internal recycling of nutrients from remineralization of previously accumulated organic matter is more important than nutrients entering the system (Gilbert and others, 2013; O'Donnell, 2014). Several studies found that high wind events, spring tides, and changes in irradiance can alter the concentrations and cycling of nutrients and other water quality constituents over short time periods (Bergamaschi and others, 2012; Collins and others, 2013).

"Determining nutrient sources and behavior, at high temporal resolution, provides vital information to allow the most appropriate mitigation options to be selected. . . thereby providing the most effective and cost-effective management."

—Bowes and others (2015, p. 619)

Nutrient Processes Revealed by Multi-Parameter Measurements

Simultaneous collection of related water quality parameters improves understanding of nutrient sources, sinks, processing, and effects. Using HF nutrient measurements in combination with measurements of DO and chlorophyll in a nutrient-rich, turbid estuary, Voynova and others (2015) found that primary productivity was tightly coupled to nitrate concentrations; specifically, influxes of nitrate supported much higher rates of primary production as measured by DO supersaturation and higher chlorophyll-*a*. This finding suggested management actions that could influence drivers of phytoplankton blooms, along with insight into how predicted increases in the frequency of storm events may affect the estuary. The extent to which primary production was controlled by nitrate was similarly demonstrated using HF monitoring in freshwater streams (Heffernan and Cohen, 2010; King and others, 2014).

HF data have been used to calculate fluxes of primary production between different regions to identify areas of net productivity and loss. For example, Voynova and others (2015) surmised that newly produced chlorophyll particles were tidally transported into marshes bordering the Murderkill Estuary in Delaware, where these particles were subsequently retained in vegetated areas, suggesting that the marshes were a net sink of primary production rather than a source of it.

Although most HF nutrient studies to date involve deployment of nitrate sensors, adoption of commercially available in situ analyzers for phosphate is increasing, as is the related published literature (for example, Rozemeijer and others, 2010; Cassidy and Jordan, 2011; Bende-Michl and others, 2013; Cohen and others, 2013; Gilbert and others, 2013; Outram and others, 2014; Bowes and others, 2015). These studies highlight that sources and pathways for P frequently contrast with those for N, particularly in relation to hydrologic transport and sediment-water interactions.

Few studies have reported results from in situ HF ammonium analyzers and, not surprisingly, these studies found that concentrations of ammonium, nitrate, and phosphate do not always co-vary (Bende-Michl and others, 2013; Gilbert and others, 2013). Gilbert and others (2013) measured elevated concentrations of ammonium, phosphate, and silicic acid during late summer in the Columbia River Estuary, which suggested high rates of remineralization from organic rich material. Quantification of nutrient recycling within estuaries, which could be a key source of both N and P, requires further study. Bende-Michl and others (2013) found hydrologic and biologic controls on nutrients in the Duck River of northwestern Tasmania, Australia. They identified different seasonally driven phases of nutrient supply, mobilization, and delivery that together affected nutrient concentrations. Snyder and Bowden (2014) used an in situ auto-analyzer to simultaneously measure nitrate and ammonium concentrations continuously (1-second data) in combination with pulsed additions of ammonium to confirm that high rates of nitrification occurred in an arctic headwater stream. This study shows that when multiple nutrients were examined simultaneously at HF, the driving mechanisms behind trends became clear.

Although no published studies to date from the Delta have reported simultaneous in situ measurement of nitrate, ammonium, and phosphate, preliminary data collected by the USGS reveal high variability and complex relationships between these nutrient species. This indicates that sources are varied and different biogeochemical pathways affect their concentrations.

Spatial Applications of High-Frequency Sensors

Recent studies have shown how HF sensors may be used to improve our understanding of environmental processes by mapping spatial variability in rivers, lakes, and estuaries (Gilbert and others, 2013; Hensley and others, 2014; Wild-Allen and Rayner, 2014; Crawford and others, 2015; Downing and others, 2016). In the Columbia River Estuary, fixed-station HF monitoring and high-resolution mapping data allowed researchers to identify nutrient sources and transformations across a salinity gradient, identifying key transition zones (Bronk and others, 1994). In Florida, longitudinal profiling of several rivers permitted nutrient removal "hot spots" to be located (Hensley and others, 2014). Wild-Allen and Rayner (2014) also used high-resolution fixed-station and mapping data in the Derwent Estuary in southeastern Tasmania to compare measured temporal and spatial variability in water quality—including nitrate and phosphate—to simulated variability from a three-dimensional biogeochemical model. Their HF observations captured variability in marine and riverine nutrient concentrations and identified nutrient enrichment sources (point discharges) by comparing against the background estuarine gradients. Crawford and others (2015) used a boat-based sensor platform to examine physical, chemical, and biological factors affecting surface-water quality in Colorado streams and lakes. They observed previously unknown variability in constituent concentrations and identified substantial chemical changes across aquatic ecosystem boundaries. By also combining multiple sensors in one mobile platform, they gained insight into nutrient sources and biogeochemical processes.

In the Delta, boat-based HF (also referred to as high resolution) mapping of water residence time conducted over a large spatial scale over a short period of time (about 4 hours), along with a suite of water quality parameters, made it possible to calculate biogeochemical rates, resolve differences in nutrient concentrations due to mixing and new inputs, and further our understanding of the complex linkages among time-dependent biogeochemical parameters (Downing and others, 2016; see section, "Example 7—Residence Time and Biogeochemical Processes"). This same USGS system recently has been deployed in the Delta to understand the effects of water barriers and water releases from upstream storage reservoirs, and to understand linkages between nutrients and phytoplankton blooms.

Networks, Databases, and Models

Several review papers have described the advantages of building a network of HF monitoring stations to understand how ecosystems function at the landscape scale (Johnson and others, 2007; Crawford and others, 2015; Pellerin and others, 2016; Bergamaschi and others, 2017; Downing and others, 2017). With an integrated network of stations, we can quantify constituent sources, calculate transport time, and calculate rates of transformation, which are likely to yield new insights into ecosystem function. These data can help us calibrate, validate, and improve predictive models relied upon by water managers and policy makers to make decisions. These data also can identify periods (their timing and duration) when water quality parameters either exceed or remain below critical thresholds (Carey and others, 2014). Rigorous evaluation of these data can improve current monitoring programs by quantifying the uncertainty and bias in data obtained from low-frequency approaches, and by informing the design of future sampling programs that take into account cost and accuracy (Hirsch, 2014; Jiang and others, 2014).

A long-term commitment to HF monitoring will mean we can track changes to the ecosystem associated with drought compared to high-rainfall conditions (Outram and others, 2014); identify changes related to irregular, unpredictable events like wildfire (Sherson and others, 2015); and measure the effects of changes due to population growth, land management, or WWTP operations (O'Donnell, 2014). These data can help reduce uncertainties in model predictions and thereby improve detection of changes related to water management and (or) climate variability over what currently is possible from models with significantly larger errors or errors that are not quantified (Pellerin and others, 2016). An integrated understanding of ecosystem processes will advance the development, implementation and evaluation of water management strategies and policies (Cassidy and Jordan, 2011; Outram and others, 2014; Pellerin and others, 2014).

Progress Toward Improved Timeliness, Reliability, and Data Quality

As the use of HF sensors becomes more widely adopted, a concerted effort has been made to develop, improve, document, and share:

- The operating principles behind operating a growing suite of these instruments;
- The protocols used by the USGS and its partners to maintain and calibrate them (for example, see Downing and others, 2012; Pellerin and others, 2013);
- The software and related efficiency tools developed to effectively quality control the data (for example, data checking, routine adjustments for sensor drift or recalibrations, data review, and finally approval);
- Approaches to make data available to managers, policy makers, and other scientists in a more timely manner (Johnson and others, 2007; Downing and others, 2012; Pellerin and others, 2013, 2016; Terrio and others, 2015; Blaen and others, 2016; Bergamaschi and others, 2017).

Insights from High-Frequency Nutrient Measurements in the Delta

Although more than 100 stations in the Delta currently record, or in the past have recorded, some type of continuous HF water quality monitoring data (Bergamaschi and others, 2017, appendix A), HF sensor measurements of nutrients only began recently. The current network is an extension of the proof-of-concept monitoring station originally installed for the Interagency Ecological Program (IEP) at Liberty Island in 2013, along with habitat characterization measurements made for the IEP fall low-salinity habitat (FLaSH) study (Brown and others, 2014). As of spring 2017, a total of 11 HF nutrient monitoring stations were operating in the Delta, with nitrate the only nutrient parameter reported from every site, and phosphate and ammonium reported intermittently on an event basis (table 1; fig. 6). The objectives for establishing these stations included (1) determining temporal changes in concentration and mass fluxes of nitrate-N and phytoplankton (as chlorophyll-*a* fluorescence); (2) identifying links between nutrients and phytoplankton; and (3) identifying drivers of nutrient and chlorophyll-*a* concentrations. The stations directly support efforts to elucidate effects of wastewater effluent from the Sacramento Regional WWTP on downstream nutrient concentrations and food web dynamics. To date, although no compilations of the data from this monitoring network are published, all these data are available (at least as provisional data) on the Web in real time (https://waterdata.usgs.gov/nwis) and in daily reports through email subscription. For more information on these stations and the data that HF-monitoring has generated, see the second report of this series (Downing and others, 2017).

The examples of studies—published and unpublished—that were selected for inclusion in the following subsections of this report illustrate some of the numerous benefits gained from the collection of HF nutrient data in the Delta.

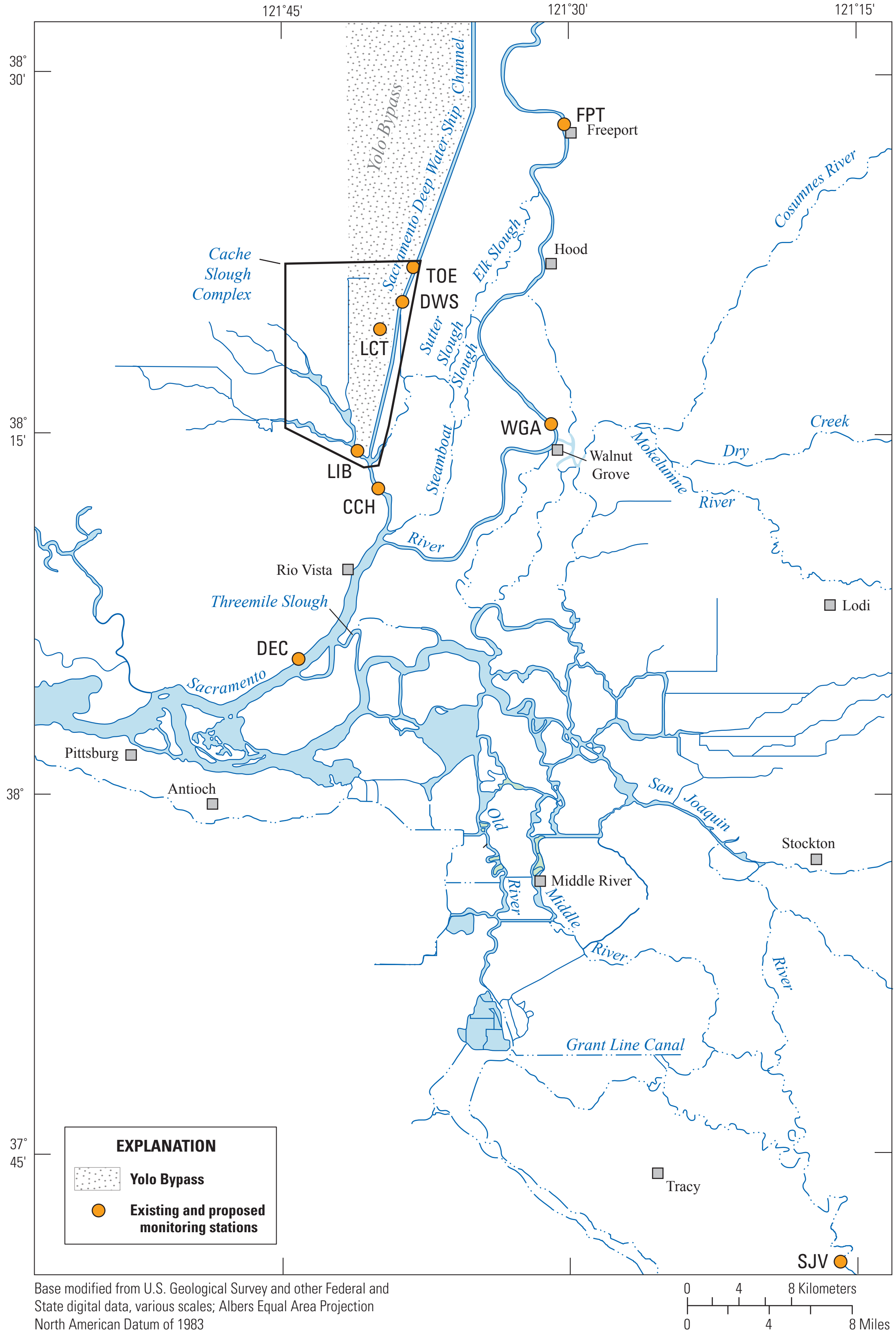

Figure 6. Location of high-frequency, nutrient-monitoring stations operated in the Sacramento–San Joaquin Delta, northern California, fall 2016. See table 1 for site abbreviations and selected station information and Downing and others (2017) for details.

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. For station details, see Downing and others (2017). 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"

Example 1—Controls on Nitrate Concentrations and Fluxes in the San Joaquin River

The San Joaquin River is one of the main sources of water to the Delta, and contains high concentrations of inorganic nitrogen from agricultural and urban inputs. To help explain hydrologic and biogeochemical controls on nitrate concentration in the river during a summer period characterized by high algal productivity, a combination of HF and discrete samples were collected in 2005 from the river at Crow's Landing (Pellerin and others, 2009). In situ measurements were made every 30 minutes for a 5-day period while discrete samples were collected every 2 hours during 2 of those days.

There was excellent agreement between nitrate concentrations measured in situ and in discrete samples analyzed at the laboratory (coefficient of determination [r^2] = 0.97, $P < 0.01$, $n = 25$). Visual inspection of the nitrate data from the discrete samples alone suggested that nitrate concentrations generally were increasing over the period of sample collection (fig. 7*A*); however, the HF data revealed a more complex pattern (fig. 7*B*). Surprisingly, nitrate concentrations varied by as much as 22 percent over a single 24-hour period, and by as much as 31 percent over the 5-day study. However, the variation in nitrate concentrations did not correspond systematically to the diurnal patterns of DO, indicating that nitrate variability was not determined solely by phytoplankton activity. From this determination, it was concluded that the variability in nitrate concentrations likely reflected a combination of source variability (in this case, likely agricultural releases) and biological processes.

The high variability in nitrate concentrations observed in this study demonstrated that sampling at weekly to monthly intervals introduces great uncertainty when estimating nitrate loads in the river. For example, nitrate daily load estimates calculated using a conventional, discrete sample approach could underestimate daily fluxes by as much as 23 percent or overestimate them by 30 percent (fig. 8).

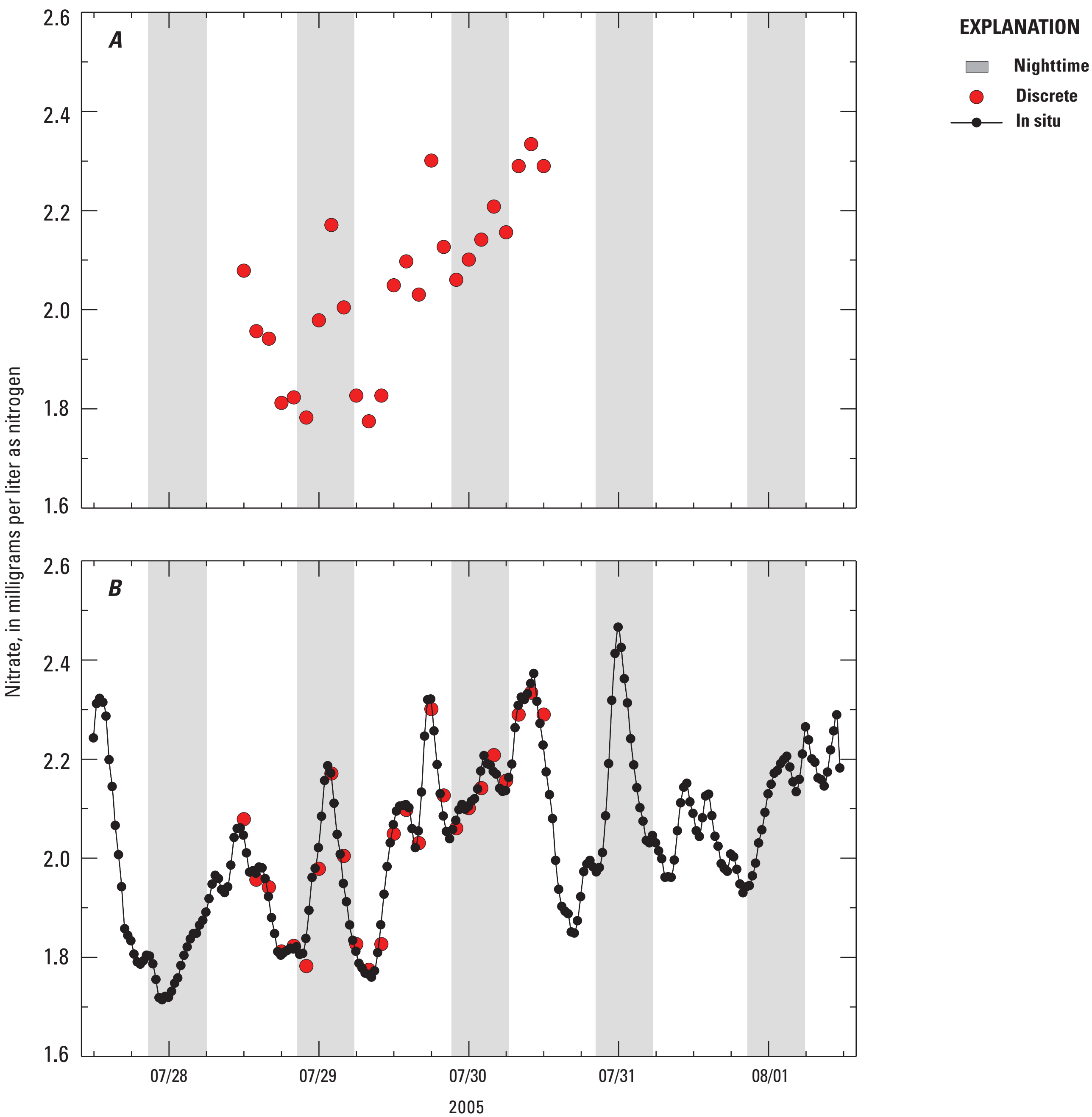

Figure 7. Time series of nitrate concentration showing the explanatory value of high-frequency (HF) data compared to discrete samples, San Joaquin River at Crows Landing, California, July–August 2005. (*A*), Although discrete samples were collected at a high sampling frequency (about every 2 hours) over 2 days, these data alone did not provide enough information to explain controls in nitrate concentrations. (*B*), HF data collected over a 5-day period provided a much richer dataset than data collected over a 2-day period, indicating high variability over short time periods likely associated with agricultural releases and biological processes. See Pellerin and others (2009) for details.

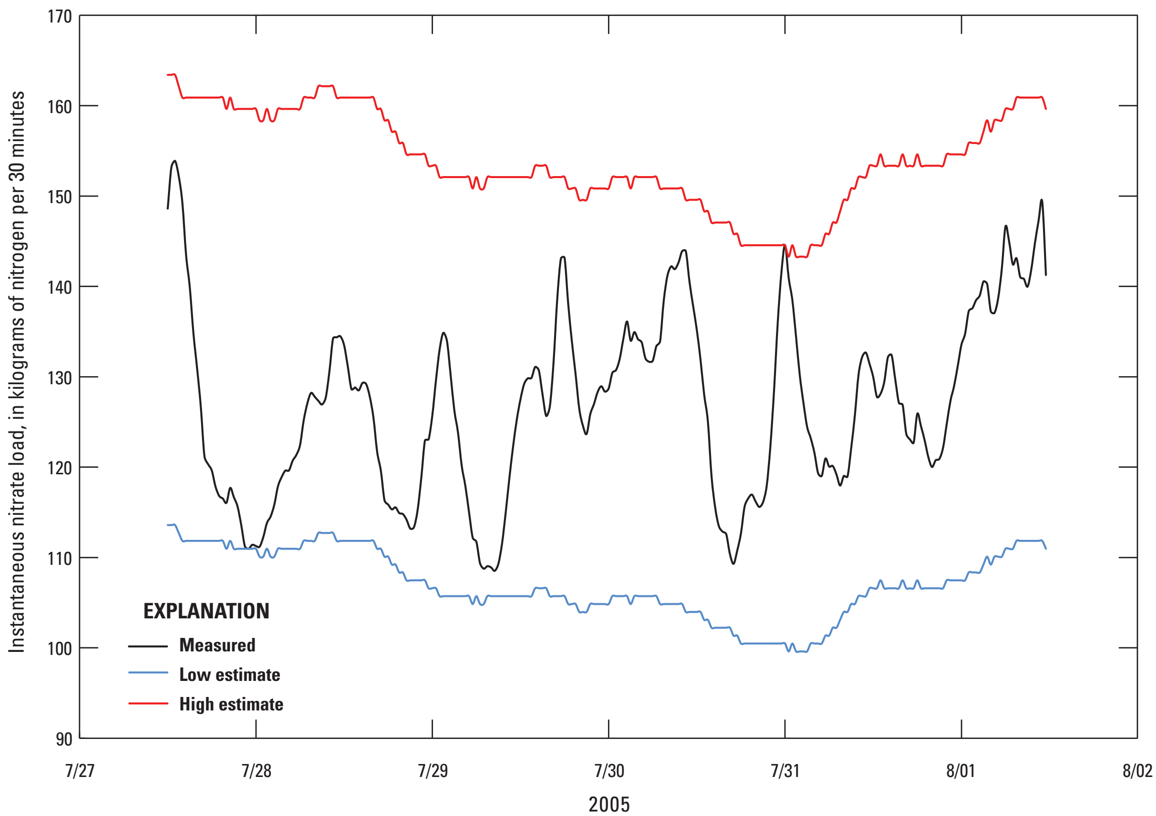

Figure 8. Time series of instantaneous nitrate load calculated from continuous high-frequency (15-minute) discharge and concentration measurements ("Measured") compared to measurements calculated using continuous discharge and the lowest ("Low estimate") and highest ("High estimate") value in the high-frequency nitrate concentration time series, San Joaquin River at Crows Landing, northern California, July–August 2005. Resulting daily load estimates range from -23 to + 30 percent of measured daily loads using continuous nitrate data. See Pellerin and others (2009) for details.

Example 2—Measuring Nitrate Fluxes in Tidal Wetlands

Tidal wetlands and shallow water habitats can be sites of high rates of nutrient cycling because of increased interaction with sediment, plants, and other organisms. Wetlands can act as sinks for nutrients in the water column owing to the nutrient demands of emergent macrophytes, phytoplankton, and microbes, and, in the case of nitrogen loss to the atmosphere, through denitrification in anoxic zones. Wetlands also can be a source of nutrients through mineralization of organic matter. Because water is continually entering and exiting these tidal, shallow-water habitats, both concentration and flow data must be collected across the tidal cycle to calculate instantaneous fluxes, and then those fluxes must be summed to determine the net load. As part of a larger published study that examined dissolved organic matter and mercury dynamics in Brown's Island, a remnant wetland in the central Delta (Downing and others, 2009; Bergamaschi and others, 2011, 2012), an HF nitrate sensor was deployed to examine nitrate fluxes.

The 15-minute HF data revealed that there was a high degree of temporal variability in nitrate concentrations and fluxes (fig. 9), which corresponded to changes in water level, light level, wind speed, wind direction, and other physical factors, as well as the background nutrient supply. There also was substantial variability between seasons (April, October, January). These findings show the complex interaction between physical, chemical, and biological factors that determine uptake, transformation, and release of nitrate in tidal wetlands and shallow water habitats, suggesting that a clearer picture of these interrelated processes is important for guiding future large-scale restoration efforts.

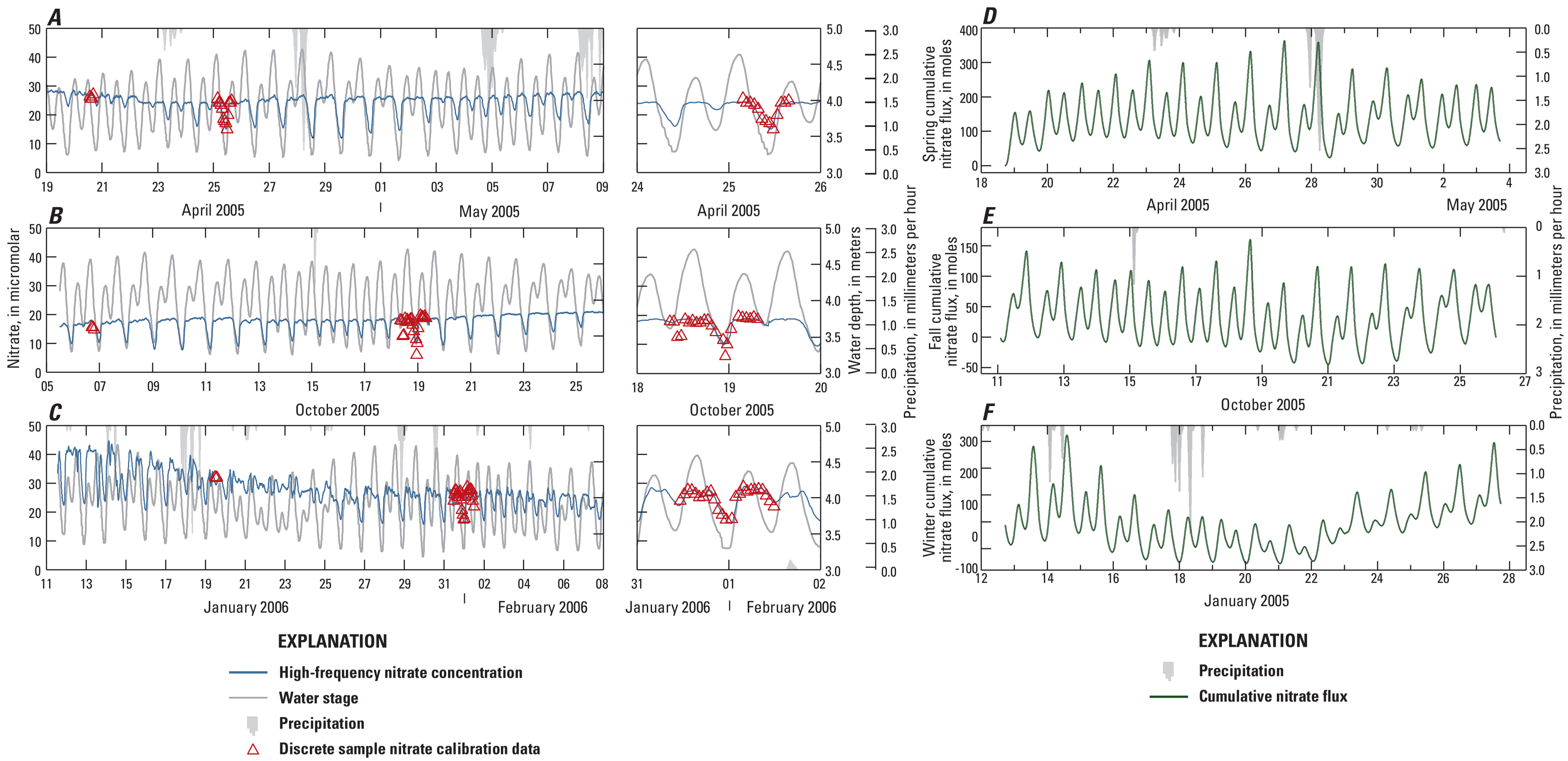

Figure 9. Time-series of nitrate concentration data collected at Brown's Island, Sacramento–San Joaquin Delta, California, 2005–06. Three deployment periods are shown—April–May 2005 (*A* and *D*), October 2005 (*B* and *E*), and January–February 2006 (*C* and *F*). For details and related data, see Bergamaschi and others (2011) and Downing and others (2009).

Example 3—Relationship Between Nitrate and Phytoplankton Blooms

There is great interest in understanding the role of nutrients as drivers of phytoplankton blooms in the Delta, given that aquatic primary productivity supports pelagic organisms (Sobczak and others, 2002) and given concerns about harmful algal blooms (Lehman and others, 2015). Because the timing and location of phytoplankton blooms are highly variable and often ephemeral, collection of continuous HF water quality data provides advantages compared to less-frequent discrete samples. As a case in point, 15-minute chlorophyll-*a* and nitrate concentration data collected at the Decker Island monitoring station (DEC, fig. 6) and at the entrance to the Cache Slough Complex (represented by the Cache Slough monitoring station, CCH, fig. 6) during spring 2013 are shown in figure 10. Two substantial phytoplankton blooms were detected at the Decker Island station during this period: (1) A larger phytoplankton bloom occurring from March 28 to April 3, 2013, and (2) a smaller bloom occurring on April 8 (fig. 10*A*, chlorophyll-*a* fluorescence). To determine the source of each phytoplankton bloom, concurrent measurements of specific conductance, nitrate, and DO were examined (fig. 10*B*–*E*). In this tidal region, specific conductance can be used as a tracer of different sources of water—higher conductance is associated with water originating from downstream or seaward sources, whereas lower conductance is associated with water originating from upstream or landward sources. High rates of in situ photosynthesis typically result in elevated DO concentrations and often are concurrent with nitrate consumption. In contrast, in instances where phytoplankton bloomed elsewhere and were dispersively mixed through tidal exchange both upstream and downstream, there should be less evidence of DO production and nitrate drawdown. Furthermore, because net flows in this region move water seaward, if a bloom originates from the Cache Slough Complex, it should be observed being transported past the Cache Slough monitoring station prior to appearing at the Decker Island monitoring station.

In spring 2013, high chlorophyll-*a* concentrations measured at the Decker Island monitoring station in the first bloom co-occurred with high specific conductance (>250 µS/cm, fig. 10*C*) and low DO concentrations (<100 percent saturation, fig. 10*D*) during flood tides, suggesting that the bloom originated downstream (seaward) of the monitoring station and was being transported past this location by the tidal energy. This bloom was not evident at the Cache Slough monitoring station (fig. 10*E*). The second, smaller phytoplankton bloom event observed at Decker Island monitoring station around April 5 was associated with low-conductance water at ebb tide (about 200 µS/cm, fig. 10*C*), representative of water originating from the upstream Cache Slough monitoring station (fig. 10*E*). Moreover, this bloom was associated with elevated DO (>100 percent saturation, fig. 10*D*) and lower concentrations of nitrate (fig. 10*B*), suggesting the phytoplankton were actively growing in this region. Together, these data suggest that this second bloom was occurring upstream of the Cache Slough monitoring station in the Cache Slough Complex and that phytoplankton generated in that shallow water region were exported downstream past the DEC station.

These data highlight the benefits of collecting a suite of HF parameters to understand phytoplankton blooms, as well as the value gained by a network of stations. Comparing data between stations allows us to identify sources of phytoplankton blooms and track how nutrient concentrations change spatiotemporally as water moves through the Delta and interacts with specific habitats.

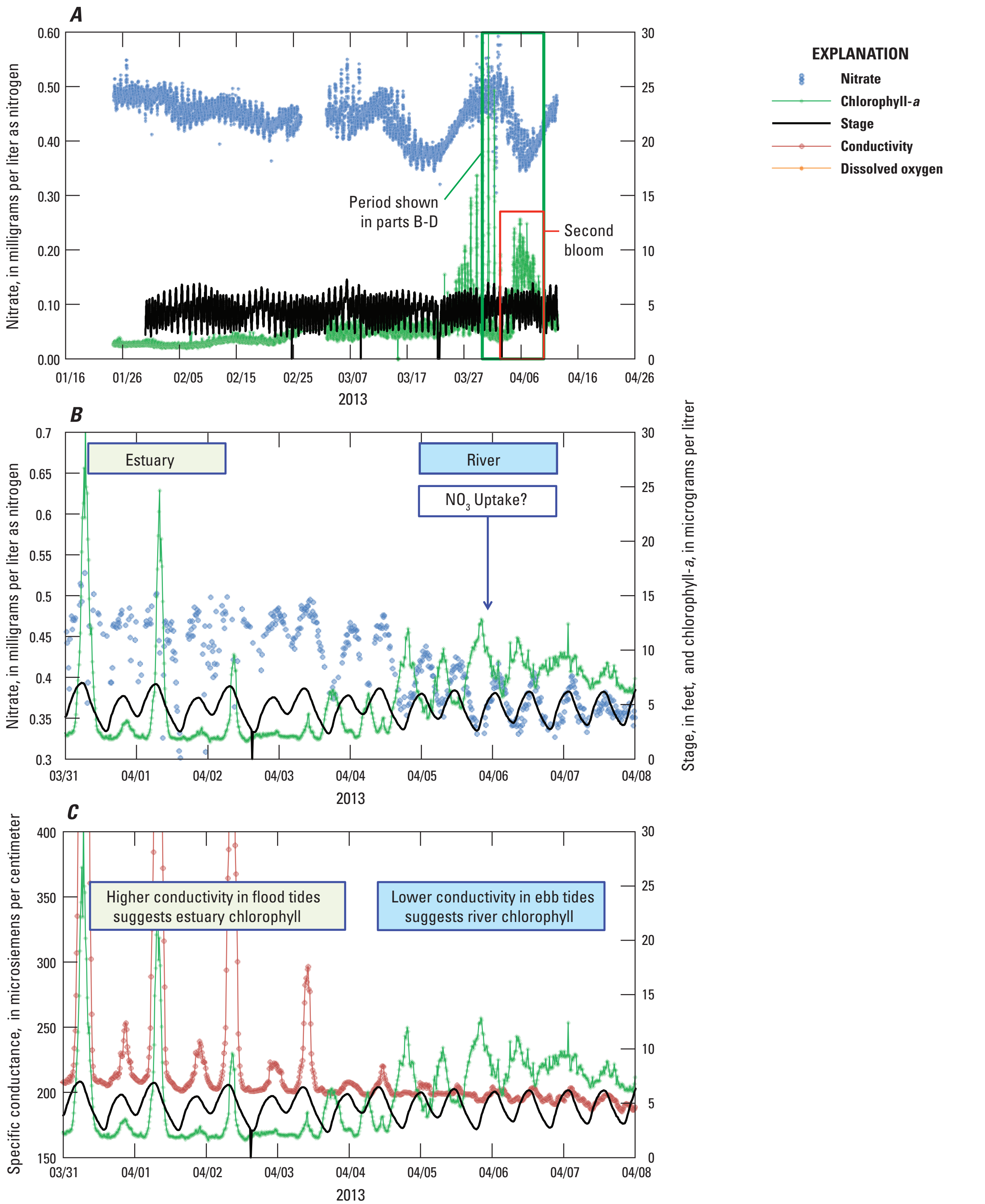

Figure 10. Time-series results for chlorophyll-*a* fluorescence, concentration of nitrate, dissolved oxygen, specific conductance, and water stage from the high-frequency monitoring stations at Decker Island (DEC, 11455478; *A*–*D*) and Cache Slough (CCH, 11455350; E), and location map for these monitoring stations (*F*), Sacramento–San Joaquin Delta, California, spring 2013. Examination of these data provides insight into where phytoplankton blooms originate. (See figure 6 and table 1 for additional details on stations and their locations. Data are available at https://waterdata.usgs.gov/nwis.)

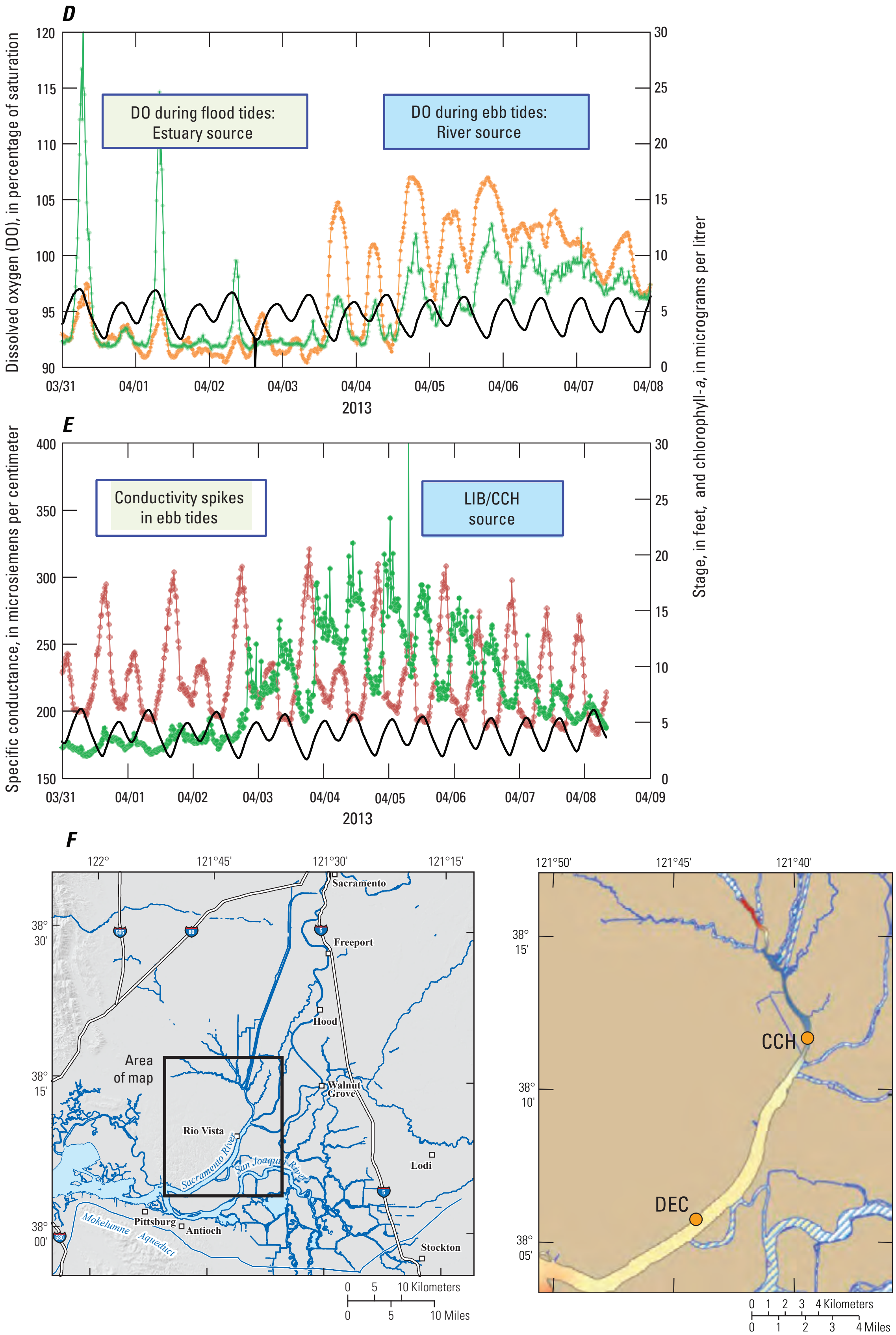

Figure 10.—Continued

Example 4—Assessing Nitrification Rates

Understanding the rate at which ammonium is converted to nitrate (nitrification) may help us identify controls on inorganic nitrogen concentrations and forms that affect San Francisco Estuary food webs. This is particularly relevant considering studies suggesting that the form and ratios of dissolved inorganic nitrogen (DIN) affect phytoplankton growth and species composition, may promote invasive aquatic vegetation, and may provide advantages to invasive clam and zooplankton species (Glibert and others, 2014, 2016). More specifically, it has been hypothesized that ammonium inputs from effluent discharged to the Sacramento River have the potential to negatively affect phytoplankton production by shifting DIN uptake from nitrate to ammonium (Dugdale and others, 2007; Parker and others, 2012; Senn and Novick, 2014; Wilkerson and others, 2015; Dahm and others, 2016; Kraus and others, 2017). The Sacramento River is the primary source of water and a phytoplankton seed source for the Delta, and effluent releases from the Sacramento Regional WWTP contribute high concentrations of ammonium at Freeport, about 50 km upstream of Rio Vista (fig. 1). Quantifying the rate at which this ammonium is converted to nitrate under changing hydrological, thermal, and other environmental conditions will help in the assessment of potential ecosystem effects of wastewater-derived ammonium, will enable improved management practices, and will help predict how changes such as WWTP upgrades will affect downstream nutrient dynamics.

Relevant to these concerns, the USGS operates monitoring stations equipped with HF nitrate sensors at two locations on the Sacramento River—the first one is located just upstream of the WWTP at Freeport and the second one is located 30 km farther downstream at Walnut Grove. Because HF flow data also are collected at these stations, the time it takes for water to travel between the two sensors can be calculated for each 15-minute time step. Taking travel time into account, the change in nitrate concentration (ΔNO_3, in milligrams per liter as nitrogen [mg/L as N]) also can be calculated for each time step, and the rate of concentration change can be calculated by dividing the change for each time step by the associated travel time (rate ΔNO_3, mg/L as N per day).

This was done for a 1-year period from September 2013 to September 2014 (fig. 11; O’Donnell, 2014). The HF data indicated that nitrate concentrations upstream of the WWTP (FPT station) typically were less than 0.3 mg/L, except during storm events when they increased to more than 1 mg/L, showing delivery of nutrients into the river upstream of Freeport. Comparison of HF data between the Freeport and Walnut Grove monitoring stations showed that nitrate concentration typically increases during travel down this 30-km stretch of river, supporting the idea that wastewater-derived ammonium is being nitrified; nitrate concentrations in effluent discharged into the river are less than the reported detection limit of 0.1 mg/L as N. However, during some periods of the winter months, nitrate concentrations are stable or decrease during transport, suggesting that rates of nitrate loss (uptake, denitrification, ammonification) are similar to or exceed the production of nitrate (nitrification, benthic release).

This study also was able to take advantage of monitored periods when wastewater effluent was not released into the river (typically owing to treatment plant maintenance or testing) to use HF nitrate data to estimate nitrification rates. This novel approach examined differences in riverine nitrate concentration measured in the presence of effluent compared to the absence of effluent, and ascribed this difference to nitrification of wastewater-derived ammonium. During the 1-year study, estimated nitrification rates varied seasonally, and were greater in summer (about 0.045 mg/L as N) than in winter (about 0.025 mg/L as N per day), which would be expected considering the higher summer water temperatures (O’Donnell, 2014). Assuming ammonium concentration just downstream of the WWTP was 0.5 mg/L as N (Foe and others, 2010), and nitrification rates that range from 0.026 to 0.045 mg/L as N per day, it would take 11–17 days to convert the entire ammonium pool to nitrate. However, with ammonium concentrations ranging from 0.3 to 1.0 mg/L as N, the time it would take could range from 7 to 36 days. These estimates, however, do not take into account other processes affecting the ammonium pool, such as biological uptake or releases from other sources, nor changes in nitrification rates that likely occur with downstream travel. The large range in estimated time to nitrify all the effluent-derived ammonium highlights the importance of quantifying not only nutrient concentrations and fluxes, but also the biogeochemical processes affecting them.

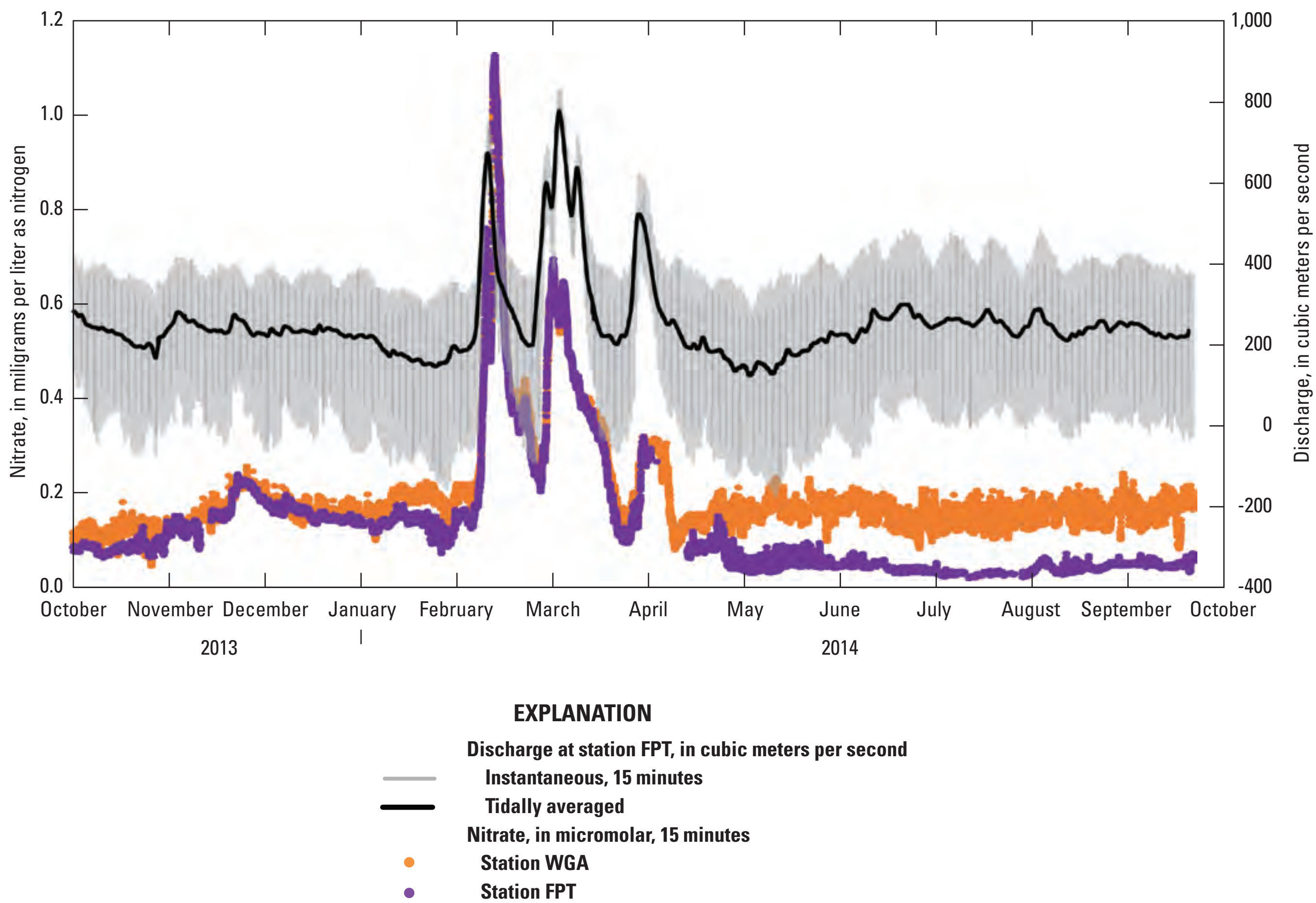

Figure 11. Time series showing instantaneous and tidally averaged discharge for the Sacramento River at Freeport (FPT; 11447650) and nitrate concentrations measured at continuous high-frequency, water-quality monitoring stations at FPT and Sacramento River near Walnut Grove (WGA; 11447890), California, 2013–14. Increases in nitrate concentration as water traveled downstream from stations FPT to WGA primarily can be attributed to nitrification of wastewater-derived ammonium. For details, see O'Donnell (2014). (See figure 6 and table 1 for additional details on stations and their locations.)

Example 5—Environmental Stoichiometry (Nutrient Ratios)

In addition to the concentration of individual nutrients, the ratios between different nutrients (for example, nitrogen to phosphorus [N:P], carbon to nitrogen [C:N], nitrate to ammonium [NO_3:NH_4]; referred to as nutrient stoichiometry) also has been shown to affect ecosystem structure and function (Glibert and others, 2011; Cloern and others, 2012; Paerl and others, 2014). Simultaneous HF measurement of concentrations of dissolved inorganic nitrogen (DIN, both nitrate and ammonium), dissolved organic carbon (DOC), and soluble reactive phosphate holds enormous potential to elucidate hydrologic and biogeochemical controls on nutrients that are difficult to detect using traditional, low-frequency sampling approaches.

A pilot study—whereby HF measurements of nitrate (every 15 minutes) and orthophosphate (PO_4, hourly) were collected concurrently with discharge measurements—was conducted in July 2015 on the Sacramento River at Walnut Grove (WGA, fig. 6) to examine the relationship between these two nutrients and gain insight into physical and chemical controls on their concentrations (fig. 12). Results showed that the ratio between molar concentrations of N in nitrate and P in phosphate varied by more than two-fold over this 2-week period. Patterns in these nutrient results in relation to the ancillary data (DO and discharge; fig. 12) highlight that diurnal, event, and seasonal factors all likely affect nutrient ratios.

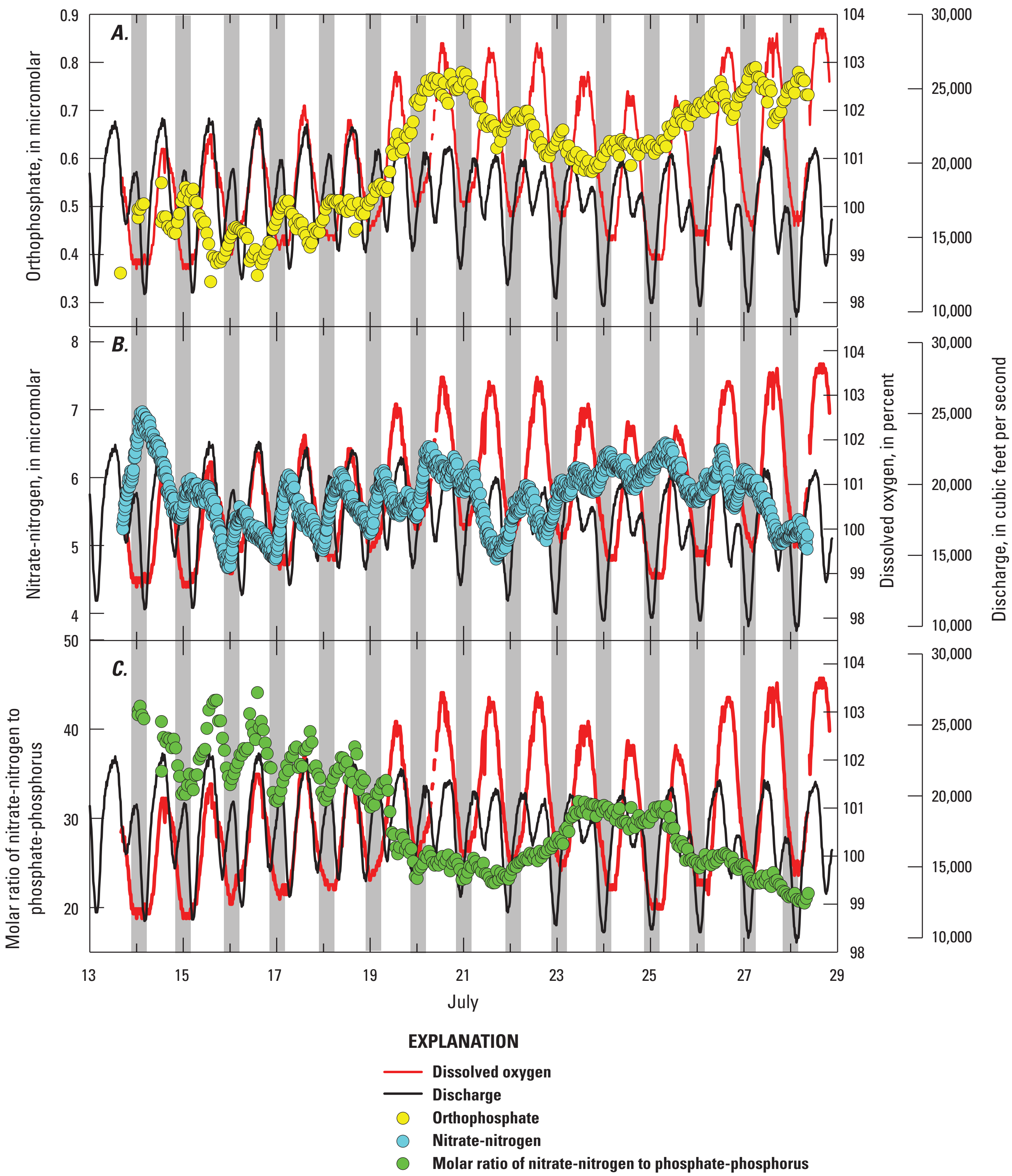

Figure 12. Time series from high-frequency monitoring of micromolar concentrations of orthophosphate (*A*), nitrate-nitrogen (*B*), and the molar ratio of nitrate-nitrogen to phosphate-phosphorus (*C*), at Sacramento River at Walnut Grove monitoring station (11447890), California, July 13–29, 2011. Discharge and dissolved oxygen data also are shown. (Data are available at https://waterdata.usgs.gov/nwis. For details see Downing and others, 2011.)

Example 6—Wastewater Detection and Mapping

In the case of wastewater detection, in situ sensors can be used to detect not only the presence and absence of effluent, but also to estimate the percentage of effluent in the water (Goldman and others, 2012) and to quantify wastewater-derived constituent concentrations. For example, in the Sacramento River, the presence compared to absence of effluent from Sacramento's Regional Wastewater Treatment Plant was clearly evident at the Walnut Grove monitoring station located about 30 km (18 mi) downstream; when effluent-free river water passed by the station, there were clear changes in nitrate, conductance, fDOM (a proxy for dissolved organic carbon concentration), DO, and pH (fig. 13; O'Donnell, 2014).

In addition to collection of HF data at fixed points, deployment of HF sensors on boats provides the ability to collect spatially high-resolution water-quality data, enabling the detailed mapping of wastewater concentrations in real time. Data collected along a reach of the Sacramento River following an extended effluent hold are shown in figure 14. The red-colored section of the river in figure 14 demarcates an approximately 15-km (10-mi) reach of waterway that was essentially effluent free, as indicated in this case by lower fDOM (fluorescent dissolved organic matter) concentrations. Similar patterns in conductivity and nitrate concentration were measured concurrently. These detailed mapping data were critical to the design of a later Lagrangian study that investigated the effects of wastewater effluent—and its attendant high ammonium concentrations—on phytoplankton abundance and species composition during transit down the lower Sacramento River (Kraus and others, 2017).

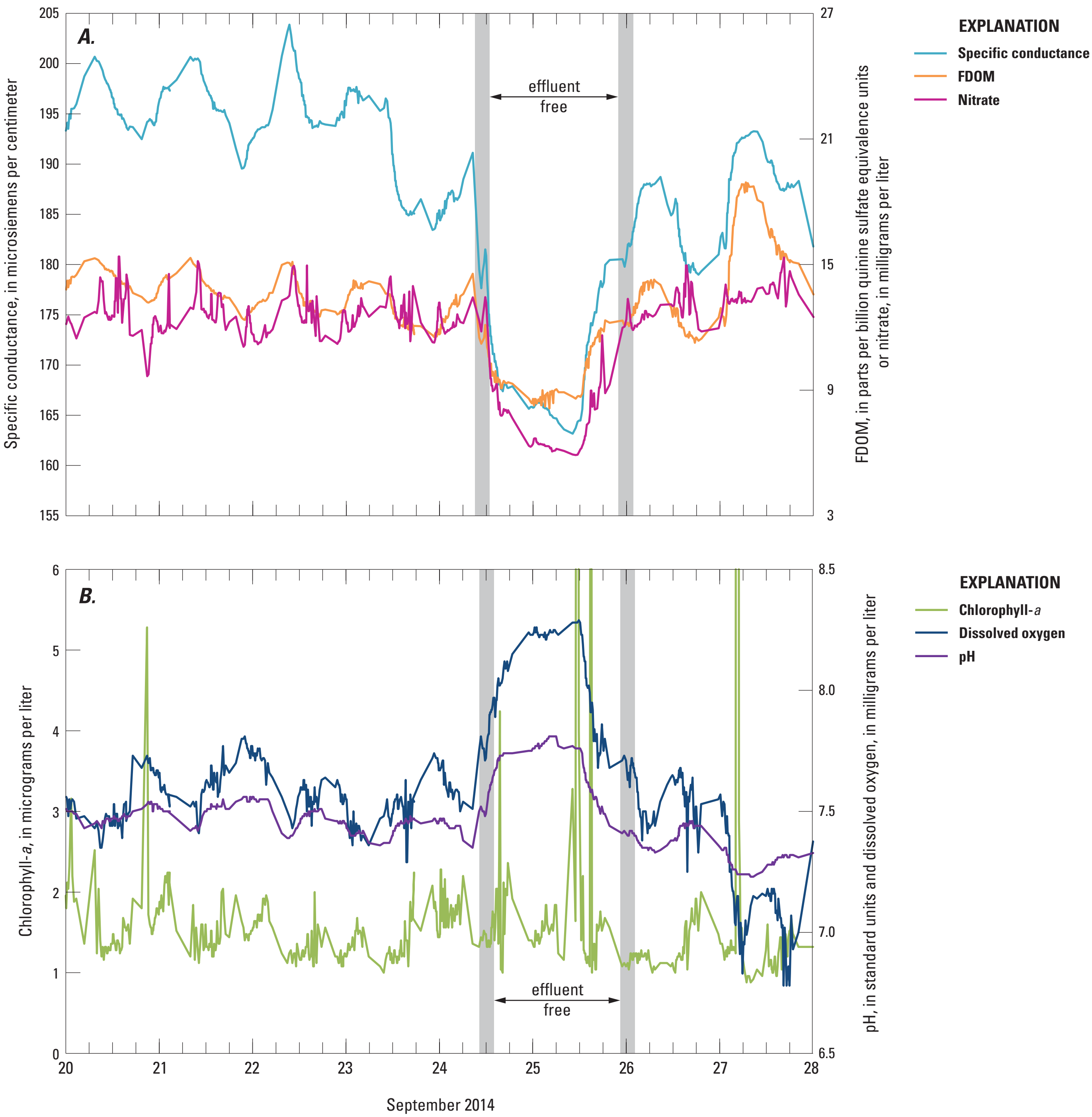

Figure 13. Time series of high-frequency water-quality data, Walnut Grove monitoring station (11447890; WGA) on Sacramento River, California, September 2014. Graphs show changes in constituent concentrations corresponding to vertical bars delimiting the time period (centered on September 25) when river flow was free of wastewater effluent from the Sacramento Regional Wastewater Treatment Plant, located about 30 kilometers upstream. *A*, lower values of specific conductance, fluorescent dissolved organic matter (fDOM) and nitrate concentration *B*, higher concentrations of dissolved oxygen and pH, but no clear effect on chlorophyll-*a* concentration. (Adapted from O'Donnell, 2014.) (See figure 6 and table 1 for additional details on the station and its location.)

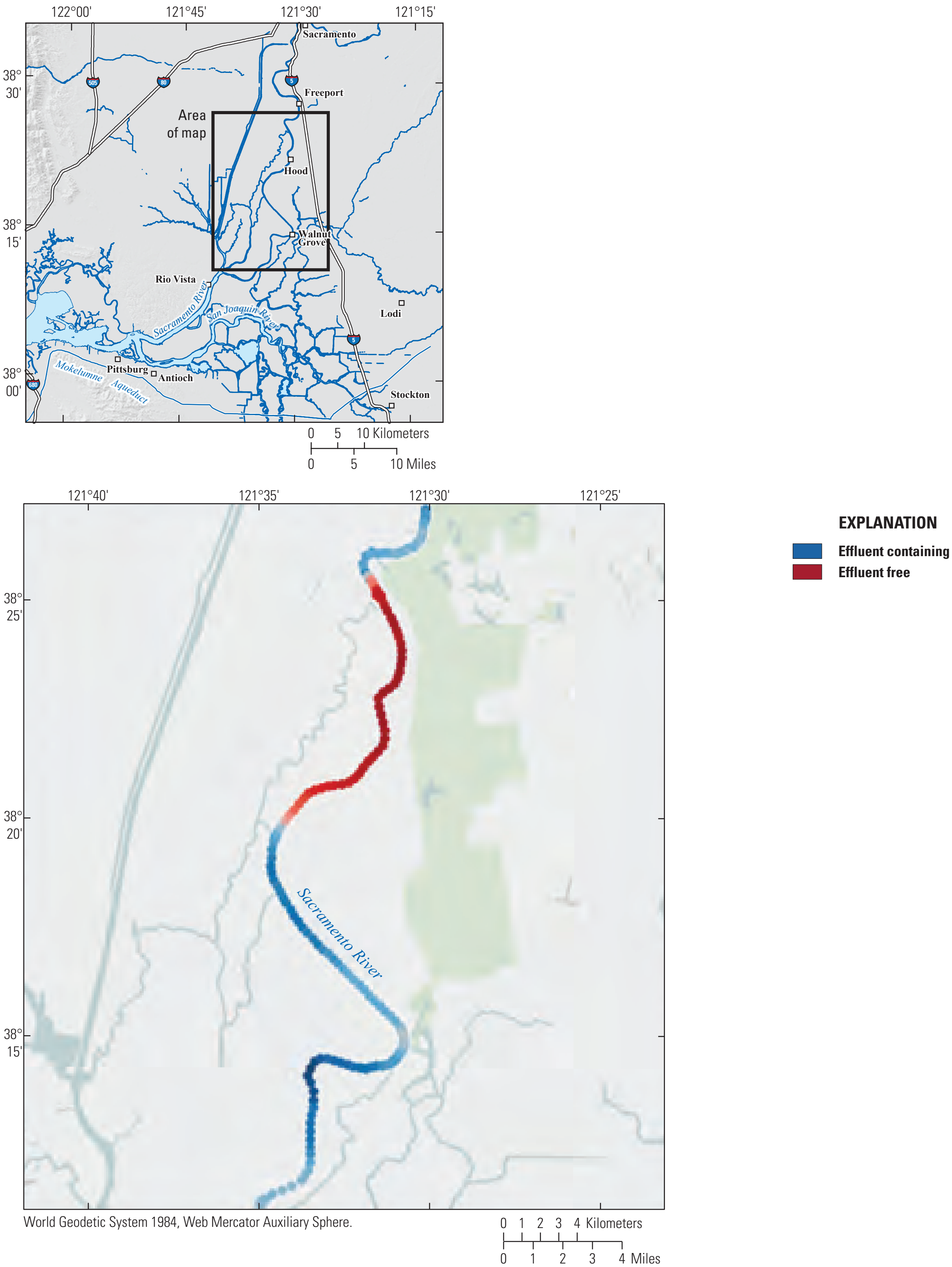

Figure 14. High-frequency dataset collected from a moving boat during an extended wastewater effluent hold showing clear demarcation between reaches with and without effluent, Sacramento River, California, 2014. Data were recorded using an in situ fluorometer sensitive to fluorescent dissolved organic matter (fDOM). (For details see Kraus and others, 2016, 2017.)

Example 7—Residence Time and Biogeochemical Processes

Water residence time (τ) is a master variable determining levels of nutrients, phytoplankton, zooplankton, suspended particles, and contaminants that affect aquatic ecosystem function in hydrologically complex freshwater ecosystems. In the Cache Slough Complex of the northern Delta, water bodies with longer residence times allow for phytoplankton biomass to accumulate and nutrients to be fully assimilated (Jassby and Powell, 1994; Cloern, 2001; Monsen and others, 2002, 2007).

High τ also can benefit phytoplankton species with slow growth rates such as cyanobacteria, allowing them to outcompete comparatively faster-growing taxa such as diatoms and green algae (Bacillariophyta and Chlorophyta). The frequency and magnitude of blooms of non-N_2-fixing phototrophic cyanobacteria, such as *Microcystis aeruginosa*, have greatly increased in parts of the Delta over the last decade, and changes in residence time are a likely contributing factor (Lehman and others, 2005; McDonald and Lehman, 2013; Paerl and Otten, 2016).

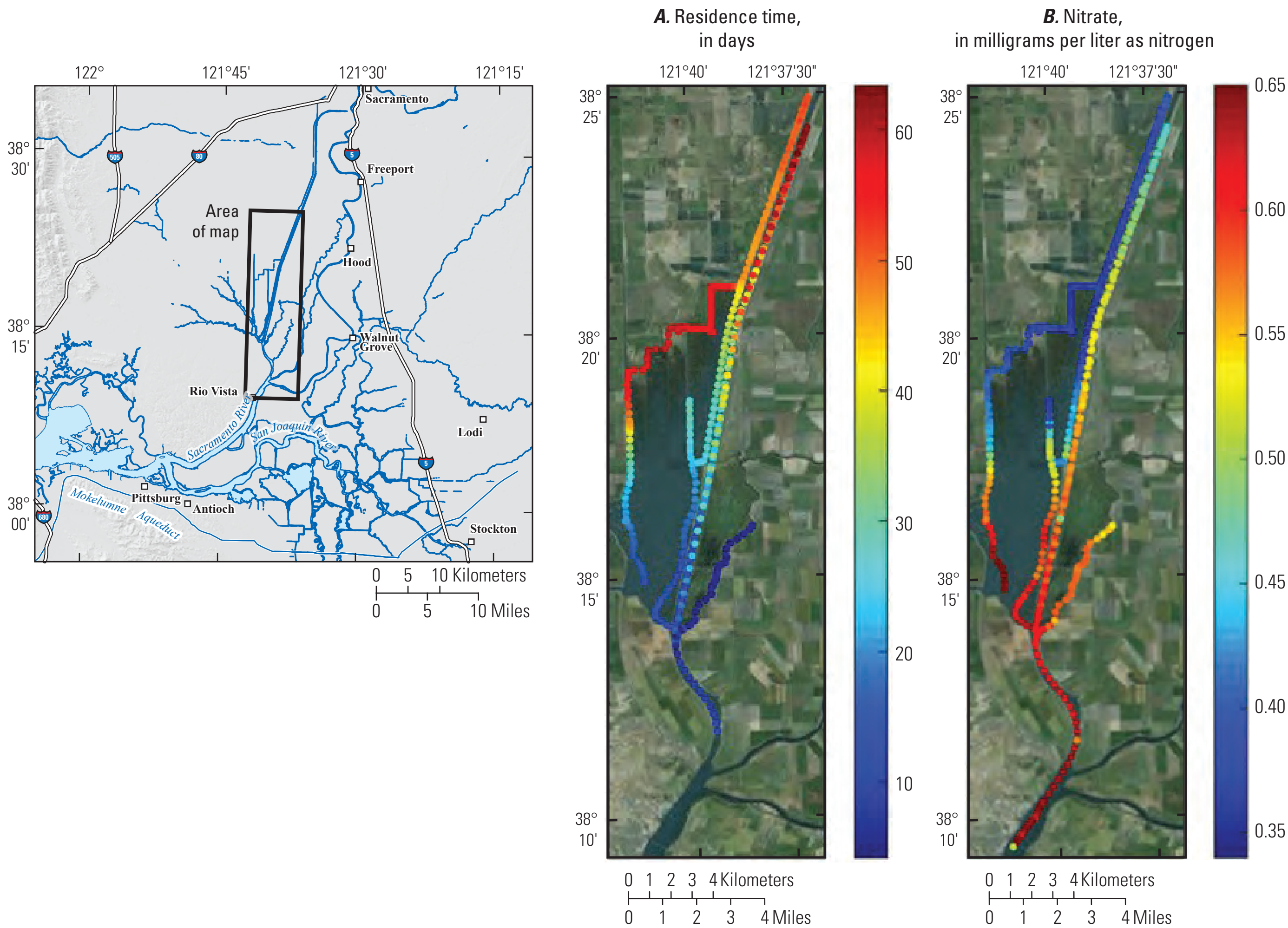

Figure 15. Concurrent high-speed mapping of *A*, residence time along with water-quality parameters, *B*, nitrate, *C*, chlorophyll-*a* fluorescence (fChl-a), *D*, pH, and *E*, dissolved oxygen, Cache Slough Complex, Sacramento–San Joaquin Delta, California. Maps showing spatial gradients provide insight into physical and biogeochemical processes. For details, see Downing and others (2016).

In a recent study (Downing and others, 2016), dual HF measurements of water isotopes (δ^2H, $\delta^{18}O$) were used to estimate the spatial distribution of residence time in the tidal environment of the Cache Slough Complex by means of high-speed boat transects (fig. 15). High-resolution maps of residence time and concomitant water quality measurements—including nitrate concentration—proved useful in identifying important biogeochemical processes such as phytoplankton production, and in estimating rates of nutrient retention in the area. Study results indicated that net ecosystem nitrate uptake differed across the Cache Slough Complex likely due to the variable extent of wetland and riparian vegetation, as well as hydrologic complexity. For example, net ecosystem nitrate uptake was higher in Prospect Slough, which has the greatest density of wetlands, compared to Shag Slough and the Deep Water Ship Channel (fig. 6).

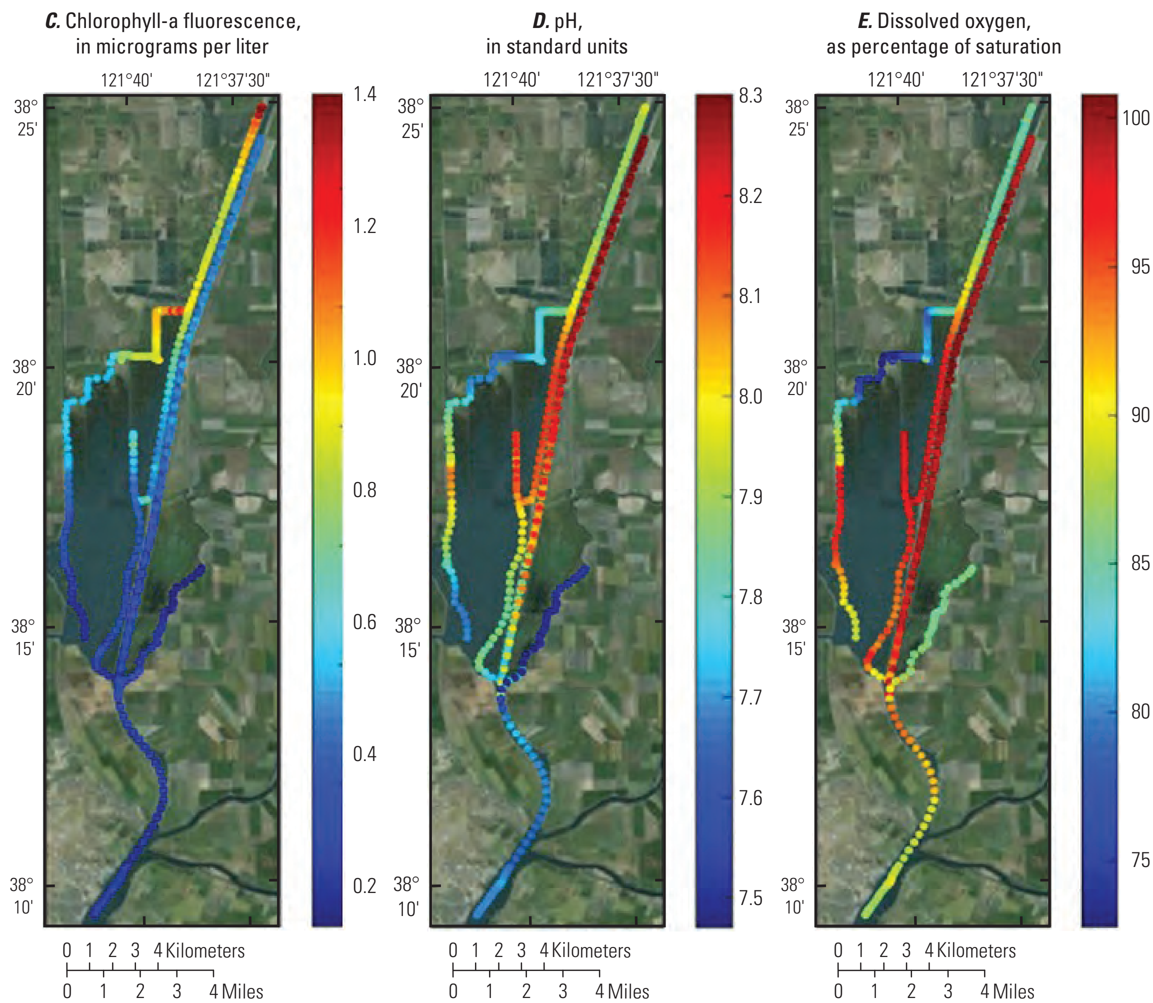

Figure 15.—Continued

Future Changes to Nutrient Loads and Ecosystem Processing

There is wide recognition that a nutrient monitoring program in the Delta should take into account known or anticipated changes to the Delta. These changes include, for example, expectations for population growth, changes in agricultural practices, wetland restoration, modifications to hydrology, expansion of urban areas, treatment plant upgrades, climate change, and potentially stricter water quality regulations.

Future changes in agricultural practices and intensity along with continued population growth are expected to increase nutrient loading to the Delta in the near- to mid-term (through 2050). To assess changes that may result from these drivers, Bergamaschi and others (2014) generated nutrient-load estimates based on prospective annual maps of land use and land cover over a range of population and development scenarios (International Panel on Climate Change scenarios A1, A1B, and B1) for 2006 through 2050, and using the USGS SPARROW modeling tool calibrated nationally with historical water quality measurements. Model results based on these scenarios suggest that fluxes of nutrients to the Delta will substantially increase over the next few decades. For example, nitrogen loading to the estuary could increase by 40 percent or more by 2050, relative to the baseline (fig. 16).

However, as Bergamaschi and others (2014) point out, this modeling approach assumes stationarity in the nutrient yield from each land-use type and does not take into account any changes induced by future regulatory or technological improvements. For the Delta, this point is particularly relevant considering that the Sacramento Regional WWTP is being upgraded presently (2017). Currently, treated wastewater effluent inputs from the Sacramento Regional WWTP are identified as the major contributor (about 95 percent) of ammonium to the Delta (Senn and Novick, 2014; Novick and others, 2015). The discharge of these inputs enters the Sacramento River just downstream of Freeport Bridge, about 50 km upstream of the Cache Slough Complex (fig. 1). The Central Valley Regional Water Quality Control Board (2010) issued a new National Pollutant Discharge Elimination System permit in 2010 requiring that the Sacramento Regional WWTP reduce average concentrations of ammonium in effluent entering the Sacramento River by spring 2021, from the current monthly average interim concentration limit of 39 to 2.4 mg/L as N (table 2). To meet these new regulations, the WWTP is upgrading their treatment process to include removal of ammonium by nitrification and excess nitrate by denitrification. The upgrades will not only decrease effluent ammonium concentrations by more than 95 percent, but also will decrease total dissolved inorganic N (DIN = $NH_4 + NO_3 + NO_2$) concentrations by 75 percent or more (table 2; http://www.regionalsan.com/echowater-project). There is no expectation that phosphate concentrations in treated effluent will change because of the treatment plant upgrade, or that changes in organic N concentrations will be substantial. However, there is potential for all effluent nutrient loadings to decrease to zero during summer months if the WWTPs effluent serves as a recycled-water supply for urban and agricultural uses, rather than being discharged to the river.

Table 2. Current and future planned regulatory limits on discharges of inorganic nitrogen (ammonium [NH_4] and nitrate [NO_3]), as an average monthly concentration in treated wastewater effluent at Sacramento Regional Wastewater Treatment Plant, California, and the estimated percentage of decrease in average concentration.

[**Source:** Central Valley Regional Water Quality Control Board (2010). **Abbreviations:** mg/L, milligram per liter. >, greater than; –, reduction unknown]

	Effluent limits		
	Current (mg/L as N)	Future (mg/L as N)	Estimated decrease
NH_4-N (April–October)	39	1.5	>96%
NH_4-N (November–March)	39	2.4	>94%
NO_3-N	10	10	–
Total inorganic-N	**49**	**12.4**	**>75%**

Another driver affecting future nutrient concentrations is the changing landscape of the Delta. The concentrations and spatial distribution of nutrients in the Delta will be altered, for example, by wetland restoration and the expanding abundance of submerged aquatic vegetation. Both occurrences exert a demand for nutrients and result in particulate-trapping habitats, that are already having documented effects on nutrient concentrations and distributions. Both also alter water velocities and change residence times, affecting the use of nutrients by phytoplankton and nutrient transformation by bacteria. Certainly, large-scale changes to the Delta, such as those currently proposed by the California Water Fix program (https://www.californiawaterfix.com/)—which would re-route freshwater from the Sacramento River around the Delta to more reliably supply the State and Federal water pumping facilities located in the Southern Delta— and California Eco Restore (http://resources.ca.gov/ecorestore/)—which would restore large expanses of wetlands—would have substantial effects on nutrient supply and cycling. A modern HF monitoring network provides critically needed data for understanding, anticipating, and managing these and other effects on the continually evolving Delta ecosystem.

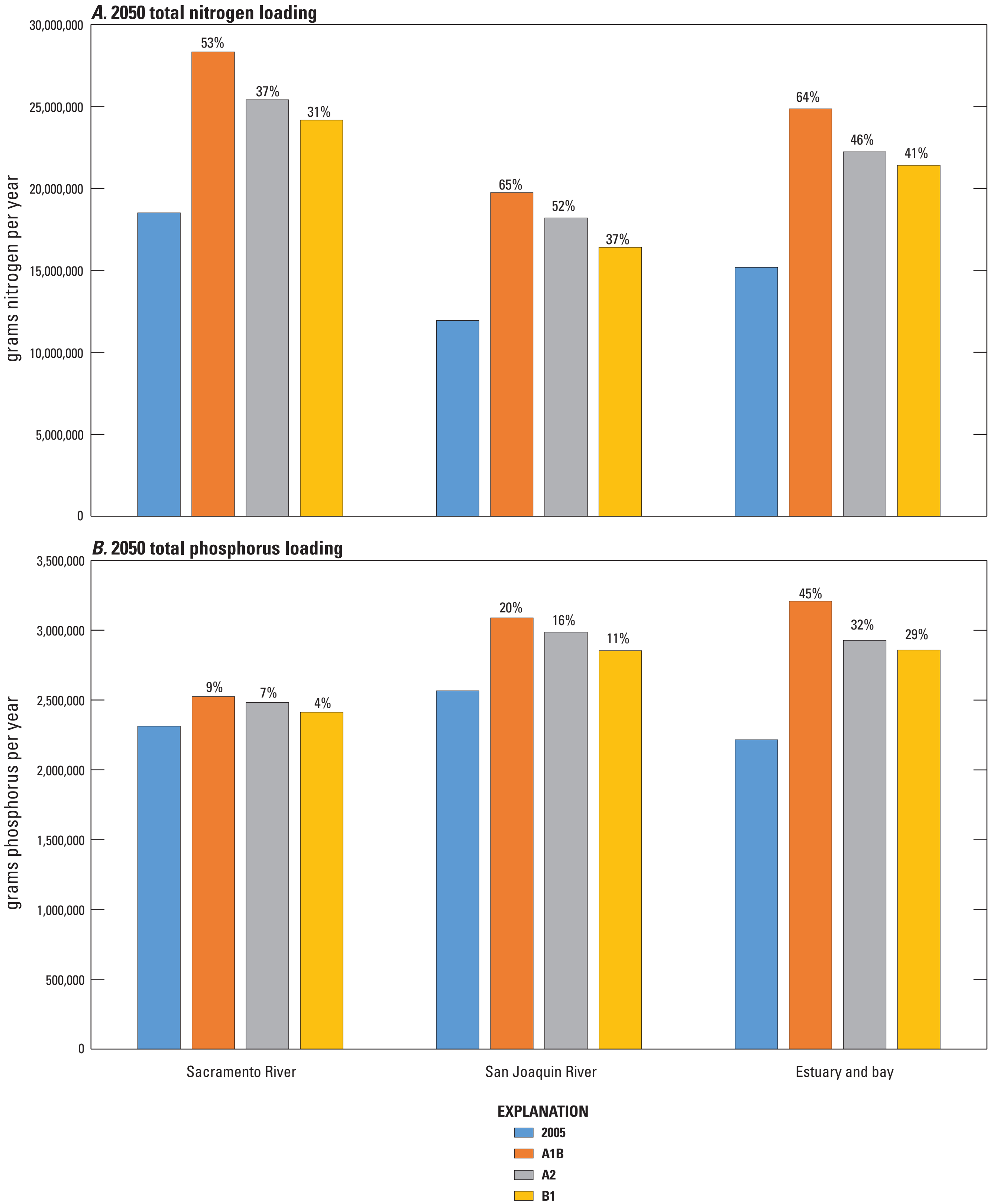

Figure 16. Prospective increases in total nitrogen (*A*) and total phosphorus (*B*) loadings annually to the Sacramento and San Joaquin Rivers and the San Francisco Estuary and Bay, California, in 2050 compared to 2005 under International Panel on Climate Change development scenarios A1B, A2, and B1, based on a USGS SPARROW model calibrated nationally. Bar height indicates total annual loading, and percentage above each bar indicates percentage increase relative to 2005 baseline. For study details, see Bergamaschi and others (2014).

Summary

This report provides background information about the utility of high-frequency (HF) nutrient and biogeochemical monitoring, and briefly describes recent advances in nutrient-sensor technology. The attributes that make up a comprehensive HF nutrient monitoring network were outlined. In addition to providing a review of recent literature on this topic from studies of aquatic ecosystems worldwide, we provided a number of examples illustrating how collection of HF nutrient data in the Sacramento–San Joaquin Delta (the Delta) has provided information and insights that cannot be easily gained from other approaches. Collection of HF data has allowed scientists, managers, and policy makers to:

- More accurately quantify nutrient fluxes and loads both external and internal to the Delta;
- Determine rates of nutrient processes such as nitrification and uptake;
- Identify diurnal, seasonal, and event-driven controls on nutrient concentrations and forms; and
- Identify ecosystem effects.

Two companion reports (Bergamaschi and others, 2017; Downing and others, 2017) in this series provide more information about the HF water-quality monitoring network that is operated by the U.S. Geological Survey (USGS) in the Delta and includes more detailed discussion of factors that were taken into consideration when designing the USGS HF monitoring program.

Acknowledgments

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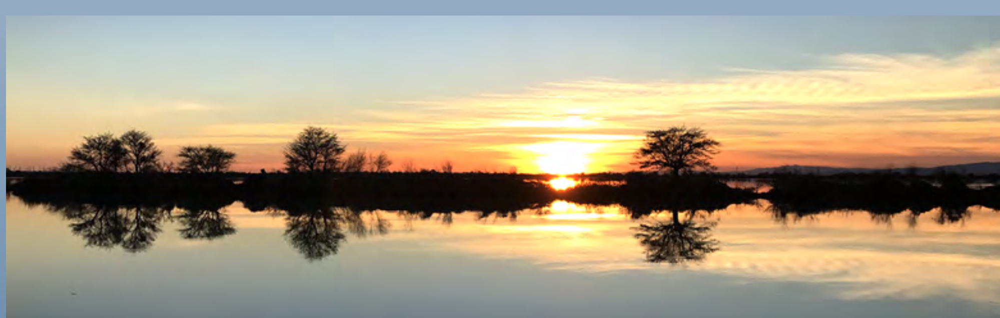

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