Summary and Evaluation of Delta Subregions for Nutrient Monitoring and Assessment

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Appendix 3. Power Analysis of Nutrient Monitoring in the Delta.

Appendix 4. Monitoring coverage of aquatic habitat in the Delta (Supplementary Materials).

1. Executive Summary

The Delta is a complex and heavily altered ecosystem, comprised of a diverse set of subregions and habitats. Loads of anthropogenic nitrogen (N) and phosphorous (P) enter the Delta from a number of sources, including treated wastewater effluent, agricultural runoff, and stormwater runoff. Subregions of and individual habitats within the Delta respond differently to these N and P inputs, and also influence nutrient concentrations differently, as evidenced by the large degree of spatial variability in ambient water quality (e.g., Novick et al. 2015).

Sound water quality management decisions in the Delta will require long-term monitoring data that capture the wide range of conditions at spatial and temporal resolutions sufficient to ensure that nutrient status and trends are being accurately characterized. Therefore, the Delta Science Program provided funding to the Aquatic Science Center (ASC) to synthesize nutrient data and analyses to identify options for optimizing the design of a status and trends nutrient monitoring program for the Delta. Specific goals were to:

1. Summarize, compare, and recommend potential subregions to be used for monitoring and assessing nutrients in the Delta;
2. Investigate spatial and temporal patterns in nutrient trends and potential drivers of these patterns relative to proposed subregions;
3. Evaluate if the current nutrient monitoring design is sufficient to characterize nutrient status and trends in proposed subregions; and
4. Assess the current monitoring coverage of different aquatic habitat types within each of the proposed subregions.

This work was conducted under the assumption that a status and trends monitoring program for nutrients in the Delta should cover all distinct subregions and representative habitats, and be able to detect trends of ecological and management interest. Based on this assumption, the report identifies limitations of the current monitoring efforts and detailed options for improving the nutrient monitoring program based on a careful review of existing data. For water quality data, we focused primarily on multi-decade monthly monitoring data collected by the CA Department of Water Resources Environmental Monitoring Program (DWR-EMP), and on a few examples of high-frequency data, where noted. The results are intended to be useful to Delta resource managers involved in the planning and design of water quality monitoring programs, including the Delta Science Program, DWR-EMP, Delta Regional Monitoring Program, and others.

What are potential subregions for monitoring and assessing nutrients in the Delta?
Seven subregions appear to be sufficient to distinguish among areas that experience distinct physical and biogeochemical drivers that will influence nutrient dynamics or nutrient-related responses in the Delta. The proposed subregions are (Figure 1.1; from north to south): Sacramento River, North Delta, Eastside, Suisun Bay, Central Delta, Confluence, and South Delta. The proposed subregions are derived from operational landscape units (OLUs), which are a newly developed planning tool for landscape-scale ecosystem restoration in the Delta (Grenier and Grossinger 2013). The OLU delineations are based on ecosystem functions and physical drivers such as water source and hydrology; therefore, there is a mechanistic linkage and scientific foundation for their use in the context of nutrient conditions and

cycling. Our review also suggests that the proposed subregions are compatible with the DMS2 hydrologic model and are in general agreement with water quality regions used by major monitoring programs.

Are nutrient trends and their potential drivers different across proposed subregions?
A statistical time-series analysis was employed to characterize nutrient variability within and across subregions of the Delta and assess similarities and differences in underlying drivers. The employed method was non-negative matrix factor (NMF) analysis, which was chosen because it facilitates physical interpretation of detected factors as potential drivers of variability.

We examined patterns of variability in nutrient concentrations and relevant ancillary data (nitrate, ammonium, phosphate, chlorophyll *a*, etc.), both *across* the seven subregions, and, when possible, within subregions. The results from the NMF analysis suggest that there are significant differences in the relative importance of underlying drivers of nutrient cycling *across* the seven subregions, which supports the notion that these subregions are indeed distinct from the perspective of nutrient cycling and ecosystem response to nutrients.

For the analysis of variability *within* subregions using contemporary data, we focused on the Suisun Bay and Central Delta subregions, because these are the only two subregions that contain more than one active monthly monitoring station. The NMF analysis detected considerably different patterns of variability for nutrient-related parameters between Central Delta stations, suggesting there are important differences in the relative strength of underlying drivers of nutrient cycling. In contrast, Suisun Bay was found to be a rather homogeneous subregion at monthly-monitoring time scales, with similar patterns of variability observed at all three stations. Absolute nutrient concentrations did differ between Suisun stations; but both the timing and the relative magnitude of variability were similar.

While the Confluence and South Delta subregions each contain only one active long-term monitoring station, prior to 1995 they each contained multiple stations. Thus, to examine variability within these subregions we used pre-1995 data. The analysis of the pre-1995 data suggests that the Confluence and South Delta exhibited moderately heterogeneous patterns of variability, i.e., intermediate between the strong heterogeneity observed in the Central Delta and the strong homogeneity among Suisun stations (Figure 4.7). The spatial variability in the Confluence and South Delta subregions appears to occur mostly along gradients representing flow paths (e.g., in the Confluence subregion along the Sacramento River) or gradually changing peripheral influences (e.g., transition from Sacramento to San Joaquin River influence).

Spatial variability within the Sacramento River, North Delta, and Eastside subregions could not be evaluated, because there is only one DWR-EMP water quality monitoring station in the Sacramento River subregion and none in the North Delta and Eastside subregions.

Is the current monitoring design sufficient to characterize nutrient status and trends in proposed subregions?
We performed historical trend analysis and statistical power analysis to evaluate the capability of the current monitoring network to detect long-term trends. The historical trend analysis examined if trends were detected with DWR-EMP monitoring data. The power analysis evaluated whether increasing the

number of stations or the sampling frequency will significantly improve our ability to detect seasonal, temporal, and spatial trends. A key assumption for this analysis was that the DWR-EMP would continue to serve as a core program for the collection of regional monitoring data for nutrients. We specifically examined a) if trend detection could be improved by resuming monitoring of discontinued stations; and b) if continuous sensor monitoring could provide better long-term trend detection capabilities than discrete monthly grab sampling.

A general observation is that the current DWR-EMP sampling does not cover all proposed subregions, and thus, therefore cannot be considered sufficient to characterize nutrient status and trends in all subregions. There are currently no DWR-EMP sampling stations in the North Delta and the Eastside. The U.S. Geological Survey (USGS) has installed 5 moored sensors in the North Delta that are generating data since August 2013. However, these sensors do not completely fill the gap, because they currently only measure nitrate and none of the other nutrient variables, such as ammonium or phosphate. Other programs are monitoring nutrients at stations located in the North Delta and Eastside, but their monitoring is currently not coordinated with the DWR-EMP in terms of parameters analyzed, frequency and timing of sampling, and comparability of data.

The results from the historic trends analyses and also from the power analysis suggest that adding more discrete sites could be beneficial for a few parameters and subregions to improve the ability to detect regional or subregional long-term trends. In historic trend analyses (using regional Kendall tests), results were nearly identical when active sites and all sites (active plus discontinued, pre-1995 data) were tested. Although one potential interpretation of this comparison is that the discontinued stations would not have influenced our interpretation of trends, power analysis results provide a different perspective. The power analysis, based on an assumed criterion of detecting a 50% change over 10 years, suggests that monthly water quality monitoring should be resumed at some of the deactivated stations in order to have sufficient statistical power to detect trends for ammonia and chlorophyll *a* in some subregions.

Results suggest that strategically placed high-frequency sensors have the potential to significantly improve trend detection capabilities for those parameters for which reliable sensors are available (e.g., chlorophyll-a and nitrate). Because sensors do not capture all the variables of interest, monthly water quality sampling sites should be co-located with continuous sensors. Options for continuous monitoring of nutrients in the Delta with in-situ sensors will be presented in an upcoming report from USGS (Bergamaschi et al., in press). The recommendations from this report (including power analysis results) along with the upcoming USGS report should be considered together to develop recommendations for additional continuous monitoring in the Delta.

Is the current monitoring representative of different aquatic habitat types?

The analyses presented here reveal significant data gaps in terms of aquatic habitat coverage. By design, current monitoring does not evenly cover all aquatic habitat types. Most of all, there is currently not any systematic nutrient monitoring for wetlands in the Delta. There is also no systematic monitoring of dead-end sloughs and shallow margin areas.

Conclusions
This study concludes that the Delta can be divided into 7 subregions for the purpose of status and trends monitoring of nutrient-related parameters. The existing DWR-EMP monitoring program has at least one station in 5 of these 7 regions but only in the deep-water habitats, not wetland areas. In terms of trend detection, the existing monthly monitoring program can, in general, detect a trend of 50% change over 10 years for most parameters investigated here. A 50% change in a water quality parameter represents a large change in ecosystem condition, and it may be necessary or desirable to identify smaller trends. Improved trend detection appears possible through well-planned placement of sensors for nitrate, chlorophyll-a, and possibly other parameters that can be measured with high-frequency in-situ sensors. To best capture nutrient variability and trends across and within proposed subregions, a sensor network and a discrete sampling program should be planned to complement each other. Modeling, advanced statistical analyses, and targeted monitoring should be used to plan and optimize the monitoring program. A detailed list of the specific options for improvements to the existing nutrient monitoring program is in Section 7.

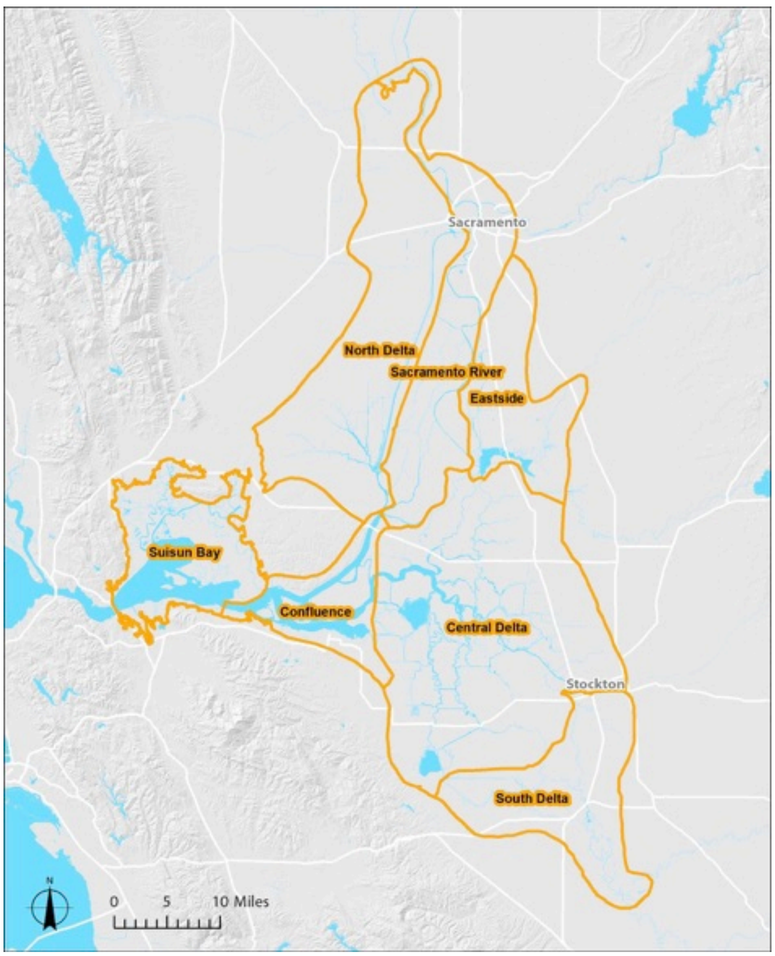

Figure 1.1. Proposed subregions for nutrient analyses. These subregions are derived from operational landscape units (OLUs), which are a proposed planning tool for landscape-scale ecosystem restoration in the Delta (Grenier & Grossinger 2013).

2. Introduction

The Delta plays an important role in shaping nutrient conditions in the San Francisco Estuary, and at the same time, it also provides important ecological habitat that is shaped by nutrient conditions and by the processes that are controlling them. Monitoring of nutrients and nutrient-associated variables will need to be designed to provide information on conditions and changes in conditions on appropriate temporal and spatial scales. This information is especially important, because large-scale ecosystem restoration and water quality improvement projects are on the way in the Delta, which might result in significantly reduced nutrient conditions within the upper estuary.

Previous work has documented a large degree of spatial variability in nutrient loads, concentrations, and losses across different geographic monitoring locations in the Delta (Novick et al. 2015), suggesting a subregional approach to data analysis. Dividing the Delta into subregions for use in nutrient monitoring and assessment will fulfill two important needs: 1) allow a comparison of trends and processes across and within subregions to gain a better understanding of the observed spatial variability and the underlying processes, and 2) provide more accurate region-wide estimates by stratifying the overall sampling frame.

Researchers have subdivided the Delta for various purposes, but not yet specifically to inform the design of monitoring for nutrients.

The primary purpose of this report is to provide useful information and planning material for optimizing the design of a nutrient monitoring program for the Delta. Specific goals are to:

1. Summarize, compare, and recommend potential subregion delineations for monitoring and assessing nutrients in the Delta;
2. Investigate spatial and temporal patterns in nutrient trends, and physically interpret potential drivers of these patterns within and across Delta subregions;
3. Evaluate if the current nutrient monitoring design is sufficient to characterize nutrient status and trends in Delta subregions; and
4. Assess the coverage of operationally defined aquatic habitat types by current nutrient monitoring efforts.

To achieve these goals, analyses were designed to evaluate the following working hypotheses:

1. The Delta has been divided into subregions for different purposes by different programs. Many of these subregions are similar or overlap suggesting that a small number of subregions are sufficient to characterize variability in the Delta. It is expected that the dominant factors affecting nutrient concentrations are similar within each subregion and are distinct from those in other subregions.
2. Within each subregion, the DWR-EMP nutrient monitoring program (number of stations, frequency, parameters) is sufficient to characterize nutrient status and trends in response to loads in the open channel habitats.
3. Within other habitats of the Delta (e.g., wetlands, back sloughs, littoral area), the EMP nutrient monitoring program is not sufficient to characterize status and trends in nutrients and nutrient-related variables (DO, phytoplankton, toxins).

3. Review of existing subregion delineations

3.1. Approach

The goal of this project element was to compile, review, and propose potential subregions for monitoring and assessing nutrients in the Delta. Researchers have subdivided the Delta for various purposes, but not yet specifically to inform the design of monitoring for nutrients. Therefore, the purpose of this review was to:

1. Summarize and compare existing delineations that are potentially relevant for monitoring and assessing nutrients;
2. Based on this review, recommend potential subregion delineations for monitoring and assessing nutrients in the Delta

The review extended to existing approaches that have been used to break the Delta into subregions for water quality monitoring and assessment, hydrologic and water quality modeling, and ecosystem process-based habitat restoration (Table 3.1). The screening process considered spatial coverage, relevance to nutrient management, agreement with groupings of Delta monitoring stations based on statistical analysis of water quality data, utility for multiple purposes (e.g., modeling and monitoring), and agreement with other existing delineations.

Table 3.1. List of reviewed subregions of the Delta.

Subregions	Summary	Source
Water quality regions	DWR-EMP water quality sampling sites represent eight regions of the Bay-Delta system. The eight regions include San Pablo Bay, Suisun Bay, and six Delta subregions.	DWR (2012)
Water quality subregions	In order to estimate mean Delta-wide aquatic productivity, biomass, and other water quality characteristics, Jassby and Cloern (2000) divided the Delta into eight subregions with similar nutrient concentrations and related biogeochemical parameters.	Jassby & Cloern (2000)
Regions of the upper estuary	Regions based on individual and combined hierarchical cluster analysis of monthly data for 14 physical and chemical variables and chlorophyll *a* concentrations.	Lehman (1996)
Regions with similar phytoplankton communities by season	Grouping of monitoring sites into geographic regions which had similar phytoplankton communities over time, determined by cluster analysis of site-year phytoplankton data.	Lehman & Smith (1991)
Benthic macrofaunal assemblages	Hierarchical cluster analysis of macrobenthic species abundance data was used to identify the benthic assemblages that occur in the San Francisco Estuary and Delta.	Thompson et al. (2013)
Hydrology-based delineation of subareas within the legal Delta and Yolo Bypass	The methylmercury source analysis and linkage analysis for the Delta MeHg TMDL divided the Delta into eight regions based on hydrologic characteristics and mixing of source waters.	Wood et al. (2010)
QUAL-Nutrient parameterization regions	The region boundaries are set to define hydrodynamically similar areas in the Delta.	Guerin (2015)

Habitat area specialization	Ecosystem areas as regions for a reconciled Delta.	Moyle et al. (2012)
Conservation zones	Conservations zones are geographic areas defined by the biological needs of the species covered under the Bay-Delta Conservation Plan. Conservation zones were identified based on landscape characteristics, land elevations, particular land features likely to be present at specific elevations, and land uses.	DWR (2013)
Potential operational landscape units (OLUs)	Draft OLU boundaries were developed to represent restoration opportunity areas based on an understanding of ecological functions, physical drivers, and elevation gradients.	Grenier & Grossinger (2013)

Subregions based on operational landscape units (OLUs) were selected as a forward-looking choice (Grenier & Grossinger 2013). OLUs are a proposed planning tool for landscape-scale ecosystem restoration in the Delta. Subregions based on OLUs are expected to facilitate the coordination of nutrient monitoring, assessment, and management with ecosystem restoration efforts. The OLU delineations are based on ecosystem functions and physical drivers such as water source and hydrology; therefore, there is a mechanistic linkage and scientific foundation for their use in the context of nutrient conditions and cycling. In addition, subregions based on OLUs would be compatible with DSM2-based modeling and are in reasonable agreement with water quality regions used by major monitoring programs.

The original OLUs are a draft product of an ongoing project and have not yet been finalized. A number of modifications were made to the draft OLUs to improve their use for the nutrient subregions. The modifications were based on a detailed review of the OLU boundaries in relation to hydrologic features, watershed boundaries, and DSM2 modeling requirements (see Appendix 1 for details). A land cover analysis was applied to characterize and compare differences between proposed OLU-based subregions.

3.2. Results and Discussion

The resulting subregions proposed here include the 6 modified OLU-based subregions and an additional subregion for Suisun Bay (Figure 3.1). The original draft OLU boundaries consider ecological functions, physical drivers, opportunity areas, major constraints, and elevation gradients. There are considerable differences in land cover distribution among these subregions (Table 3.2, Figures 3.2 and 3.3). Agriculture is the dominant land cover in most of the Delta regions, covering 56% of all Delta subregions combined, whereas wetlands are covering 86% of the Suisun Bay subregion[1]. The proposed subregions and their key features are:

North Delta. The North Delta includes the Yolo Bypass, Liberty Island/Cache Slough Complex, and the Sacramento Deep Water Ship Channel. The North Delta also has the highest proportion of wetland and riparian land cover (14%) of all Delta subregions.

[1] An analysis of the impacts of hydrological connectivity on the potential influence of land use on water quality was beyond the scope of this project.

Sacramento River. The Sacramento River subregion includes and is influenced by large urban areas within its boundaries. However, agriculture is the dominant land use and accounts for 57% percent of the land cover compared to 15% urban.

Eastside. The Eastside subregion includes the lower Mokelumne and Cosumnes rivers and Stone Lakes. Agriculture is dominant land cover type (45%), followed by urban (13%), and wetland/riparian (9%). The Eastside subregion has a slightly higher proportion of grassland/woodland (7%) compared to other subregions.

Central Delta. The Central Delta is a transition zone with drowned islands, tidal influence, and multiple influences from surrounding regions. It is also the subregion with the highest proportion of agricultural land cover (70%).

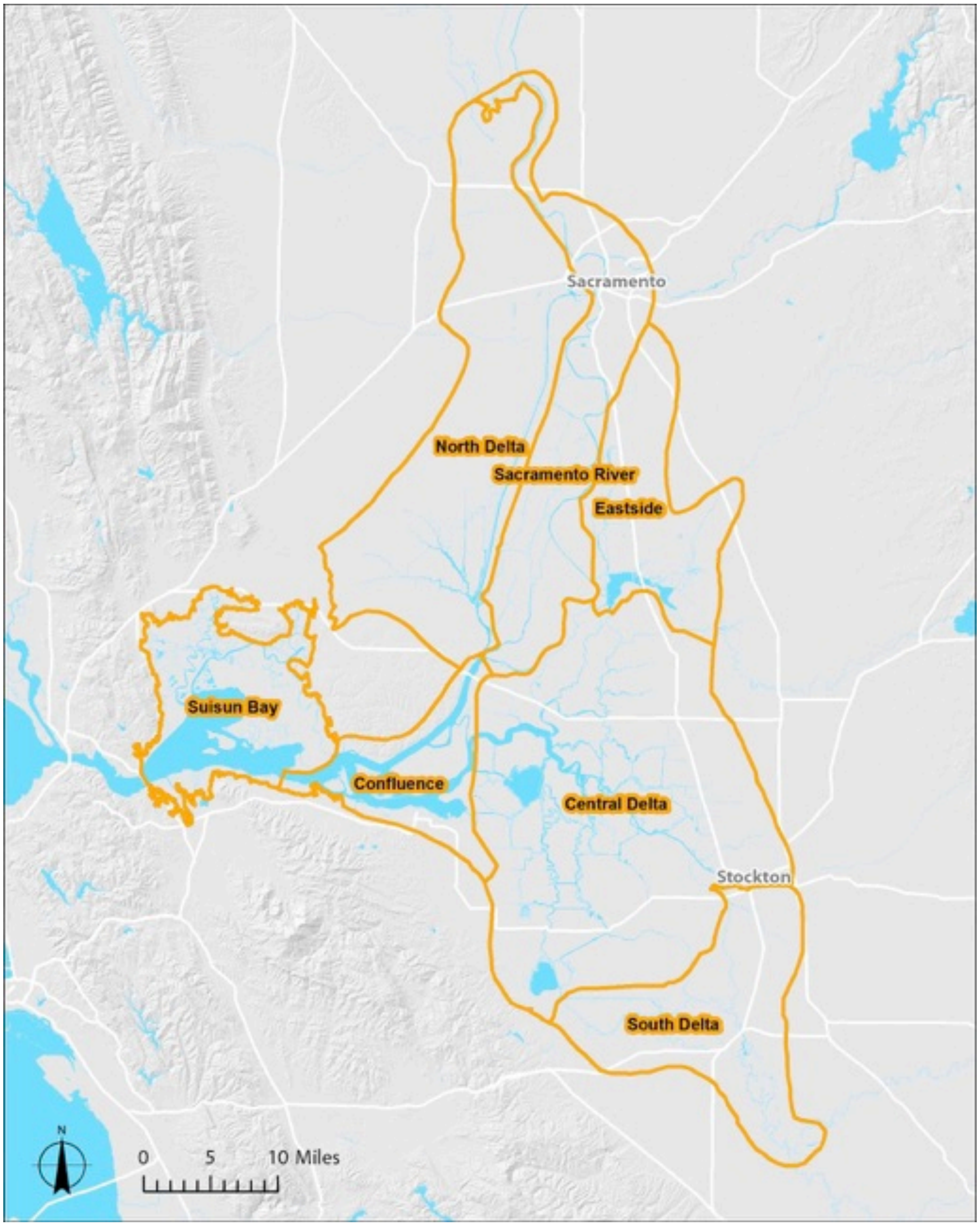

Figure 3.1. Proposed subregions for nutrient analyses, derived from potential OLUs.

Table 3.2. Land cover summary table.

	Subregions (Land cover in acres and percent)						
Land Cover	Central Delta	Confluence	Eastside	North Delta	Sacramento River	South Delta	Suisun Bay
Agriculture	221,944 (70%)	15,094 (24%)	40,581 (45%)	116,270 (53%)	74,632 (57%)	65,706 (56%)	0 (0%)

Grassland/Woodland	7.977 (3%)	3,455 (6%)	6,002 (7%)	10,365 (5%)	1,096 (1%)	1,805 (2%)	0 (0%)
Urban	30,219 (9%)	2,674 (4%)	12,031 (13%)	6,526 (3%)	19,719 (15%)	16,595 (14%)	0 (0%)
Water	28,042 (9%)	18,682 (30%)	2,362 (3%)	11,246 (5%)	5,777 (4%)	3,558 (3%)	27,471 (29%)
Wetland/Riparian	14,960 (5%)	6,842 (11%)	8,347 (9%)	30,278 (14%)	3,008 (2%)	2,861 (2%)	57,914 (60%)
Unclassified*	15,068 (5%)	15,803 (25%)	20,543 (23%)	42,753 (20%)	27,554 (21%)	26,009 (22%)	10,818 (11%)
Total	318,210 (100%)	62,550 (100%)	89,866 (100%)	217,337 (100%)	131,517 (100%)	116,533 (100%)	96,204 (100%)

*Large unclassified areas are the result of the extension of subarea boundaries beyond the area included in the Delta habitat mapping effort that was used as the basis for the land cover analysis.

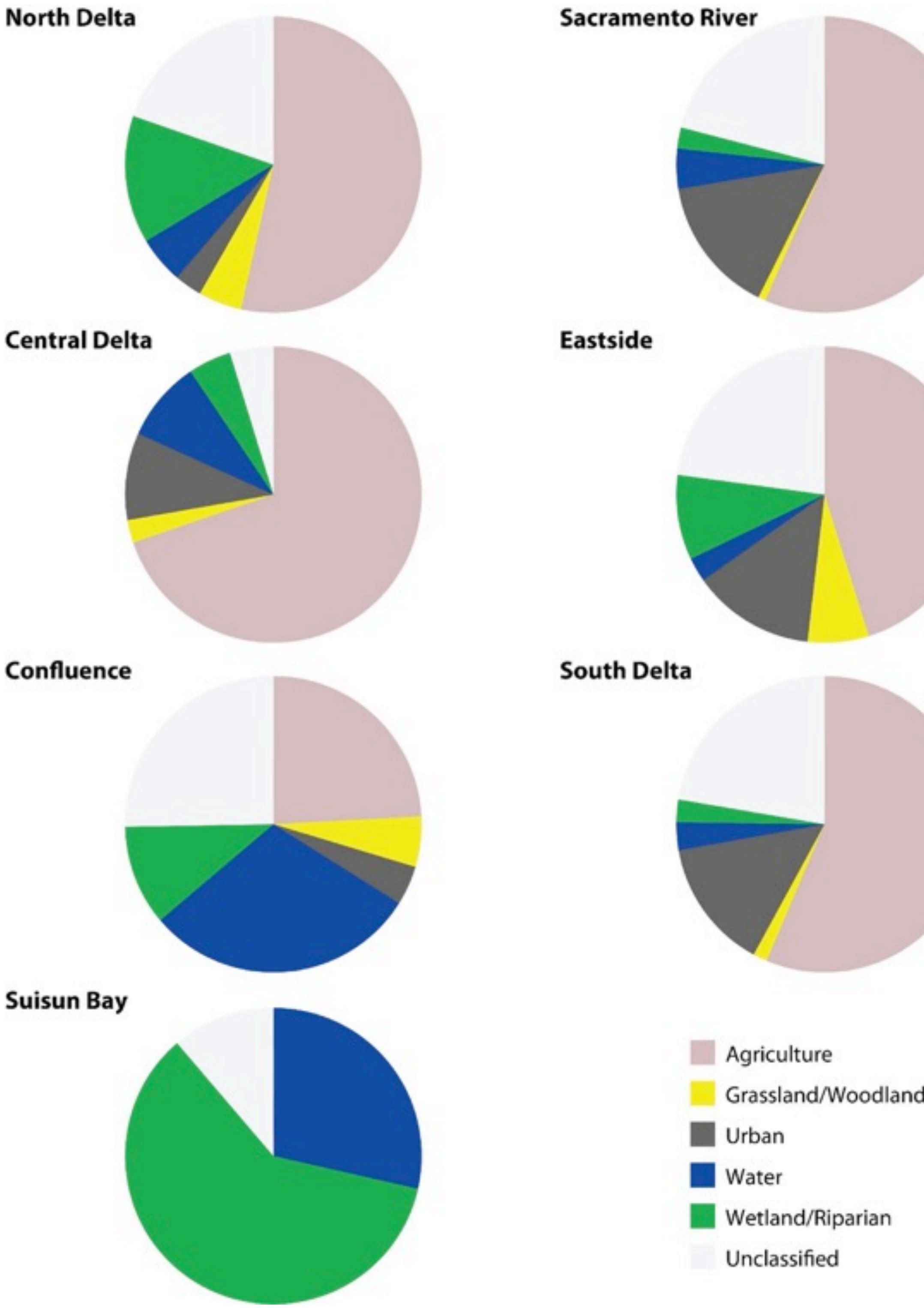

Figure 3.2 Land cover distribution by subregion.

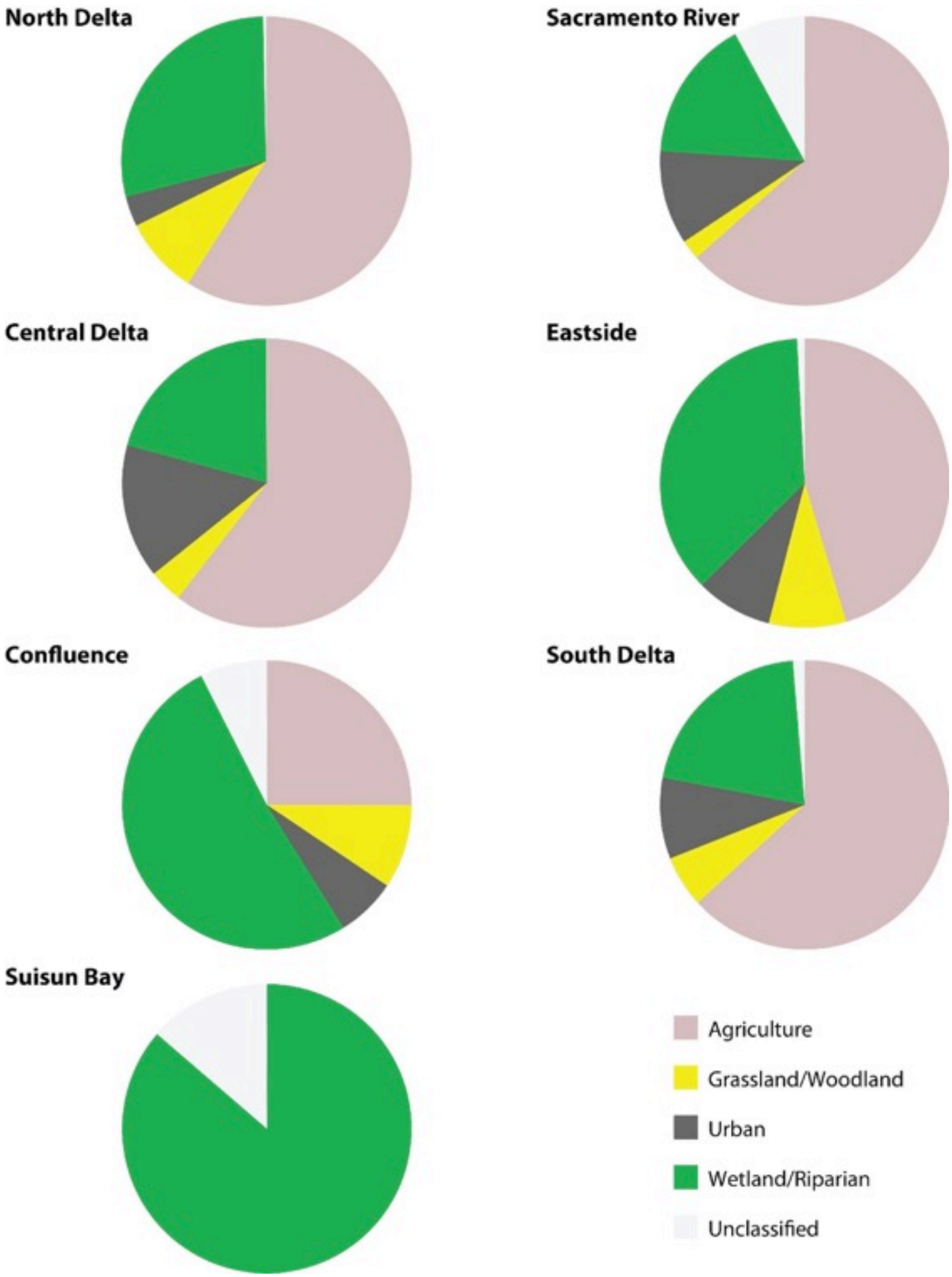

Figure 3.3. Land cover distribution by subregion, 100-m-buffer zone.

South Delta. Main hydrological influences in the South Delta include the San Joaquin watershed, the central Delta, and the pumps of the Federal and State water projects. Agriculture is the dominant land cover type with 56%. Urban land cover is significant with 14%.

Confluence. The key feature in the Confluence is the tidal influence. The confluence has the larger proportion of open water (30%) of all subregions and a smaller proportion of agricultural land cover types (25%) compared to other Delta subregions.

Suisun Bay. Suisun Bay has by far the largest proportion of wetland areas (60%). The remainder of the classified land cover consists of open water (29%).

The DWR-EMP is the longest-running regional nutrient monitoring effort and its current monitoring network does not represent all proposed subregions (Figure 3.4). The active DWR-EMP sampling sites are located in the Sacramento River, Central Delta, South Delta, Confluence, and Suisun Bay subregions (Figure 3.4). There are no active DWR-EMP stations in the Eastside and North Delta subregions. High-frequency nutrient sensors maintained by USGS provide limited spatial coverage and are located in the North Delta, Sacramento River, and Confluence subregions (Figure 3.4). Additional programs measure nutrients and nutrient-associated variables across the Delta and expand the spatial coverage (Figure 3.5). However, these efforts are not coordinated with the DWR-EMP or USGS sensor network, in terms of parameters analyzed, frequency and timing of sampling, and comparability of data. Therefore, data collected by these programs cannot be readily integrated with DWR-EMP data for status and trends analyses. Modeling and advanced statistical analyses would be a useful next step to inform a regional monitoring design that would be stratified based on the proposed subregions.

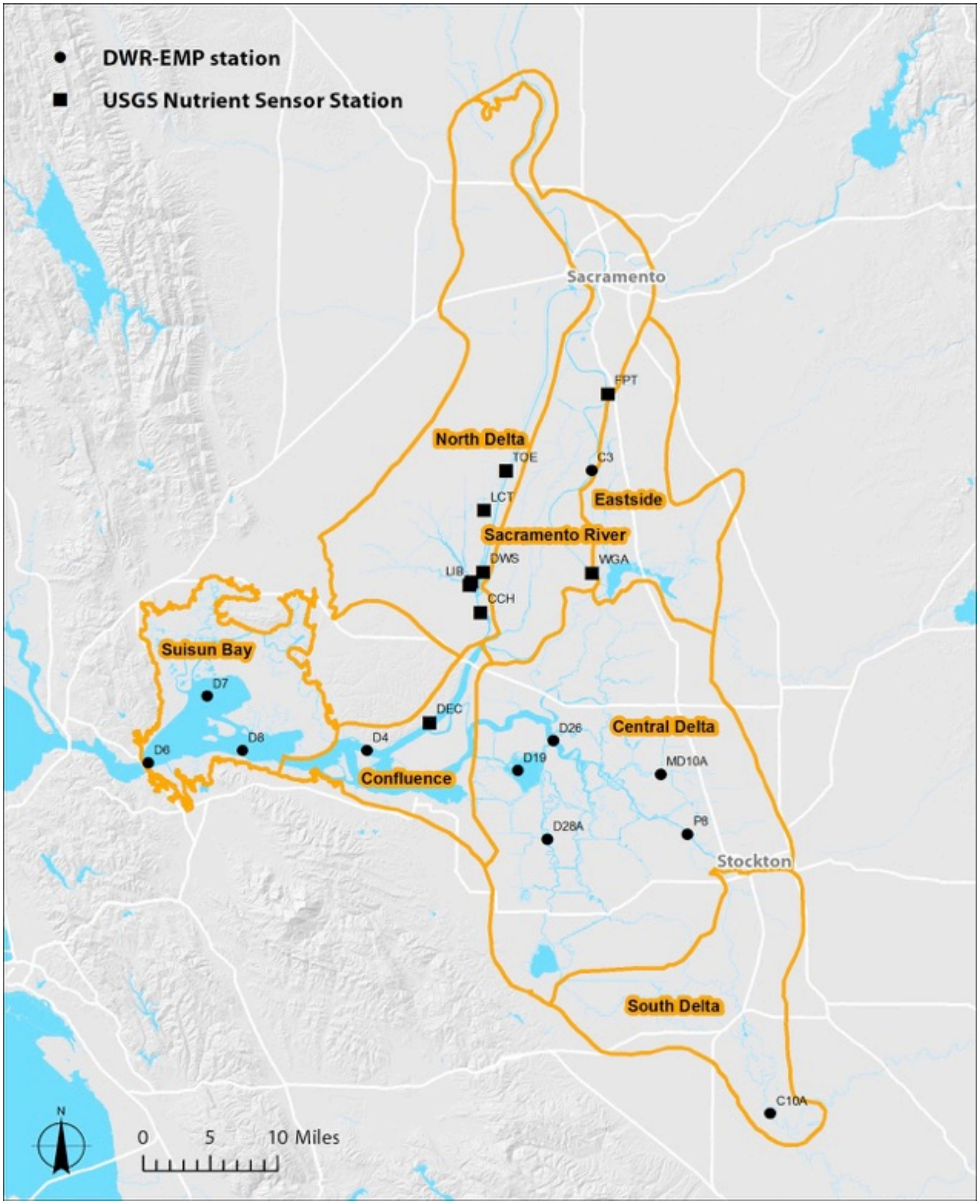

Figure 3.4. Location of DWR-EMP discrete water quality monitoring sites and USGS nutrient sensor stations relative to OLU-based Delta subregions. The USGS sensor stations are not co-located with discrete sampling stations and measure a limited set of parameters (nitrate, chlorophyll *a*, and dissolved oxygen).

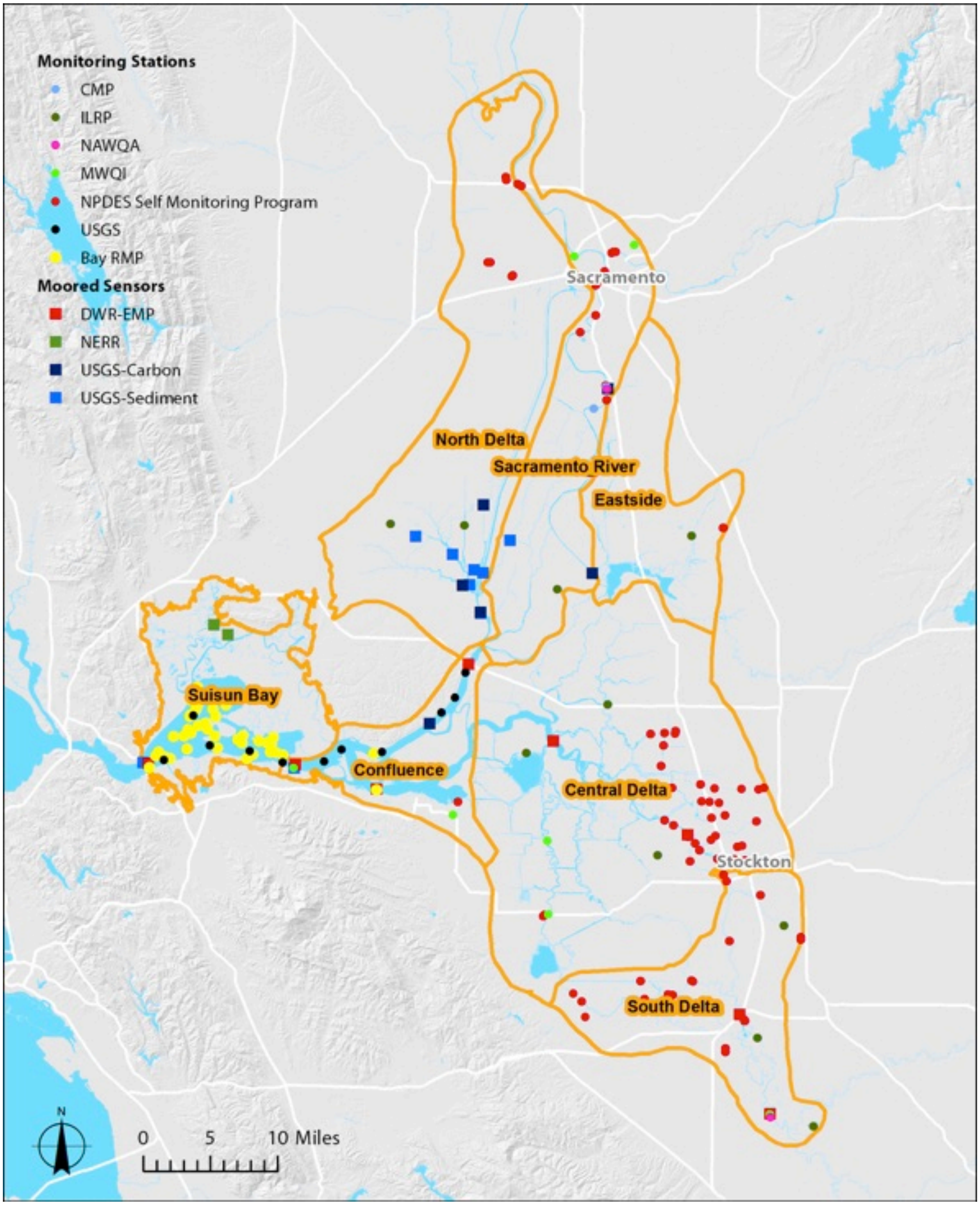

Figure 3.5. Location of additional monitoring stations relative to OLU-based subregions, including receiving water compliance monitoring sites (NPDES, Irrigated Lands Regulatory Program, Stormwater), DWR and US Bureau of Reclamation continuous recorders, and USGS NAWQA sites.

4. Time-series analysis to assess dominant factors driving nutrient variability in the Delta

4.1. Approach

A statistical time-series analysis was employed to characterize nutrient variability within and across subregions of the Delta and assess similarities and differences in underlying drivers. The employed method was non-negative matrix factor (NMF) analysis. The analysis focuses on the active discrete water quality monitoring stations of the DWR-EMP. These stations have been maintained at the locations shown in Figure 4.1 from 1975–present. Many other stations have been sampled as well but are no longer active (see Section 5). Factor analysis on historic data (1975 -1995) from active and discontinued stations combined was also performed, because it allowed the evaluation of nutrient variability within the Confluence and South Delta subregions, which each currently only have one active nutrient monitoring site, but had multiple nutrient monitoring stations prior to 1995.

In this analysis, we focused on inorganic macronutrients—nitrate + nitrite (NO3), ammonium (NH4), and phosphate (PO4)—as they are understood to be among the primary chemical drivers of phytoplankton productivity. We also examined chlorophyll a (chl-*a*) concentration time-series in order to more directly probe changes in productivity. Temperature and conductivity were examined in order to illustrate physical drivers of variability. Time-series of these variables are shown in Figure 4.2.

Figure 4.1. DWR-EMP discrete water quality stations maintained from 1975–present in Suisun Bay and the Delta.

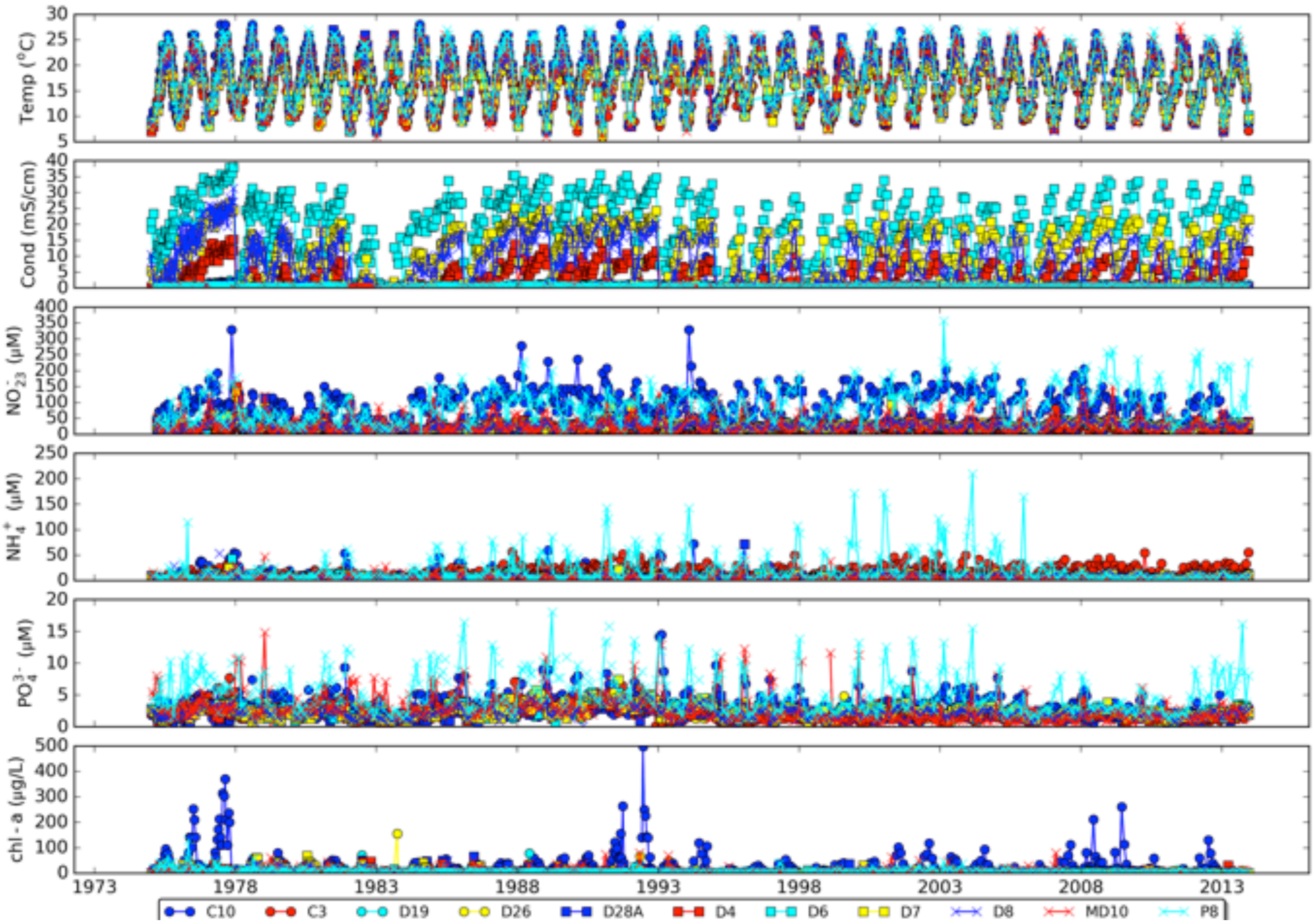

Figure 4.2. Time-series of temperature, conductivity, nitrite +nitrate, ammonium, phosphate, and chlorophyll across the Delta. Stations listed in legend with their corresponding symbols.

We utilize multiple numerical methods to extract the dominant modes of spatiotemporal variability from this dataset. Several are described in greater depth in Appendix 2; here we focus on the results of the NMF analysis. Within a complex dataset consisting of time-series at many stations across many variables, there are often "latent" or hidden drivers that account for significant amounts of variability in the dataset but cannot be easily spotted via visual inspection of the many time-series. Water quality variability can be thought of as the sum or superimposition of various processes (*e.g.*, seasonal + interannual cycles + step changes + linear trends). NMF analysis is an advanced data analysis method that is similar in approach to principal component analysis (PCA). Both methods are used to emphasize variation and bring out strong patterns in data. Whereas PCA allows for the sum and subtraction of processes, which can lead to non-physical interpretation, NMF constrains the factors to be positive contributions only. For instance, NMF can extract seasonal and interannual modes of variability and superimpose them according to the strength across stations and parameters. Importantly, the constraint of non-negativity does not imply that removal processes (*e.g.*, nutrient removal via assimilation or transformation) cannot occur. We use NMF here (described in depth in Appendix 2) in order to tease apart the various drivers of biogeochemical variability in the Delta.

4.2. Results and Discussion

We utilize the NMF analysis in order to attempt to extract additional information not as readily apparent in the raw or climatological time-series. As described in greater depth in Appendix 2, the number of modes of variability can range from one to the number of input vectors (in this case, the number of stations). Visual inspection using a range of modes tested here suggested that four modes successfully captured sufficient variability across all variables.

The NMF analysis of ammonium (Figure 4.3) shows some additional features beyond the seasonality evident in the time-series plots. First, the grouping of stations based on the weight or influence for each of the four dominant modes of variability (top row) suggests that, while the Suisun Bay subregion stations behave similarly, stations in the Central Delta subregion tend to be more heterogeneous (evident in the heterogeneous colors of the dots in the top row of NMFs 2–4). Also noteworthy is that, while seasonality appears to be a primary driver of variability, the NMF analysis also suggests unique seasonal patterns across different subregions, and even among different stations within a given subregion. Modes 1, 2, and 4 all have a notable seasonal component (as evident in the vertical banding in the bottom row). However, there is significant interannual variability in this seasonal component that also varies across stations.

An important trait of the NMF analysis approach is that, since factors are all non-negative, they can be reconstructed through a straightforward superimposition. Continuing with the ammonium example, we attempt to reconstruct the original time-series for each station (Figure 4.4). This time-series reconstruction helps to emphasize several features from the NMF mode plot. For example, it is immediately clear that, while the absolute magnitudes of ammonium concentrations vary across stations, similar drivers (i.e., modes) are found at many of the stations (Figure 4.3). Figures 4.5 and 4.6 show the NMF mode strength and time-series (Figure 4.4) as well as the full variable reconstruction (Figure 4.6) for phosphate following the same procedure described above. The phosphate NMFs (Figures 4.5 and 4.6) show several features similar to those in the ammonium NMFs, including some seasonal (NMF modes 2, 3) and some interannual (NMF modes 1, 4) modality as well as similarity within and heterogeneity across subregion.

The most striking features of the dataset revealed by NMF analysis are:

1. Patterns of variability at C3, C10, P8, and MD10 are unique and considerably different from those observed at other stations.
2. There is strong seasonality in most parameters. A seasonal pattern was extracted in many individual NMF modes.
3. Interannual variability is frequently apparent in individual NMF modes. These interannual trends can be attributed to natural cycles (*e.g.*, El Niño/La Niña) and management actions (*e.g.*, phase-out of phosphates in detergents, changes to nitrification of wastewater).
4. Several "hidden" drivers were extracted that may be difficult to detect through other means (Table 4.1).

While the NMF analysis suggests that the Suisun Bay stations behave fairly similarly, there is significant heterogeneity across the remainder of the region, both in comparison to Suisun Bay and in comparison of stations to each other. This feature is evident in the spatial representation of the NMF analysis results (top rows of Figures 4.3 and 4.5). The weight or influence of each of the four dominant modes varies considerable across the remainder of the region. We further demonstrate significant heterogeneity *within* the Central Delta subregion (different colored dots in Central Delta in Figures 4.3 and 4.5), where each of the NMF modes, for several of the variables examined, are weighted differently at different stations, sometimes covering the full range of variability in a given mode just within that subregion (for an example, see NMF4 of NH4 in Figure 4.3). Factor analysis of the historic data suggests that the Confluence and South Delta are fairly homogeneous subregions with respect to variability in the parameters of interest (Figure 4.7). Although there is spatial variability in both subregions, it appears to occur mostly along gradients. For the Confluence, most of the observed spatial variability in NMFs appears to correspond either to a gradient along the Sacramento River from station D24 (which is close to the boundaries with the North Delta and Sacramento River subregions) to station D4, which is close to the boundary with Suisun Bay) or to a gradient between the Sacramento River and San Joaquin River influence (Figure 4.7). Similarly, spatial variability in the data from historic South Delta stations suggests a gradient from upstream (C10) to the Central Delta boundary (Figure 4.7).

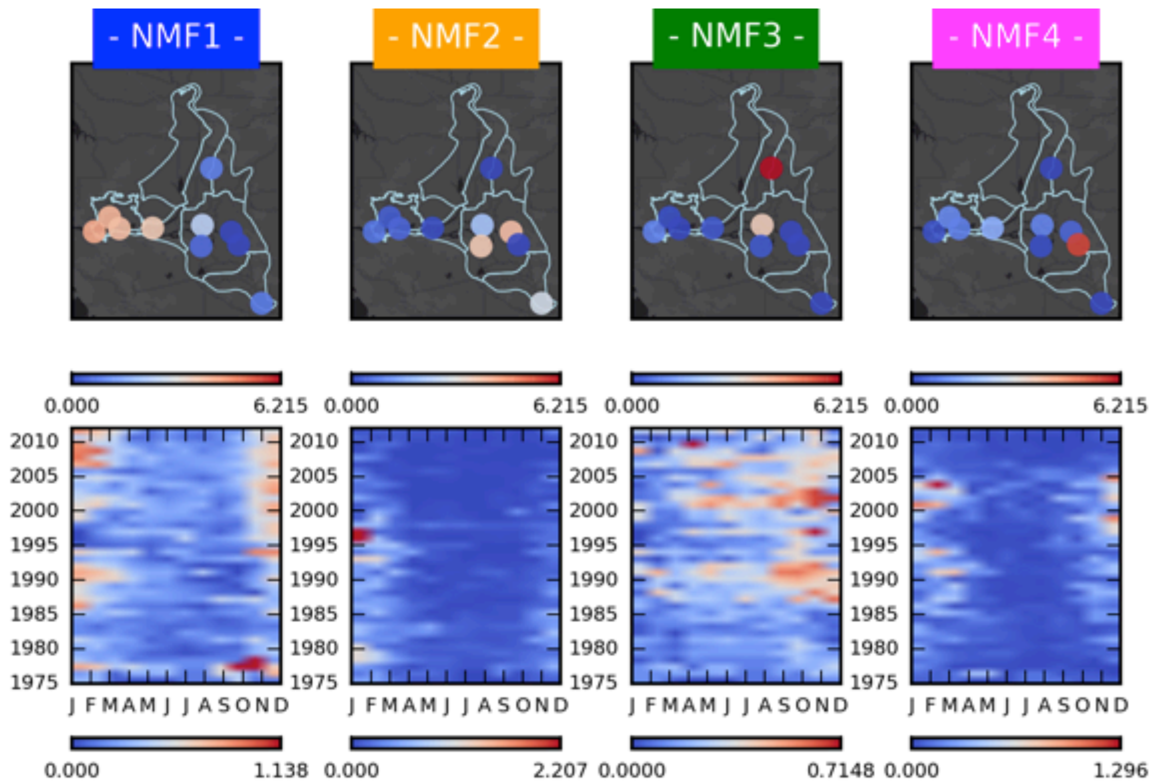

Figure 4.3. Regional (top row) and time-series (bottom row) expressions of the NMF analysis for ammonium. Regional expressions show the spatial pattern of the modes. The light outlines show the subregions as described in Section 3. Time-series expressions visualize variability with respect to year (y-axis) and month (x-axis). Vertical banding of red (positive values) in the time-series plots may be interpreted as seasonal variability, whereas the striking horizontal banding seen in NMF3 represents interannual variability. Specific interpretations of modes for all variables are in Table 4.1.

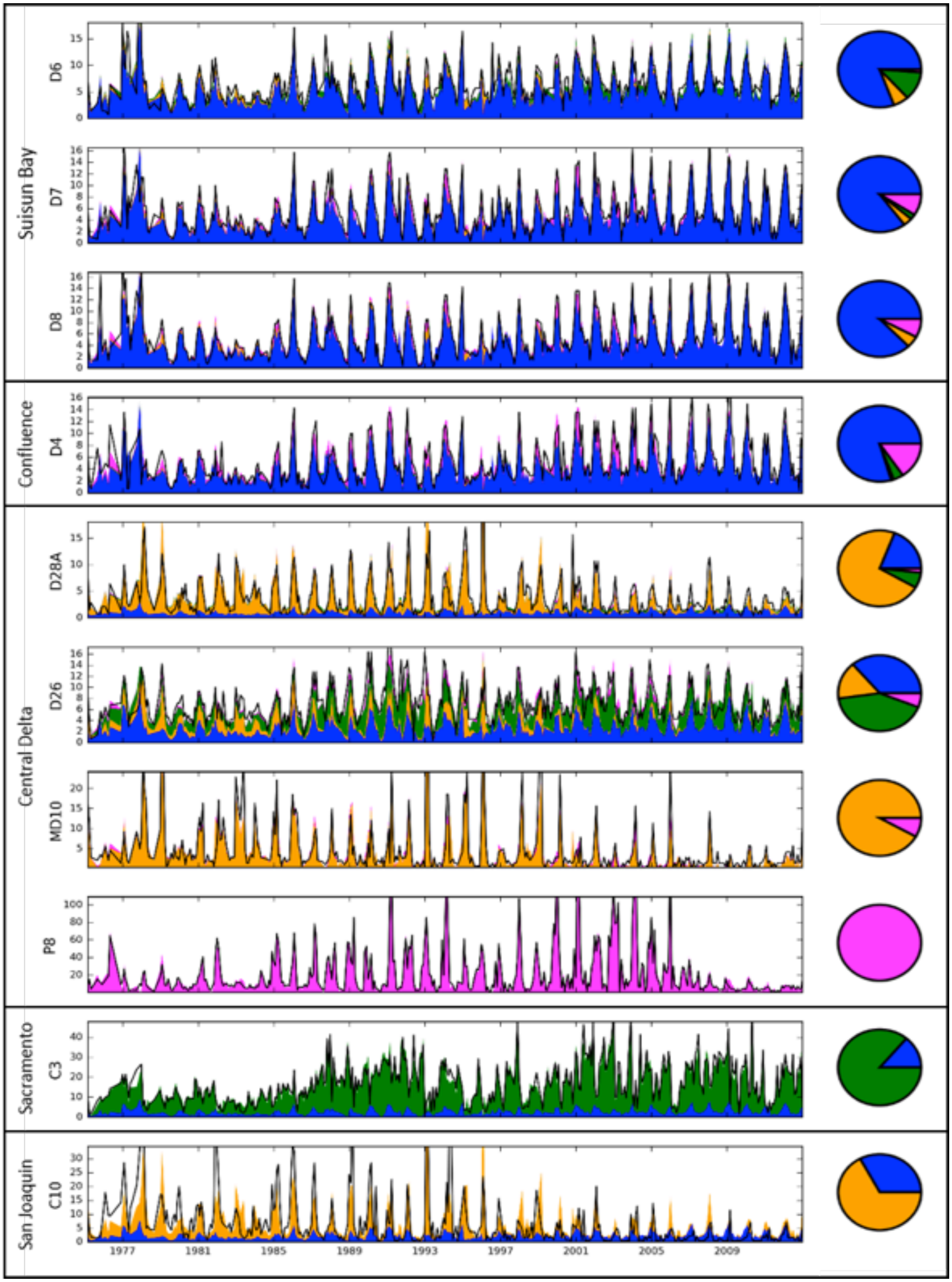

Figure 4.4. Time-series (left) and percent contribution of modes (right) for ammonium (in units of micromoles). The time-series are reconstructed by superimposing the four factors. Colors represent contributions from the NMF modes—1-blue, 2-orange, 3-green, 4-magenta—and the black line represents observations. Please see Appendix 2 for additional details on superimposition of NMF modes and additional figures.

Table 4.1. Observed parameter–mode combinations and hypothesized drivers.

		Nitrate	Ammonium	Phosphate	Chlorophyll
NMF Mode #	1	Strong influence at Suisun Bay stations and moderate influence in the Confluence; strong influence in winter/spring months of late 1970s and early 2000s; moderate influence in spring/summer period in early 1990s and 2007/08 => all of these years are critical water years; therefore, this factor presumably represents a drought effect in tidally influenced subregions	Strong seasonal (winter months) influence at Suisun Bay and Confluence stations; consistent with strong seasonal variability and seasonal highs in NH4 concentrations at these stations (Novick et al. 2015).	Strong influence at Suisun Bay and Confluence stations in critical water years post 1985 (hypothesized drivers TBD)	Varying seasonal and interannual influence at Suisun Bay and Confluence stations. Influence weakens after 1985, when the overbite clam invaded the brackish regions of the upper Estuary. The mode may correspond to fluctuations in chlorophyll (presence/absence of blooms) and the reduction of chlorophyll after the clam invasion (Kimmerer 2002)
	2	Observed mostly in Dec-Feb, presumably seasonal flow effects	Highly localized seasonal (January, February) influence at Central Delta stations D28 and MD10 in 1996 and 1997 (hypothesized drivers TBD)	Highly localized seasonal (winter) influence at Central Delta stations D26, D28, and MD10 with high interannual variability (hypothesized drivers TBD)	Seasonal influence (spring) at stations C3, MD10, and P8 (hypothesized drivers TBD)
	3	Observed increasingly after 1985 at San Joaquin River stations C10 and P8, pronounced seasonality. Presumably a San Joaquin watershed influence; possibly related to a change/decrease in upstream loadings	Highly localized interannual influence at stations C3 and D26 that emerges after 1985. It may correspond to increased loadings from wastewater to the Sacramento River starting in the mid-1980s (Jassby 2008)	Highly localized seasonal (winter) influence with high interannual variability; observed at the two stations most upstream on the San Joaquin watershed (C10 and P8); may correspond to seasonal and interannual variability in upstream loadings	Seasonal influence (summer) at stations D26 and D28, very strong in 1983 and 1993. May correspond to localized blooms (see Figure 4.3)
	4	Local effect at C3 Sacramento River at Hood in Feb 2006 and Feb 07 (hypothesized drivers TBD)	Highly localized seasonal influence (winter) at station P8 that starts in the early 1990s and ends by 2005. It likely corresponds to ammonium loadings from the Stockton WWTP to the San Joaquin River (Beck et al. 2016)	Strong interannual influence at stations C3 and D26, which are both strongly influenced by Sacramento River flow. Ends in early 1990s. May correspond to the reduction of phosphate from upstream point sources (Kratzer et al. 2011)	Seasonal influence (summer) at stations C3 and C10, much stronger at C10. May correspond to upstream contributions of chlorophyll from the upper Sacramento River and San Joaquin River watersheds (Jassby AD, Van Nieuwenhuyse EE. 2005)

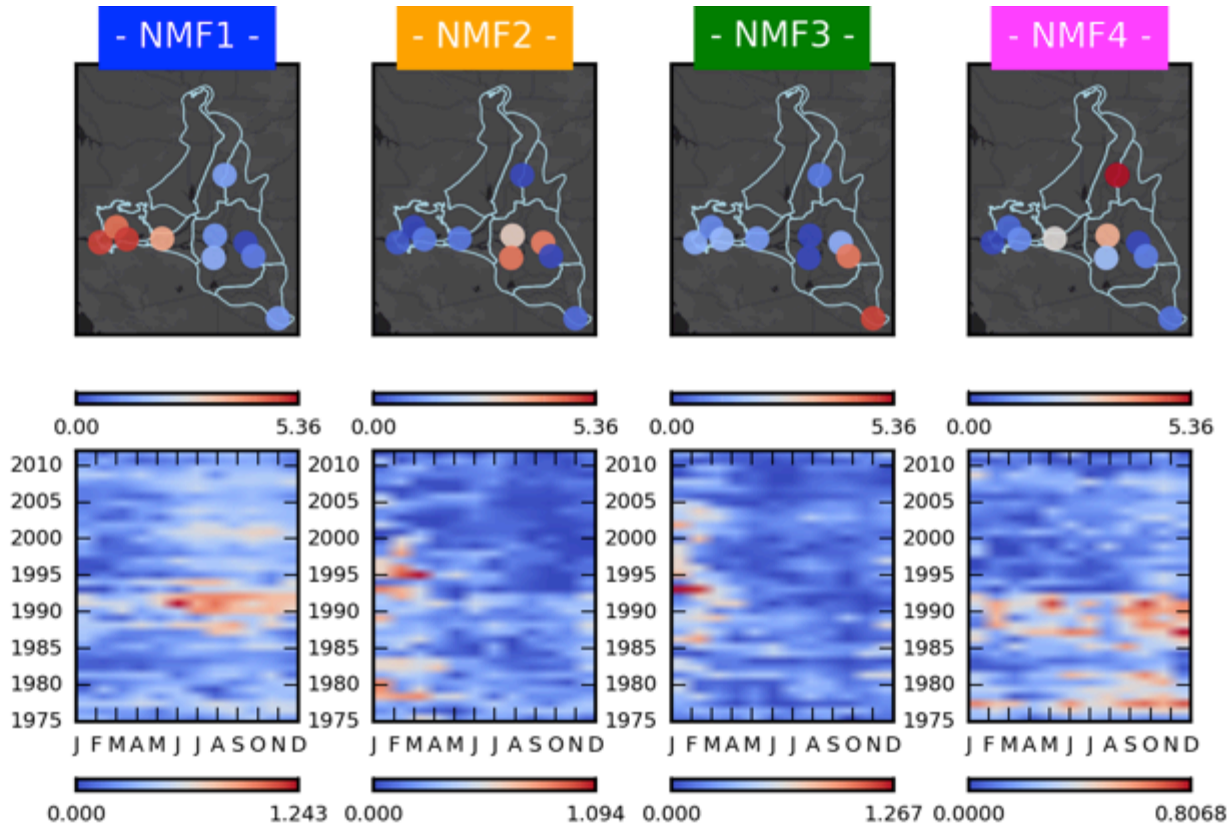

Figure 4.5. Same results as shown in Figure 4.3 shown here for phosphate.

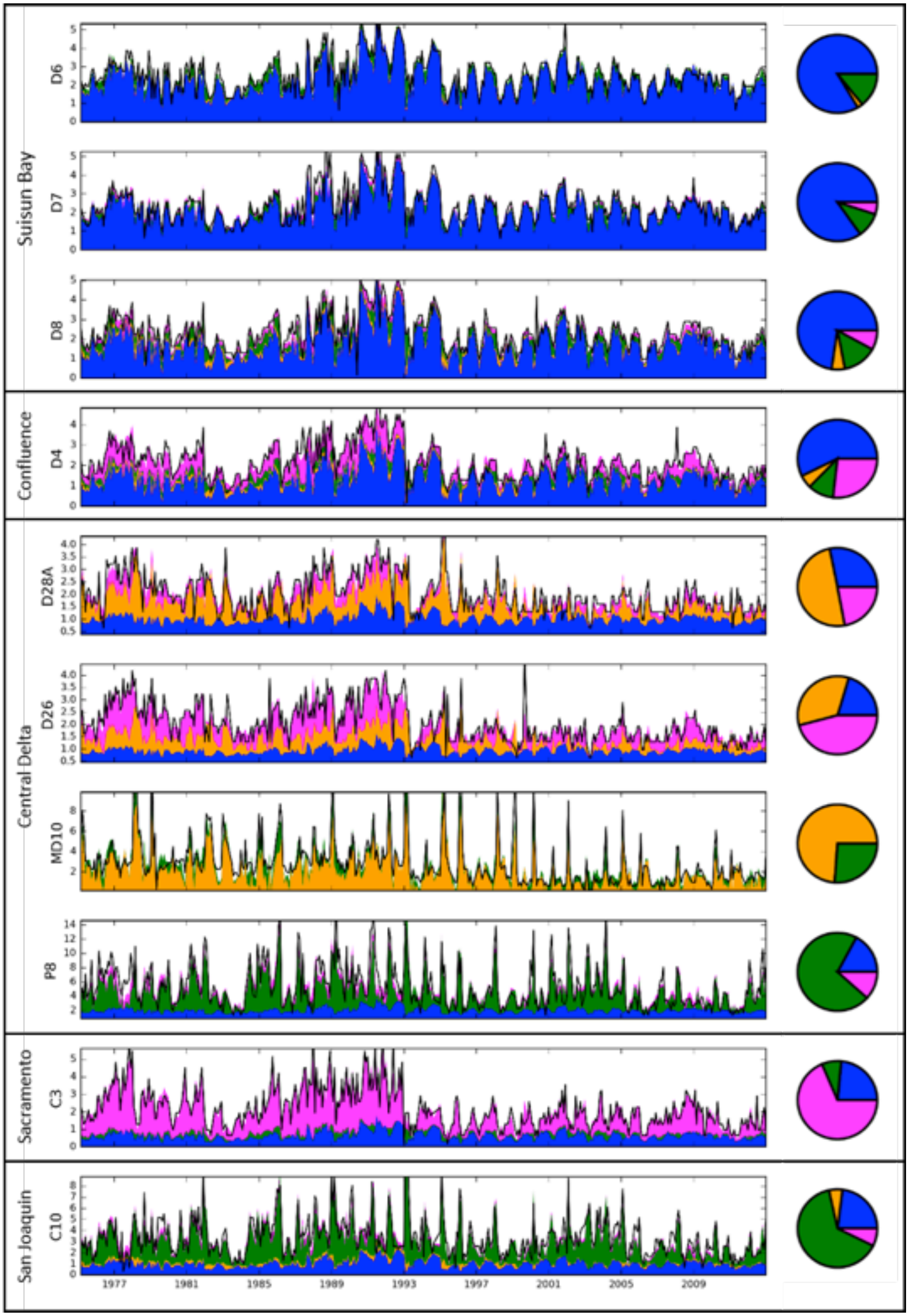

Figure 4.6. Time-series (left) and percent contribution of modes (right) for phosphate (in units of micromoles). The time-series are reconstructed by superimposing the four factors. Colors represent contributions from the NMF modes—1-blue, 2-orange, 3-green, 4-magenta—and the black line represents observations**.** Please see Appendix 2 for additional details on superimposition of NMF modes and additional figures.

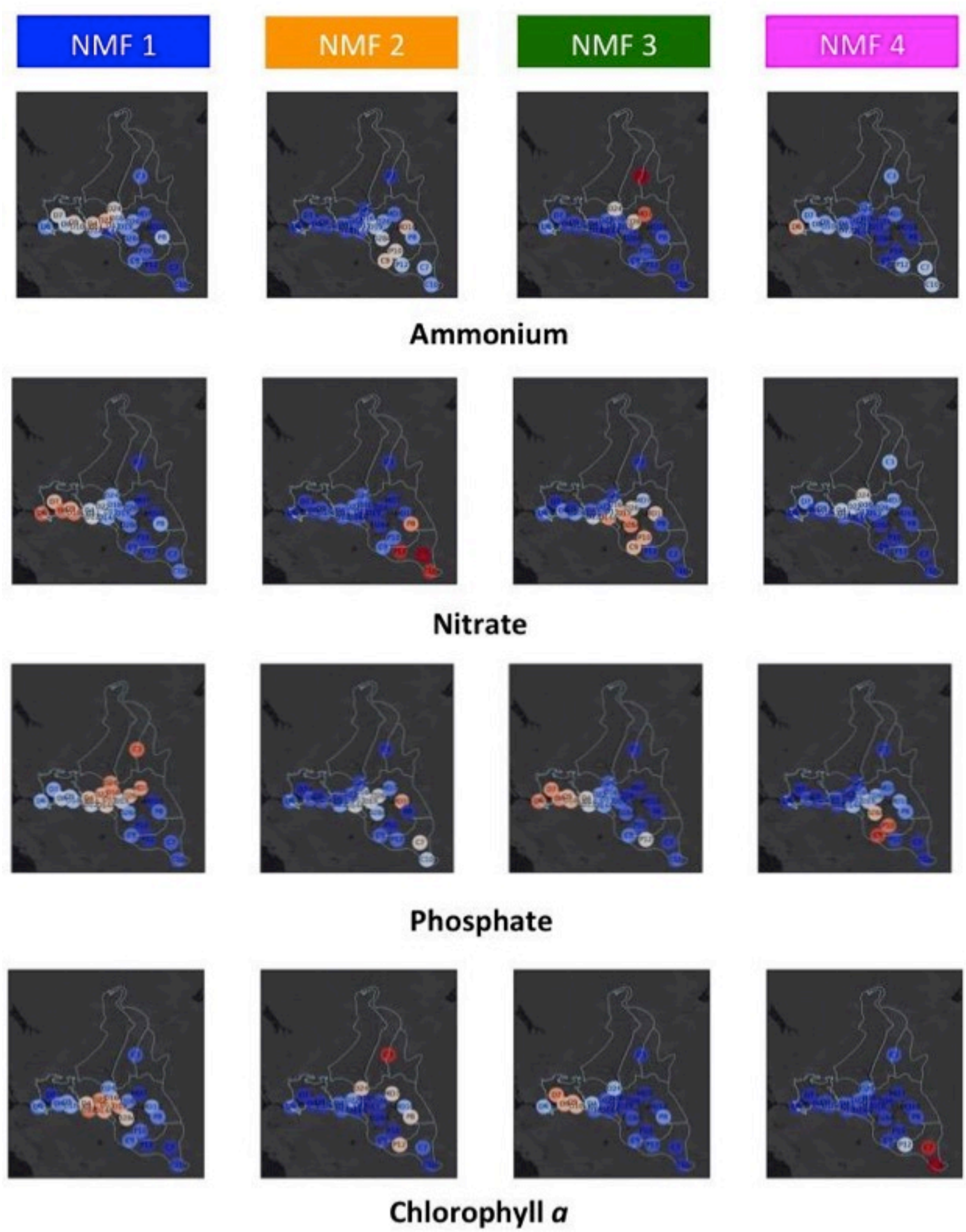

Figure 4.7. Spatial expressions of the factor analysis for historic data (1975-1995) including discontinued sites. Color represents the influence or weight of each NMF mode at a station. The color gradient is identical with that used in Figures 4.3 and 4.5. Dark red represents the strongest influence of a mode, dark blue the weakest.

We are unable to characterize variability in the North Delta (Cache Slough and Deep Water Shipping Channel) and Eastside (Mokelumne and Cosumnes Rivers) subregions as there are no long-term monitoring stations within those. We recommend that each subregion have at least two stations in order to characterize heterogeneity both within and among subregions. The Central Delta has proven to be particularly heterogeneous through the NMF analysis and we therefore recommend that at least four time-series stations be maintained there. Stations D7 and D8 behave most similarly across all parameters throughout the NMF analysis; if any station must be moved to accommodate the recommendations above, we suggest that one of two be relocated as the biogeochemical information collected there appears to be largely redundant.

5. Power Analysis of Trend Detection

5.1. Approach

This section seeks to determine whether the existing monitoring program collects the appropriate data to predict if future management changes will have positive, negative, or no impacts on nutrient conditions and ecosystem health in the Delta. Monitoring of nutrients and nutrient-associated variables will need to be designed to provide information regarding conditions and changes in conditions on appropriate temporal and spatial scales. This information is especially important because large-scale ecosystem restoration and water quality improvement projects are impending and are expected to have significant (and presumably beneficial) effects on nutrient conditions in the upper estuary. The most significant change is the planned treatment upgrade at the Sacramento Regional Wastewater Treatment Plant, which will be resulting in a nearly 95 percent reduction in ammonia discharged to the Delta by 2023 (Regional San 2016). The DWR-EMP water quality dataset has been a main resource for data on water quality conditions, trends, and controlling drivers in the upper estuary. We anticipate that the DWR-EMP will continue to serve as a main provider of data for evaluations of water quality condition and trends. It is therefore the focal point of the statistical analyses presented here.

The goal of the analyses was to evaluate if the current DWR-EMP design is sufficient to characterize nutrient status and trends (in open channels) in monitored subregions. The specific objectives were:

1. Historic trend analysis: Assess if trends were detected with DWR-EMP monitoring data, for each subarea, for each season.
2. Forward-looking power analysis: Evaluate whether increasing the number of stations (resuming monitoring at discontinued stations) or the sampling frequency will significantly improve our ability to detect seasonal, temporal, and spatial trends. The power analysis scenarios are summarized in Table 5.1.

The historic trend analyses were performed with the nonparametric Mann-Kendall suite of tests, including the seasonal Mann-Kendall (SKT) test for individual sites and the Regional Kendall (RKT) test for combined sites within a subregion (Hirsch et al.1982). The Mann-Kendall suite of tests was chosen because they are non-parametric methods and do not require assumptions of parametric methods (normality, linearity, independence) that are usually not met by typical water quality data. They are also more flexible in handling problems such as missing values, censored data, and seasonality (Van Belle & Hughes 1984).

Power was evaluated via Monte Carlo simulation. Variance in all simulations was calculated as the standard deviation of each parameter by season (spring, summer, fall, winter). For simulations of discrete sampling data from monthly data, the seasonal variance was calculated as the variance of measured concentrations relative to seasonal means. For simulations of daily means from continuous data, the seasonal variance was calculated from measured continuous data using the variance of measured daily means relative to the seasonal mean. For simulations of discrete data from continuous data, the seasonal variance was calculated as the variance relative to seasonal means calculated from monthly data points that were either a) randomly selected from all continuous data readings recorded between 7AM and 7PM (for chlorophyll at Antioch and Hood), or b) randomly selected from all continuous data readings recorded between 7AM and 7PM at high slack tide (for nitrate at Freeport). Trends (5%, 10%, 20%, 50%, and 100% linear declines over 10 years) were superimposed on the simulated data. For any given scenario, we ran the simulation 1000 times and calculated power by determining the number of times, out of 1000, a significant trend in flow-adjusted concentration over time could be detected. By convention, if the trend were detected in >80% of the simulations, the test was deemed to have sufficient statistical power.

Table 5.1. Power analysis scenarios. (NH4 = ammonium, NO3 = nitrate, TN = total nitrogen, P = phosphate, TP = total phosphorus, chl-a = chlorophyll *a*).

Design aspect	Comparison	Data used	Trend analysis	Varied
Spatial coverage/ site representativeness by subregion	Power to detect regional long-term trends in data for NH4, NO3, TN, P, TP, chl-a for 1. All seasons combined 2. Individual seasons	DWR-EMP discrete water quality data (1975 -1995)	5%, 10%, 20%, 50%, and 100% decline over 10 years	Number of stations per subregion
Sampling frequency	Power to detect long-term trends in continuous data vs. monthly grab samples	USGS continuous sensor data from Freeport (FPT) site (2014-2015); USGS discrete water quality data (2014-15) for FPT[2]. Parameter: NO3	5%, 10%, 20%, 50%, and 100% decline over 10 years	Sampling frequency of simulated data: Continuous sensor data vs. monthly grab samples at high slack tide. Assumes sensors result in ~30 results per month (daily means) vs 1 result per month for grab samples.
Sampling frequency	Power to detect long-term trends in continuous data vs. monthly grab samples	DWR continuous sensor data and IEP-EMP discrete water quality data for C3 and D12 (2008 -2016). Parameter: Chl-a	5%, 10%, 20%, 50%, and 100% decline over 10 years	Sampling frequency of simulated data: Continuous sensor data vs. monthly grab samples collected between 7am and 7pm. Assumes sensors result in ~30 results per month (daily means) vs 1 result per month for grab samples.

The analyses presented here allow relative comparisons of different sampling design options but should be cautiously used and are not intended to establish numerical benchmarks for decision-making. A key limitation for the analyses was data availability. In the historic trend analysis and spatial component of the power analysis, historic data from the past era of 1975 to 1995 was selected, because it includes the period of record for the largest number of stations to compare for the variable of interest (ammonium, nitrate, total nitrogen, phosphate, total phosphorus, chlorophyll a). The temporal component of the power analysis was limited to a comparison of continuous sensor data and monthly grab sample data and was conducted only on NO3 and chl-a, because these are the only variables investigated here for which moored sensor data are currently available. However, the longest active NO3 sensors were established only in August 2013, limiting the data availability to a short time span of only 2 years that may not fully

[2] The comparisons where limited to a few example locations where grab sampling sites are co-located with moored sensors, due to the long duration and large computing capacity needed for running the simulations of the continuous data.

represent the variability that may be seen in a larger dataset that spans a longer period of time with a wider range of conditions and may artificially increase the difference in results for continuous data and discrete data.

5.2. Results and discussion

For most of the nutrient variables, most of the sites had no statistically significant trend. However, when long-term trends were detectable, the direction of trend was mostly consistent across the entire region (Figures 5.1 and 5.2). The exception was ammonium, for which the direction of trend was positive at sites in the Sacramento River, Confluence, and Suisun Bay subregion; negative at South Delta sites; and mixed at Central Delta subregion sites. As discussed in Section 4, the Central Delta subregion is also very heterogeneous with regards to factors driving variability and their relative influence across sites in this subregion. Mixed, diverse, and localized influences affecting variability are expected to make regional long-term trends more difficult to detect. The clearest regional trend was detected for chlorophyll, with a significant decrease over time at 22 of the 24 stations (The only two stations with no detectable chl-a trend were South Delta stations C7 and C10).

Combining results of datasets from more than one site in an appropriate test for trend may help in the detection of regional or subregional trends in highly variable datasets, if there is consistency in trends. The dark blue circles in Figure 5.3 represent the regional Kendall test results for regional trend detection in subregions based on current stations. The light blue circles in Figure 5.3 represent the regional Kendall test results for trend detection in subregions based on all stations combined (active and discontinued stations). The test for trend detection based on current stations could only be done for the two subregions that currently have multiple monitoring stations for all variables included in the analysis: Suisun Bay and Central Delta. In addition, the Confluence has three active monitoring sites for chlorophyll and could be included in the trend analysis for chlorophyll. Therefore, the comparison of trends detected by combining results from active sites in a subregion with trends detected by combining active and discontinued stations in a subregion were limited to the Central Delta and Suisun Bay subregions. For chlorophyll, the comparison could also be made for the Confluence subregion.

Overall, the tests results suggest that trends that occurred between 1975 and 1995 would have been detected, if only the currently active sites would have been monitored. Test results were nearly identical for both test groups and there was no improvement in long-term trend detection by combining the active and discontinued stations in the trend analysis. For TN, an increasing trend in Suisun Bay was detected in the active stations only (D6, D7, and D8), but was not detected when the inactive station D9 was added back in.

The results from the power analysis suggest that the current IEP-EMP sampling can detect a 50% change over 10 years for most subregions and parameters. Exceptions are ammonium in the Confluence and South Delta; and chlorophyll in the Confluence, Suisun Bay, and South Delta. Trend detection power for ammonium can be improved (decrease sensitivity of detectable decline over ten years from 68% to 36%) by adding this analyte to two active DWR-EMP sampling sites (D12, D22) that are currently not sampled for nutrients. Adding back discontinued stations D12 and 22 would also significantly increase the sensitivity for trend detection in nitrate (42% to 18%r), total nitrogen (40% to 17%), and phosphate (39%

to 26%). The sensitivity for ammonium trends in the Confluence could be further reduced to 18% detectable change over ten years, by resuming monitoring at all four discontinued Confluence stations. Monitoring at all discontinued Confluence station would also increase the sensitivity for trends in total phosphorus from currently 43% to 24% detectable change over ten years. In the Central Delta, the sensitivity of trend detection for total could be nearly doubled for all parameters by resuming monitoring at discontinued stations. However, the analysis if historic trends suggests that trends are not always consistent across stations in the Central Delta and that the added statistical power may be outweighed by important site-specific factors that either cancel out or mask a regional trend at individual stations. In the South Delta, total nitrogen is the only parameter for which sensitivity of trend detection could be significantly increased by resuming monitoring at discontinued stations. In Suisun Bay, the benefits of adding D9 would be marginal for trend detection capabilities. In Suisun Bay, the Confluence, and the Central Delta, reducing monitoring to a single station would not result in a considerable loss in sensitivity for trends in total phosphorus.

For chlorophyll, the results shown in Table 5.3 suggest that strategically placed continuous sensors would provide much better trend detection capabilities than additional discrete sampling stations. Comparative simulations of continuous data (daily means) and discrete sampling data (monthly sampling) suggest a non-trivial increase in statistical power to detect a 10% decrease (1% annual percent change) at Antioch from 14% to 94% when using continuous data instead of discrete sampling data in a long-term trend analysis (Table 5.3, Figure 5.4). At Hood, the same comparison suggests an increase in statistical power to detect a 20% decrease (2% annual percent change) from between 22% and 54% to 94% (Table 5.3, Figure 5.4). At Freeport, the power analysis results suggest that the power to detect a 10% decrease (1% annual percent change) in nitrate is 91% percent, compared to 6% when sampling monthly at high slack tide (Table 5.4, Figure 5.5). The absolute numbers in this comparison need to be viewed with caution, as discussed in the Methods section.

In summary, the results from the power analysis suggest that the current IEP-EMP sampling can detect a 50% change over 10 years, or 4% per year change, for most subregions and parameters. Exceptions are ammonium in the Confluence and South Delta; and chlorophyll in the Confluence, Suisun Bay, and South Delta. Trend detection power for ammonium can be significantly improved by adding this analyte to three active IEP-EMP sampling sites that are currently not sampled for nutrients. For trend detection in chlorophyll, the analyses suggest that better utilization of sensors would be more beneficial than adding more discrete sampling points. The results from the power analysis suggest that continuous chlorophyll sensors maintained by the IEP-EMP may be able to detect a 10% decrease over ten years in chlorophyll.

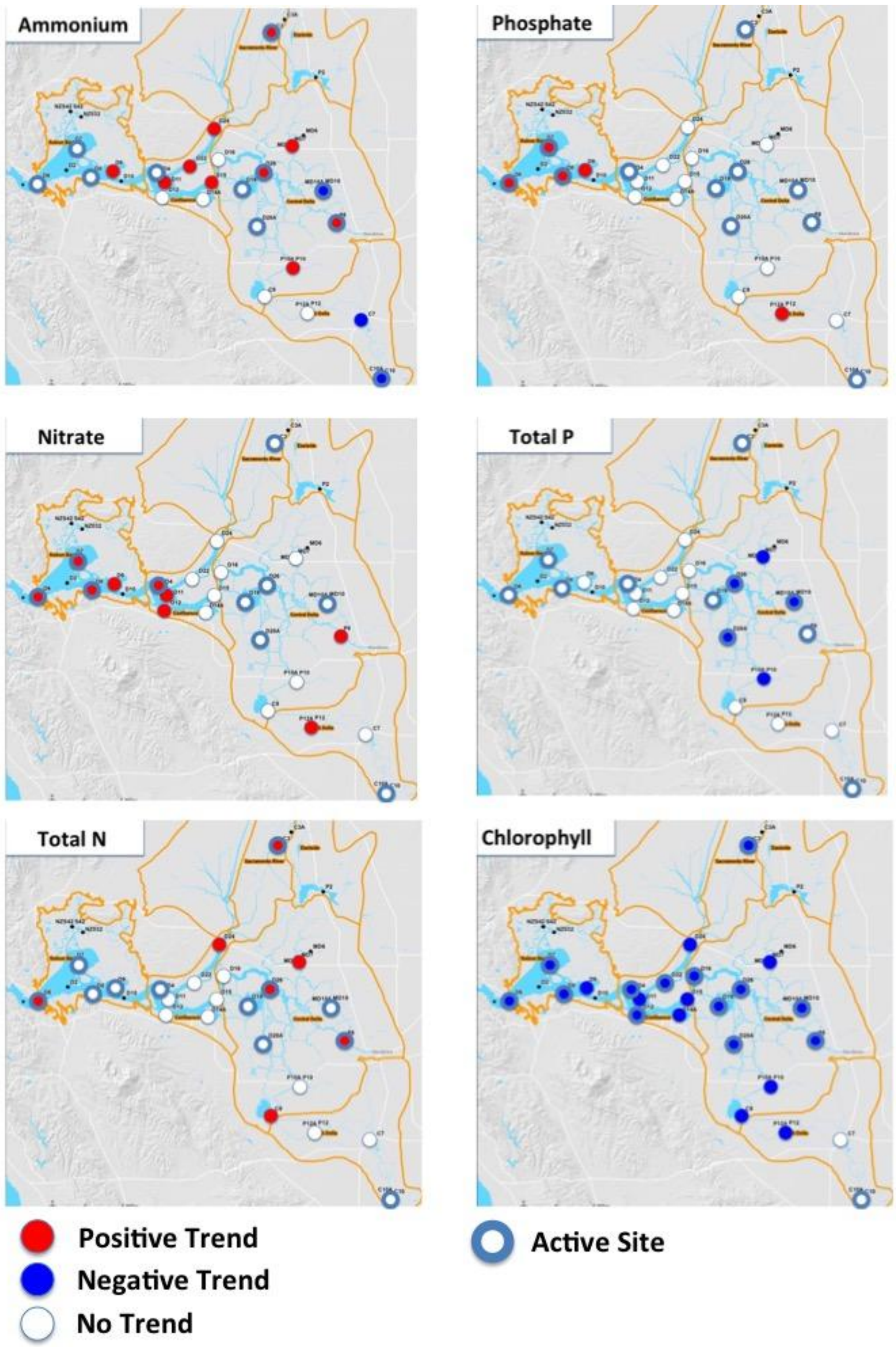

Figure 5.1. Site-specific detection of long-term trends at DWR-EMP stations, 1975-95 data (significance at $p \leq 0.05$).

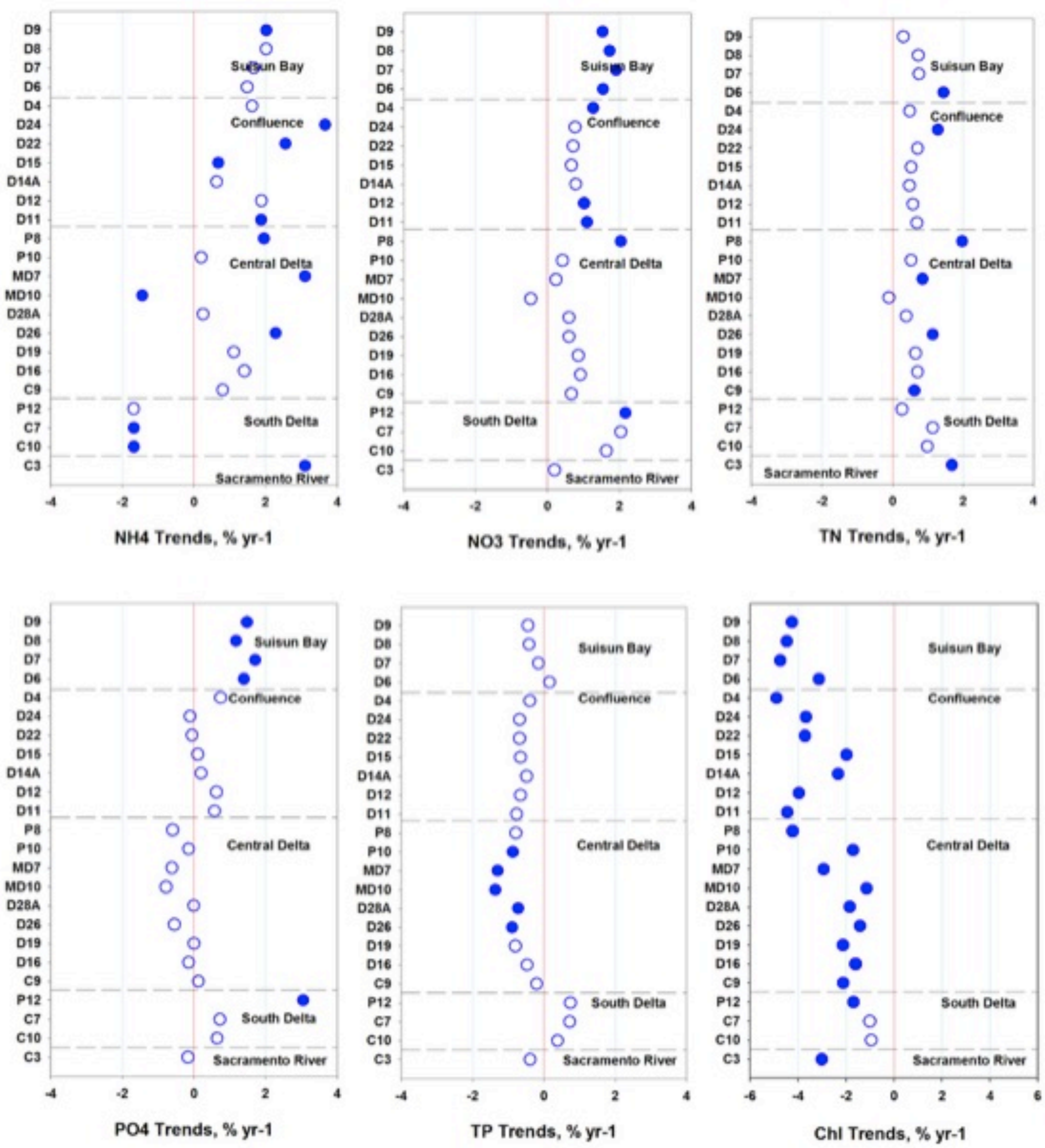

Figure 5.2. Magnitude (% change per year) of detected trends at DWR-EMP stations, 1975-95 data (significance at $p \leq 0.05$), for NH3, NO3, TN, PO4, TOP, and chl-a. Percent change per year is the ratio of the Sen slope to the long-term median for each variable. Full circles = significant trend.

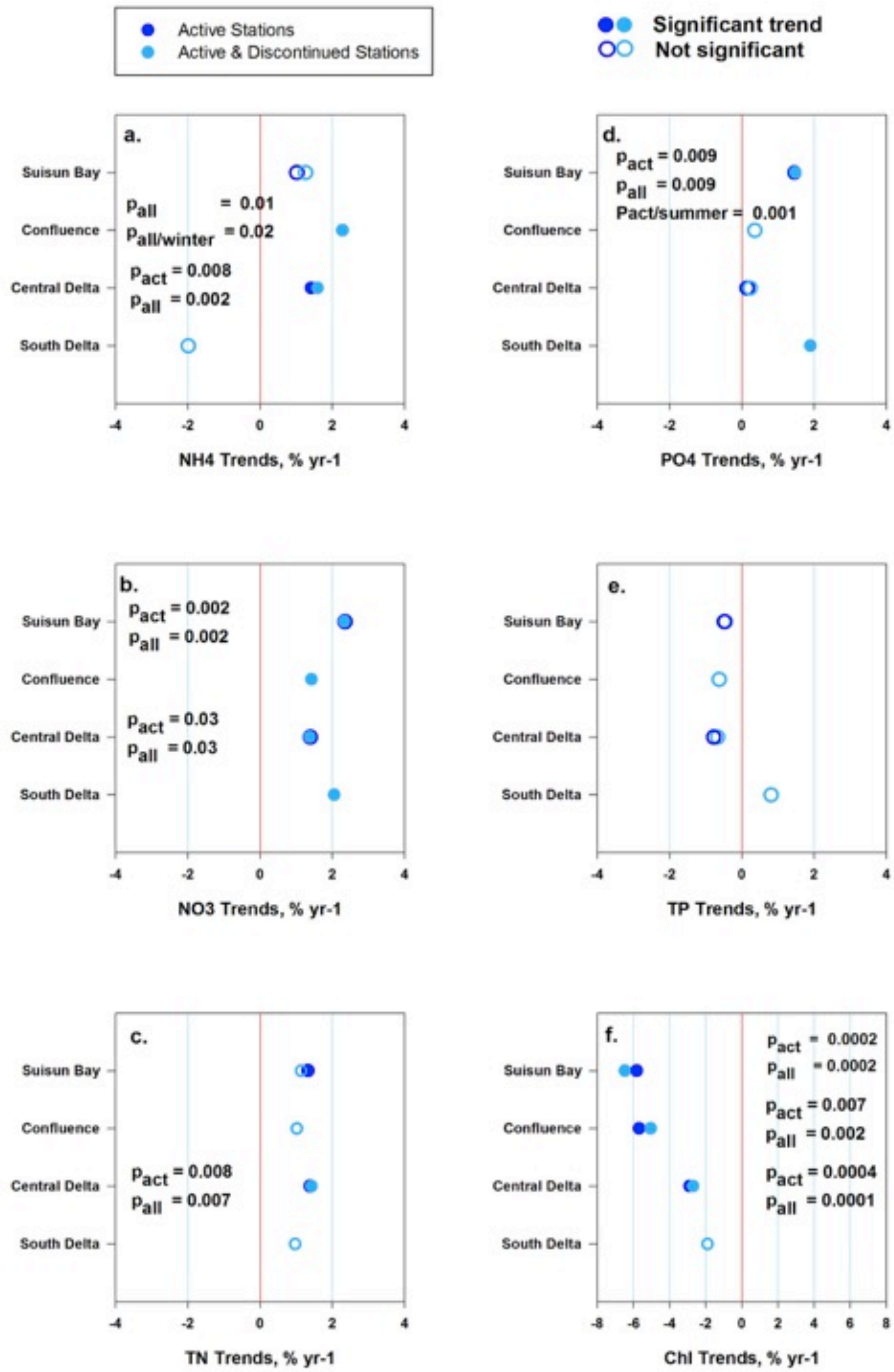

Figure 5.3. Comparison of detected trends at active DWR-EMP stations and all stations (active plus discontinued), 1975-95 data (significance at $p \leq 0.05$), for ammonium (NH4), nitrate (NO3), total nitrogen (TN), phosphate (PO4), total phosphorus (TP,) and chlorophyll *a* (Chl). Trends are expressed as the Sen slope divided by the long-term median for each subregion.

Table 5.2. Summary of power analysis results for detecting long-term trends in ammonium (NH4), nitrate (NO3), total nitrogen (TN), phosphate (PO4), total phosphorus (TP,) and chlorophyll a (Chl) based on IEP-EMP monthly discrete sampling data. The table shows the minimum percent change over ten years that is detectable with 80% power. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assuming consistent long-term trends across all sites. Red text represents the current monitoring network.

	NH4	NO3	TN	PO4	TP	Chl
Suisun Bay						
Single station: D6	63%	43%	40%	39%	43%	70%
Active stations: D6, D7, D8	42%	26%	17%	26%	48%	54%
All historic stations D6, D7, D8, D9	36%	18%	14%	19%	43%	48%
Confluence						
Single station/active station: D4	68%	42%	35%	38%	43%	82%
Active stations (only Chl): D4, D12, D22	36%	18%	14%	18%	41%	60%
All historic stations: D4, D11, D12, D14, D15, D22, D24	18%	13%	8%	12%	24%	41%
Central Delta						
Single station: D19	47%	44%	40%	38%	37%	78%
Active stations: D19, D26, D28	30%	27%	17%	18%	37%	79%
Historic stations[3]: C9, D16, D19, D26, D28, MD7, P10	16%	15%	9%	12%	19%	45%
South Delta						
Single station/active station: C10	47%	45%	40%	38%	37%	78%
All historic stations: C7, C10, P12	58%	31%	18%	36%	42%	66%

[3] Stations MD10 and P8 were not included because trends at MD10 are not always consistent with regional trends, and because seasonal data for some variables at P8 did not meet the chi-square test criterion for homogeneity.

Table 5.3. Evaluation of power to detect long-term trends in chlorophyll at stations SRH/C3 (Sacramento River at Hood) and ANC/D12 (San Joaquin River at Antioch) from a) simulated daily means of continuous data, b) monthly grab sampling simulated from continuous data, and c) monthly grab sampling simulated from grab sampling data. The blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

Simulations based on data for Nov 2008 – Jun 2015:*	**Trend - 10yr Decline**				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Chlorophyll – Sacramento River at Hood					
a. Daily mean (continuous) from continuous data	15%	45%	94%	**100%**	**100%**
b. Monthly grab sampling from continuous data	4%	8%	22%	85%	**100%**
c. Monthly grab sampling from discrete data	6%	17%	54%	**100%**	**100%**
Chlorophyll – San Joaquin River at Antioch					
a. Daily mean (continuous) from continuous data	42%	94%	**100%**	**100%**	**100%**
b. Monthly grab sampling from continuous data	7%	14%	45%	**100%**	**100%**
c. Monthly grab sampling from discrete data	8%	14%	48%	**99%**	**100%**

*Based on data availability.

Table 5.4. Evaluation of power to detect long-term trends in nitrate from a) simulated daily means of continuous data recorded by the USGS sensor at Sacramento River at Freeport (FPT), and b) simulated monthly grab sampling. The blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

Simulations based on data for Oct 2014 – Sep 2015:*	**Trend - 10yr Decline**				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Nitrate					
a. FPT - Daily mean (continuous)	39%	91%	**100%**	**100%**	**100%**
b. FPT - Monthly grab at high tide slack	6%	6%	18%	75%	**100%**

*Based on sensor data availability.

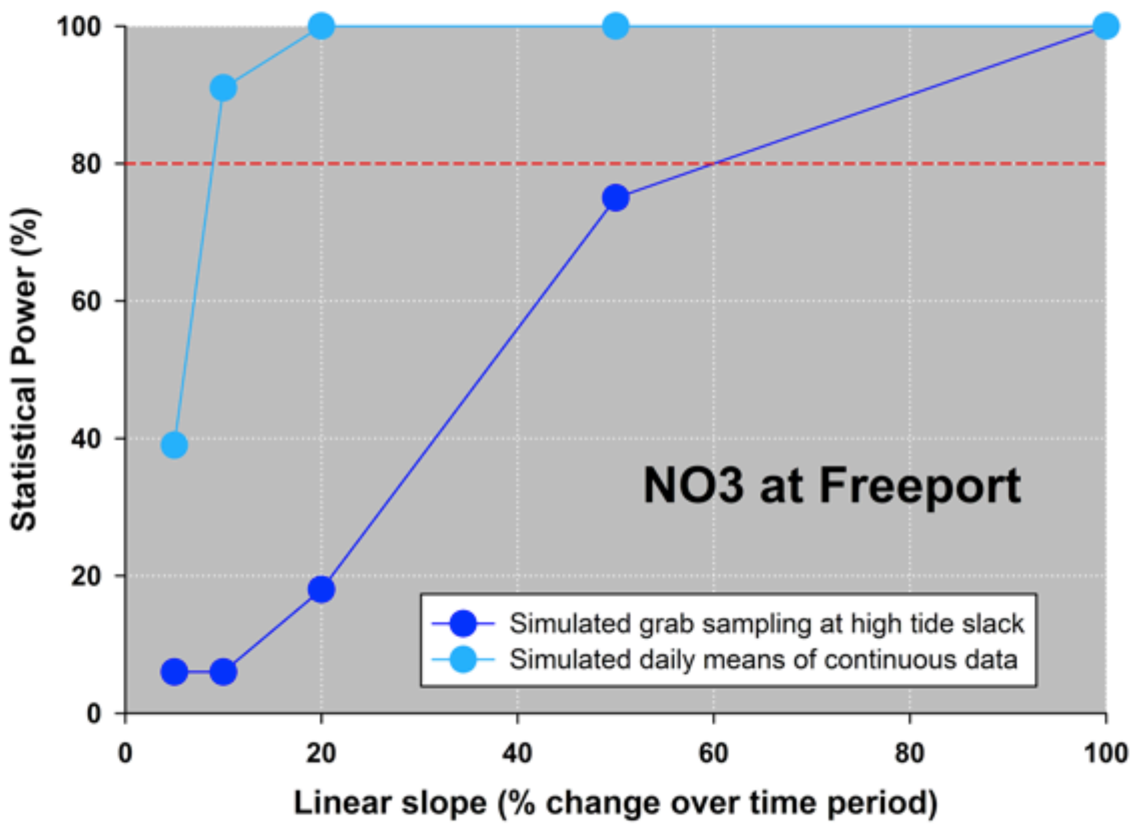

Figure 5.4. Power curves for the detection of long-term trends in nitrate from a) daily means and b) monthly grab samples collected at high slack tide, each simulated from continuous data recorded by the USGS sensor at Sacramento River at Freeport (FPT). The red dotted line represents 80% power.

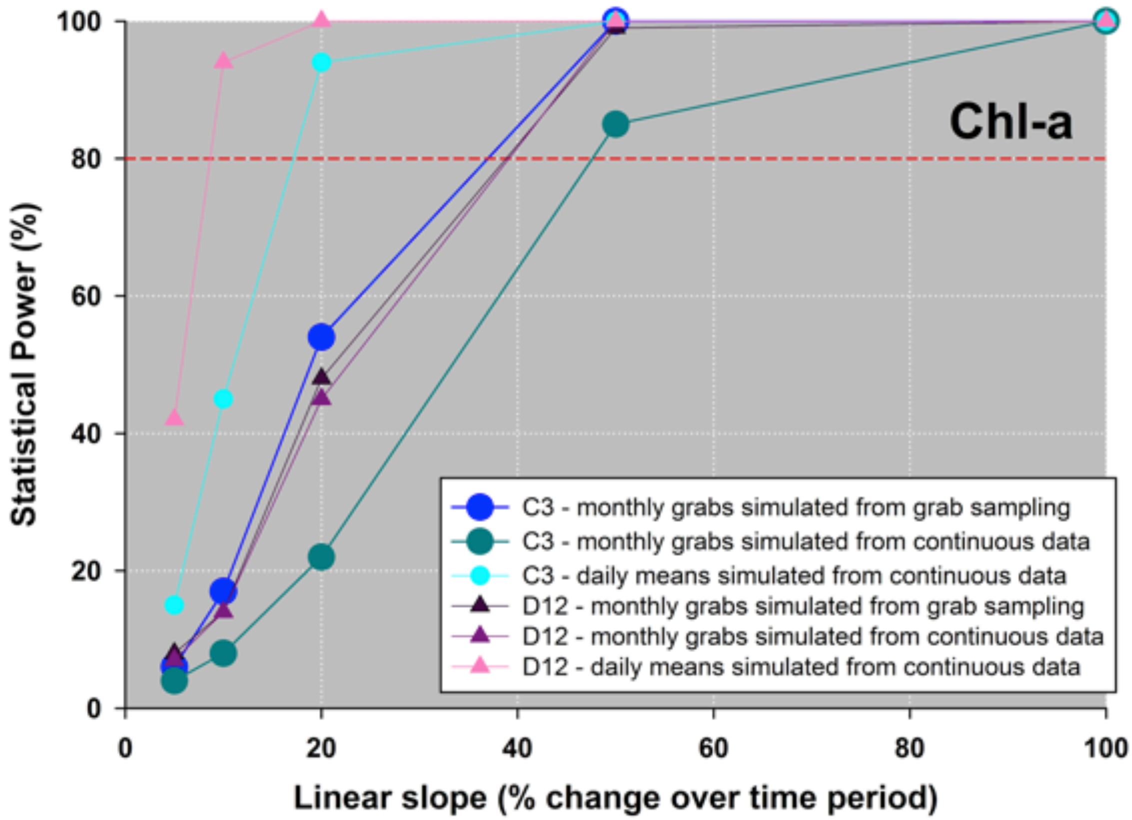

Figure 5.5. Power curves for the detection of long-term trends in chlorophyll from a) daily means simulated from continuous data b) monthly grab samples simulated from continuous data, and c) monthly grab samples simulated from grab sample data. The data are from two DWR-EMP monitoring stations that are co-located with moored chl-a sensors, Sacramento River at Hood (C3) and San Joaquin River at Antioch (D12). The red dotted line represents 80% power.

6. Monitoring coverage of aquatic habitat in the Delta

The concept of this report is to inform the design of a nutrient status and trends monitoring design that would be stratified based on existing subregions and aquatic habitat types, depending on the purpose of the assessment. Overall, this report focuses mainly on potential geographic subregions and their coverage by current nutrient monitoring efforts. As an important measure of ecological condition, nutrient measurements also need to be representative of the types of habitats that are being assessed. Therefore, this section addresses the coverage of operationally defined aquatic habitat types by current nutrient monitoring efforts.

Aquatic habitat types for assessing nutrient condition have been defined as part of a Numeric Nutrient Endpoint (NNE) assessment framework for California estuaries (McKee et al 2011). Such a classification does not yet exist for the Delta. Moreover, aquatic habitat in the Delta has not yet been systematically mapped using standardized methods. In lieu of using standardized aquatic habitat types, we binned Delta aquatic habitat into four operational categories representing different conditions with regards to nutrient biogeochemistry and potential nutrient responses: deep channels, shallow margin areas, dead-end sloughs, and wetlands:

- *Deep channels* are typically light-limited, and therefore heterotrophic, and characterized by lateral physical and chemical gradients (turbidity, temperature, oxygen, etc.). Deep water was operationally defined as surface water areas exceeding 2 m water depth.
- *Shallow margin areas* are typically more productive than deep-water habitat, autotrophic, and well mixed (Lopez et al. 2006). Shallow margin areas were operationally defined as surface water areas that are less than 2 m water deep and not identified as dead-end sloughs.
- *Dead-end sloughs* exhibit less exchange and thus longer residence times and consequently are particularly susceptible to low DO problems and nutrient enrichment (Foe 2013, Siegel et al. 2010). Dead-end sloughs were operationally defined as blind channels less than 2 m deep.
- *Wetlands* have a key role in nutrient processing and retention and were operationally defined as areas classified as wetland (permanent and seasonal, including rice fields and other managed wetlands) and riparian areas in existing habitat maps[4].

To assess the coverage of these habitat types by the existing monitoring network, we calculated the acreage of each habitat type within each subregion, number of monitoring stations and moored sensors in each subregion/habitat type, and the "station density" (stations per 1,000 acres) per habitat type. We generated the aquatic habitat layer by using a combination of the following layers:

- Habitat data from "A Delta Transformed" (SFEI-ASC 2014) to identify water and wetlands within the Delta;
- Channel data from "A Delta Transformed" (SFEI-ASC 2014) to help identify dead-end sloughs;
- San Francisco Bay and Sacramento-San Joaquin Delta Digital Elevation Model (DEM Version 3.0, Wang and Ateljevitch 2012) to separately attribute deep channels and shallow margin areas in the Delta;
- BAARI v2 (SFEI-ASC 2015) to identify wetlands, deep channels, and shallow margin areas in Suisun Bay; and
- Limited manual digitization and attribution of some features and attributes not adequately captured in the layers listed above.

Figure 6.1 shows the resulting aquatic habitat type map and the pie charts in Figures 6.2 show how the four operationally defined aquatic habitat types are distributed across subregions. Wetlands and riparian areas are the most abundant aquatic habitat type across all subregions and account for 57% of the total classified aquatic habitat acreage in the region. Wetlands and riparian areas are also the most abundant aquatic habitat type in four individual subregions and account for 77% of all classified aquatic habitat in the North Delta and Eastside subregions, 69% in Suisun Bay, and 46% in the South Delta. Deep channels

[4] Hydrological connectivity of wetlands to the watershed was not evaluated.

are the most abundant habitat type in the Confluence (48%) and Central Delta (44%) subregions. In the Sacramento River subregion, deep channels and wetlands/riparian areas each account each for 33% of total aquatic habitat.

By design, current monitoring does not evenly cover all four aquatic habitat types (Figure 6.3). 10 of the 12 DWR-EMP stations are located in deep channels, and the remaining 2 are located in shallower open water areas (< 2 m depth). Likewise, 6 of the 8 USGS nutrient sensors are moored in deep channels, and 2 are located in shallower channels. By design, these two monitoring efforts are not covering dead-end sloughs and wetlands/riparian areas. Overall, the majority of inventoried water quality monitoring stations (78 of 152)[5] are located in deep channels (Figure 6.5). In most subregions, most of the inventoried stations are located in deep channels. Exceptions are the South Delta (equal number of stations in deep channels and shallow areas), Suisun Bay (most stations in shallow areas), and the Eastside. The only mapped Eastside station located in a classified aquatic habitat type area is located in wetlands/riparian area[6].

Station "density" shows a slightly different picture (Figure 6.3). The relative monitoring coverage of aquatic habitat appears to be highest in dead-end sloughs. In the total region, there are 3 monitoring stations per 1,000 acres of dead-end slough habitat. However, dead-end sloughs are a small fraction of the total aquatic habitat, which skews the results. The station density in other habitat types is 2 for deep channels, 1 for shallow areas, and 0.1 for wetlands.

Station density per habitat type varies by subregion (Figure 6.3). A relatively high proportion of stations is located in dead-end sloughs in the South Bay (15 per 1,000 acres) and Central Delta (4 per 1,000 acres). In Suisun Bay and the North Delta, the deep-water habitat type has the highest station density (3 and 2 per 1,000 acres, respectively). In the confluence, there is approximately 1 station per 1,000 acres of deep water and one per 1,000 acres of shallow water. In the Sacramento River subregions, there are 3 stations each for each 1,000 acres of deep water, shallow water, and dead-end sloughs. Wetlands have a station density close to zero across the entire region (the station density of 0.1 for the Eastside is most likely a mapping artifact).

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[5] All monitoring locations listed in the Central Valley Monitoring Directory (www.centralvalleymonitoring.org) where nutrient (nitrate, ammonium, phosphate, etc.) or nutrient-related data (dissolved oxygen, chlorophyll) are currently collected.

[6] It is possible that this classification represents a mapping artifact (e.g. inaccurate site coordinates), which also points to the limitations of this evaluation. For example, two of three inventoried stations in the Eastside are located in unclassified areas and are therefore not considered here. However, manual correction of such errors was beyond the scope of this project.

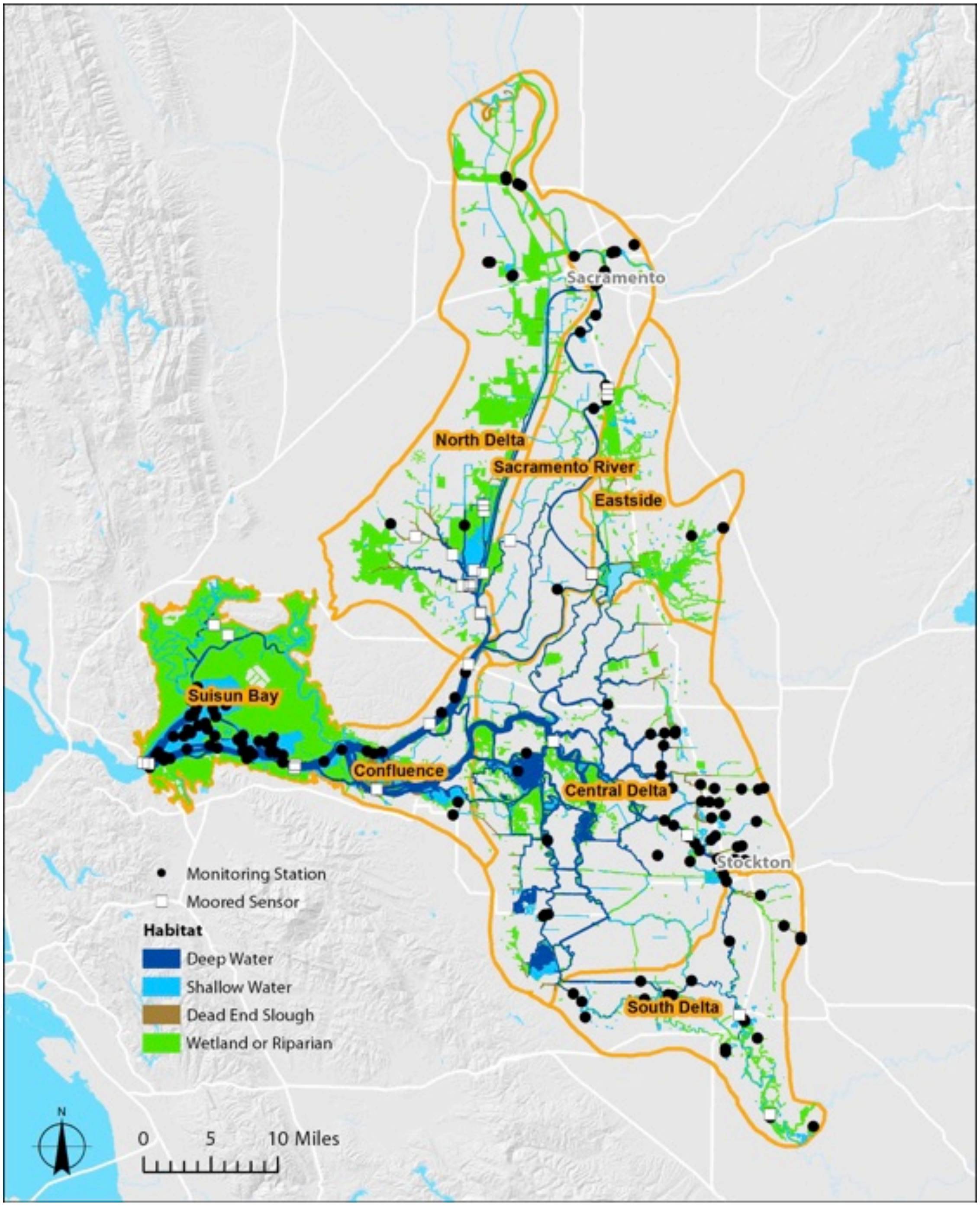


Figure 6.1. Distribution of operational aquatic habitat types in the Delta, in relation to proposed subregions and existing monitoring locations. The map shows all inventoried monitoring locations where nutrient (nitrate, ammonium, phosphate, etc.) or nutrient-related data (dissolved oxygen, chlorophyll) are currently collected. Not all locations are currently monitored for all of these constituents. For example, there are currently only eight active nitrate sensors and nine active chl sensors, but there are numerous additional moored sensors measuring dissolved oxygen.

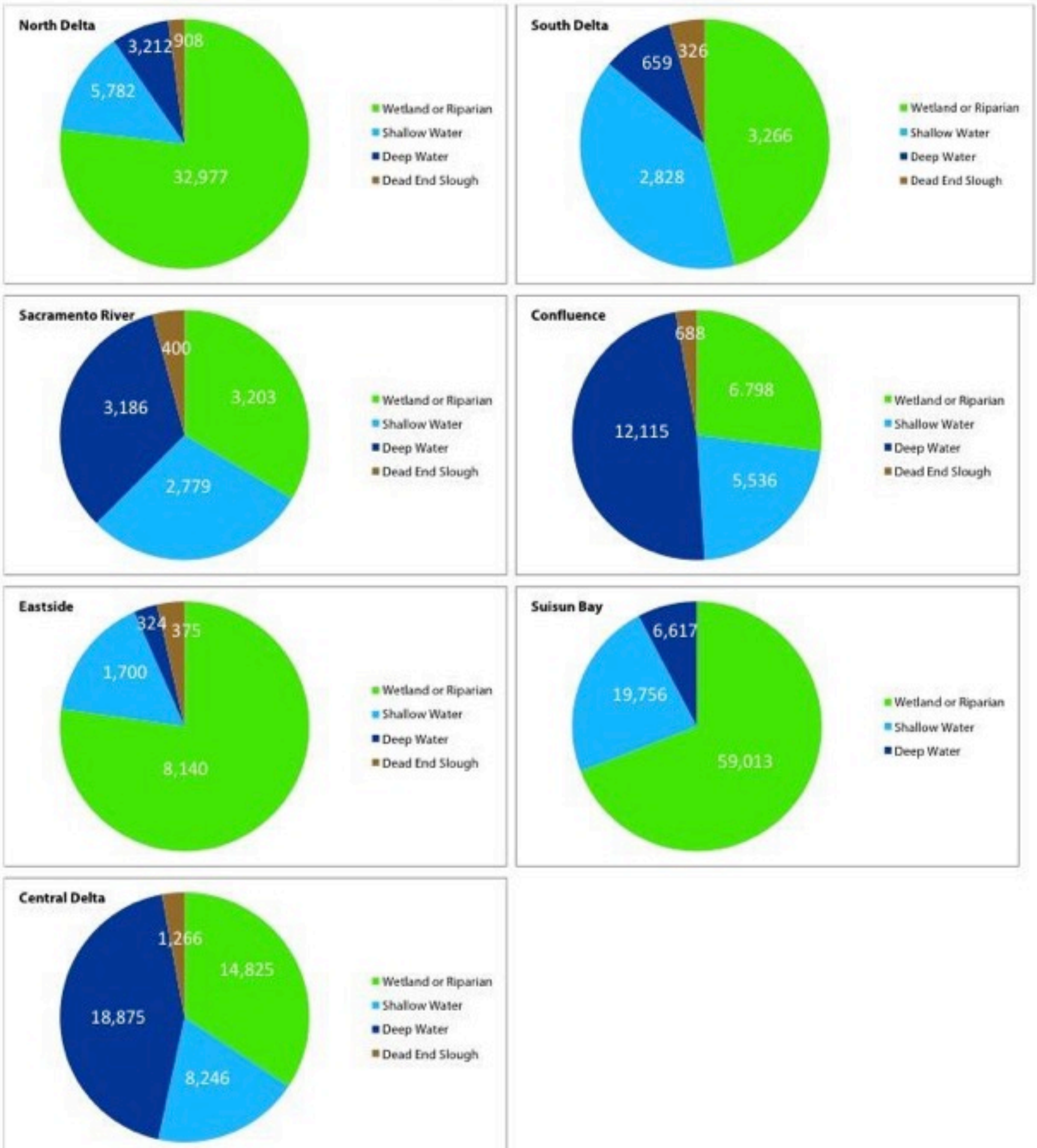


Figure 6.2. Total acreage of aquatic habitat type by subregion.

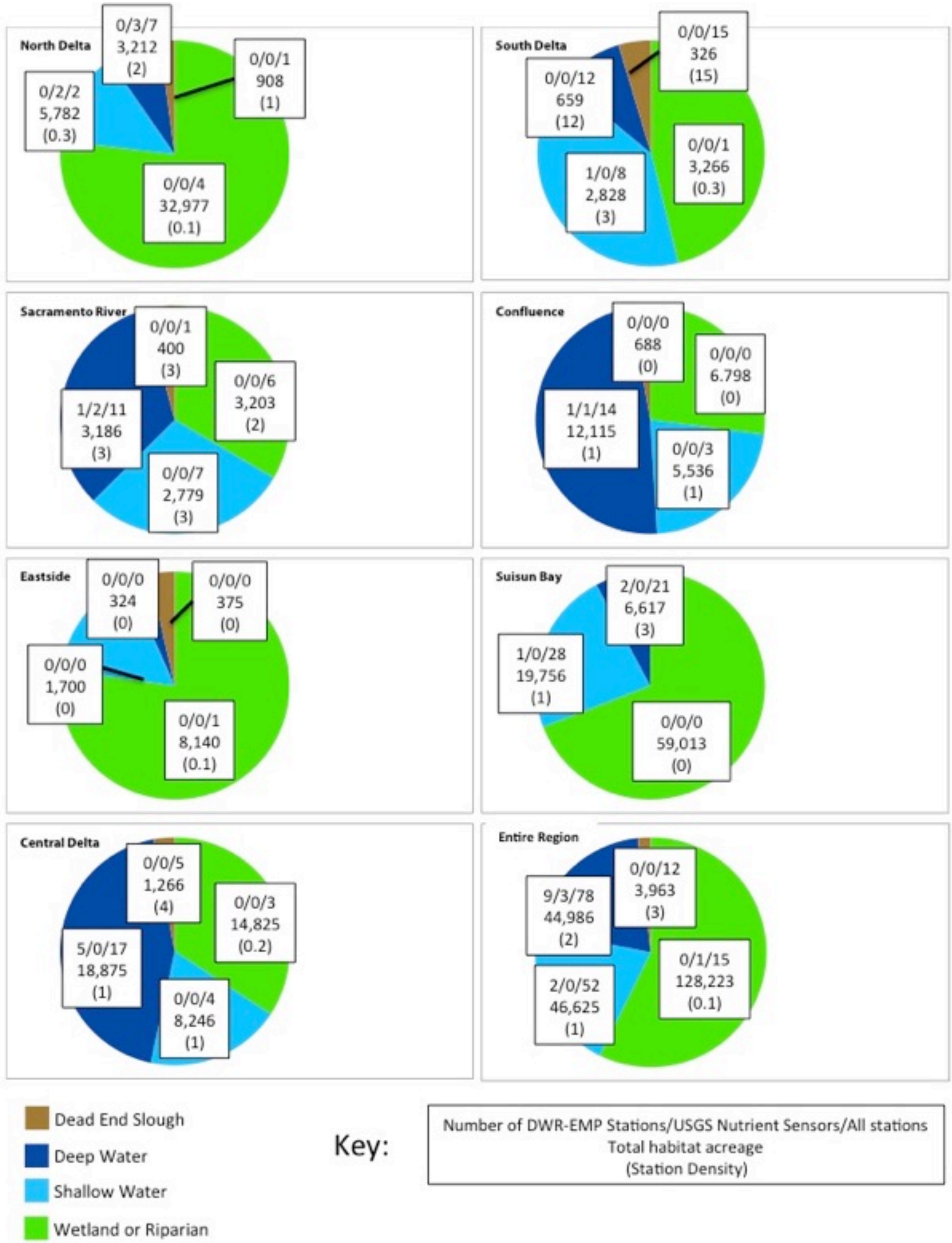


Figure 6.3. Distribution of monitoring stations (DWR-EMP/USGS nutrient sensors/All nutrient monitoring sites) and station density by subregion and aquatic habitat type.

The station density comparisons also suggest that the North Delta is the least monitored subregion overall. There are 0.3 stations per 1,000 acres of aquatic habitat in the North Delta, compared to an overall average of 1 station per 1,000 acres across the entire region. The South Delta has the highest station density overall with 3 stations per 1,000 acres.

One general conclusion that can be drawn from these comparisons is that wetlands are currently under-monitored for nutrients across the entire region. One potential approach for starting to fill this gap would be a pilot study that One potential approach for filling this gap would be a pilot study that builds on previous CalFed wetland mercury studies by strategically collecting nutrient data at the mouths of selected tidal marsh sloughs and selected outfalls from diked wetlands to develop the methodology and begin assessing the magnitudes of the tidal flux and discharge concentrations of nutrients. The pilot study would also identify essential co-variants such as tidal prism and diked wetland discharge volumes and schedules. Assuming that the pilot indicates further monitoring is warranted, a comprehensive map of tidal and diked Delta wetlands would be needed as a sample frame to support a probabilistic regional sampling plan consistent with the proposed tidal wetland special study of the San Francisco Bay RMP and the emerging Bay-Delta Wetlands Monitoring Program.

We can further conclude that the DWR-EMP and the USGS nutrient sensors do not currently monitor any dead-end sloughs and their combined efforts also do not cover all habitat/subregion combinations for deep water and shallow water. However, the information presented here also suggests that for many areas that are currently not covered by these efforts, monitoring locations already exist. If a more complete coverage is desired, a good approach might be to partner with programs that are currently monitoring other sites that are potentially of interest, or co-locate new sampling stops or sensor installations with the existing sites. Strategically placed high-frequency sensors are generally preferable, because they more fully capture the full range of variability encountered (see Figure 6.4) and at the same time provide better trend detection capability (see previous section on trend detection). However, sensors do not capture all the variables of interest. Therefore, it might be desirable to add wet chemistry at continuous sensor stations that are currently missing it. This could be done by piggybacking, i.e. by adding a stop at these stations to existing cruises or sampling runs. High-frequency mapping can cover large swaths of geographic area over a short amount of time and also inform strategic placement of fixed sites.

However, the key question to address will be how to capture the variability in the system, rather than the spatial coverage per se, within and across aquatic habitat types, within and across subregions. Modeling and advanced statistical analyses can be used to optimize monitoring. For example, simulated particle tracking studies with the DSM2 model can be used to identify stations where water masses are mixing as well as potential transformation "hot spots", i.e. potential transition zones with higher residence times where important nutrient processes would be expected to happen but that are currently not monitored. Figure 6.5 provides examples for the output from such a simulation. For example, these initial simulations suggest heterogeneity and thus potentially important transition zones in the Cache Slough area, the central and southern portions of the Central Delta, and along the Old River in the South Delta.

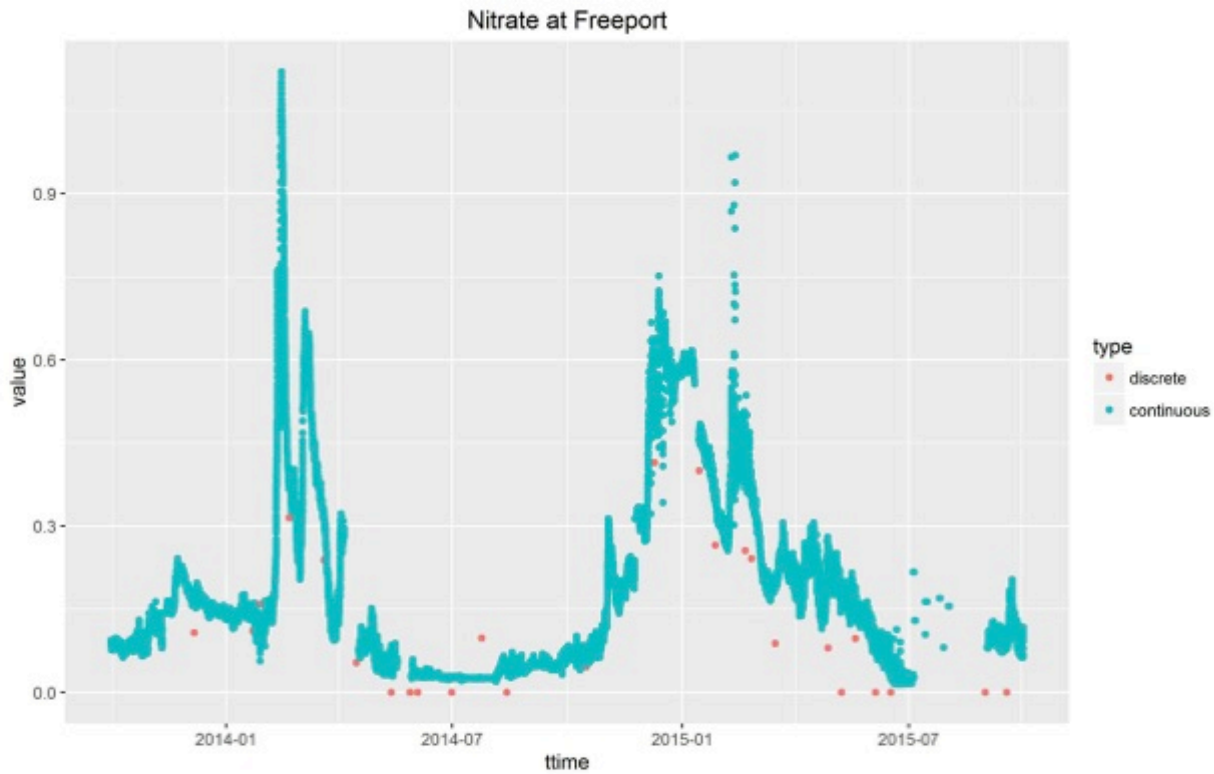
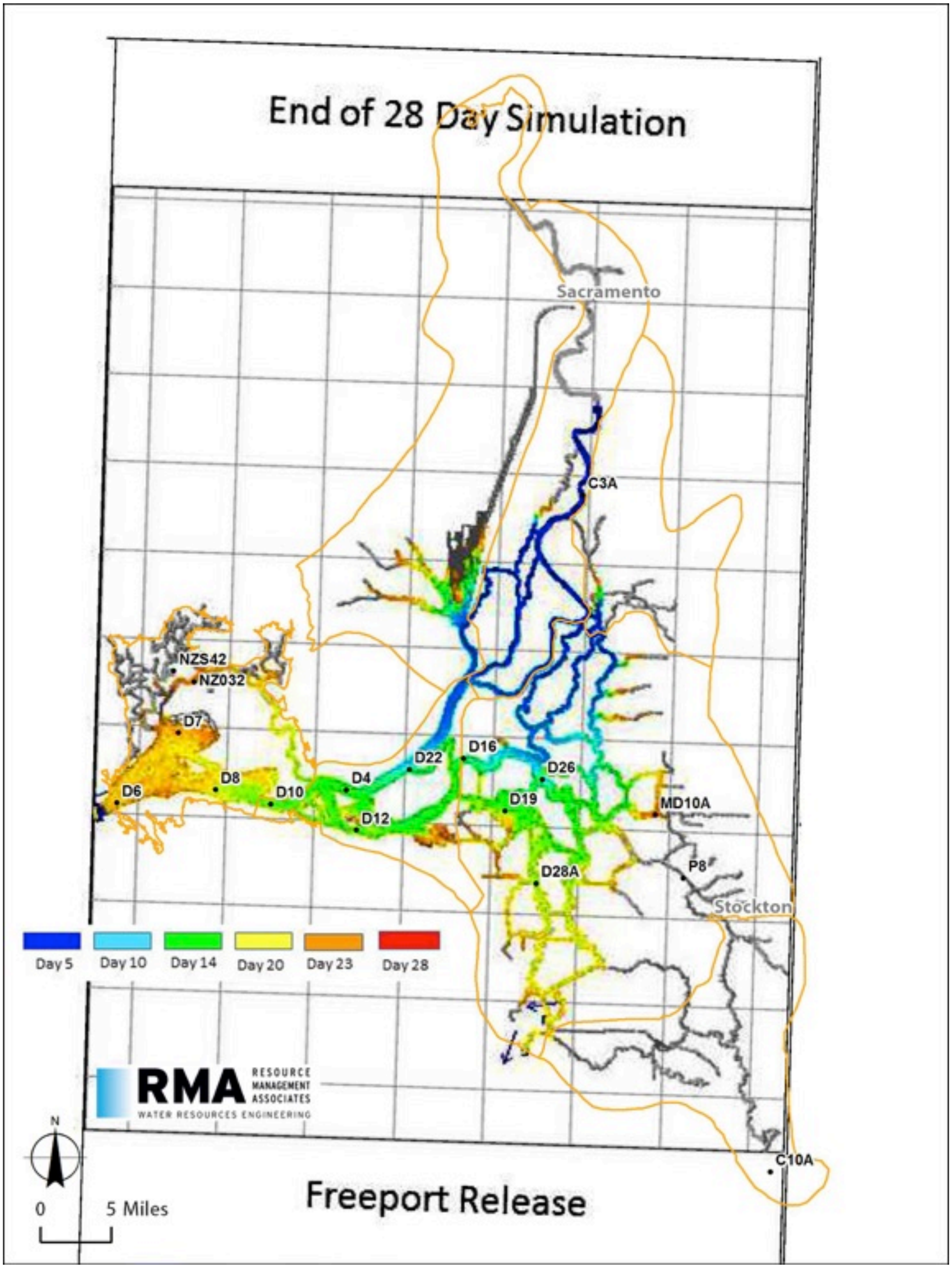


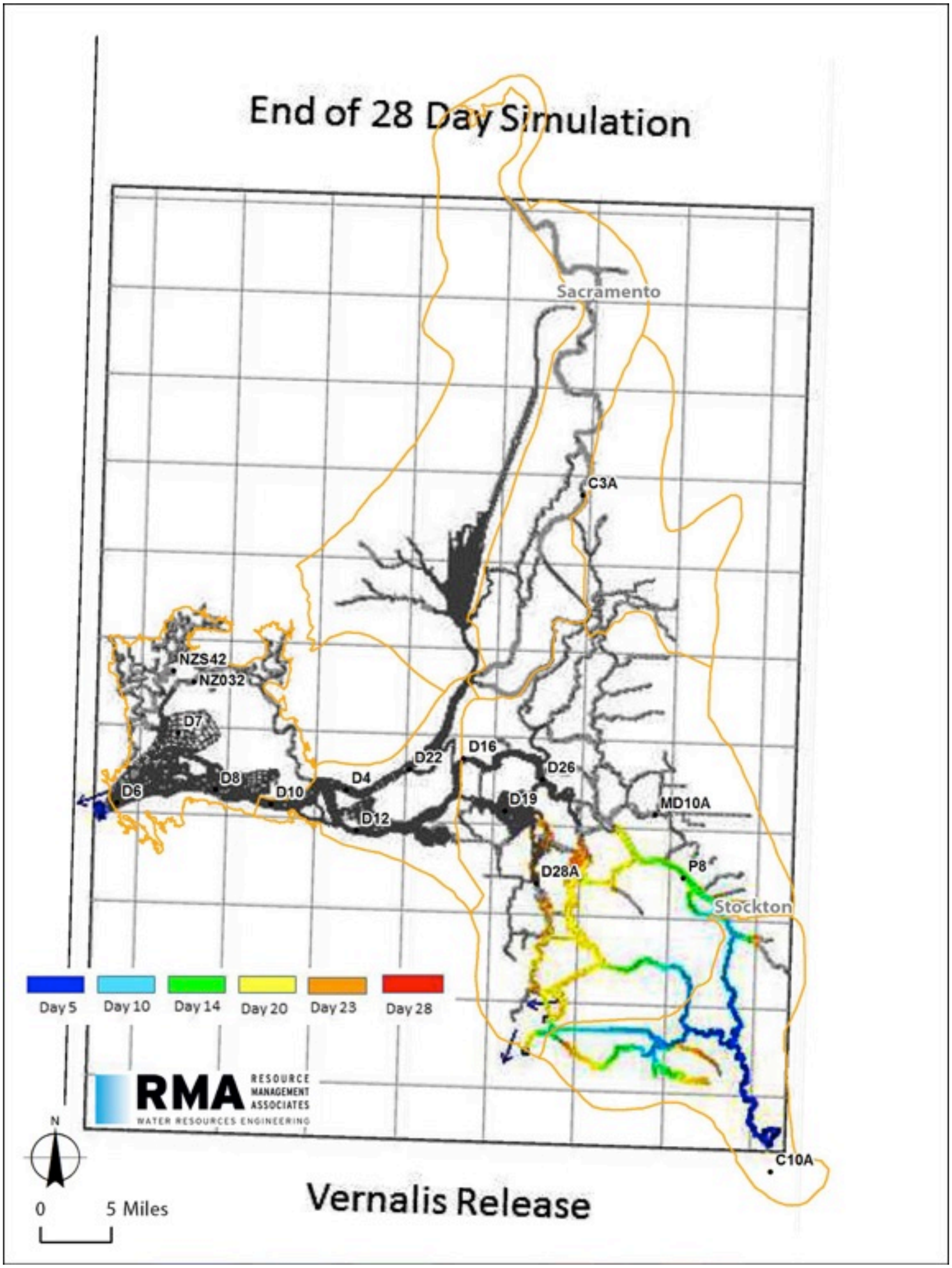
Figure 6.4. Time series for discrete (monthly sampling) and continuous (daily means) NO3 data (mg/L as N) collected at Sacramento River at Freeport.

Figure 6.5.a.



End of 28 Day Simulation
Sacramento
C3A
NZS42
NZ032
D7
D6
D8
D10
D4
D22
D16
D26
D12
D19
MD10A
D28A
P8
Stockton
Day 5
Day 10
Day 14
Day 20
Day 23
Day 28
RMA
RESOURCE MANAGEMENT ASSOCIATES
WATER RESOURCES ENGINEERING
N
0
5 Miles
C10A
Freeport Release

Figure 6.5.b.


End of 28 Day Simulation
Sacramento
C3A
NZS42
NZ032
D7
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D8
D10
D4
D22
D16
D26
D19
D12
MD10A
D28A
P8
Stockton
C10A
Day 5
Day 10
Day 14
Day 20
Day 23
Day 28
RMA
RESOURCE
MANAGEMENT
ASSOCIATES
WATER RESOURCES ENGINEERING
N
0
5 Miles
Vernalis Release

Figure 6.5.c.

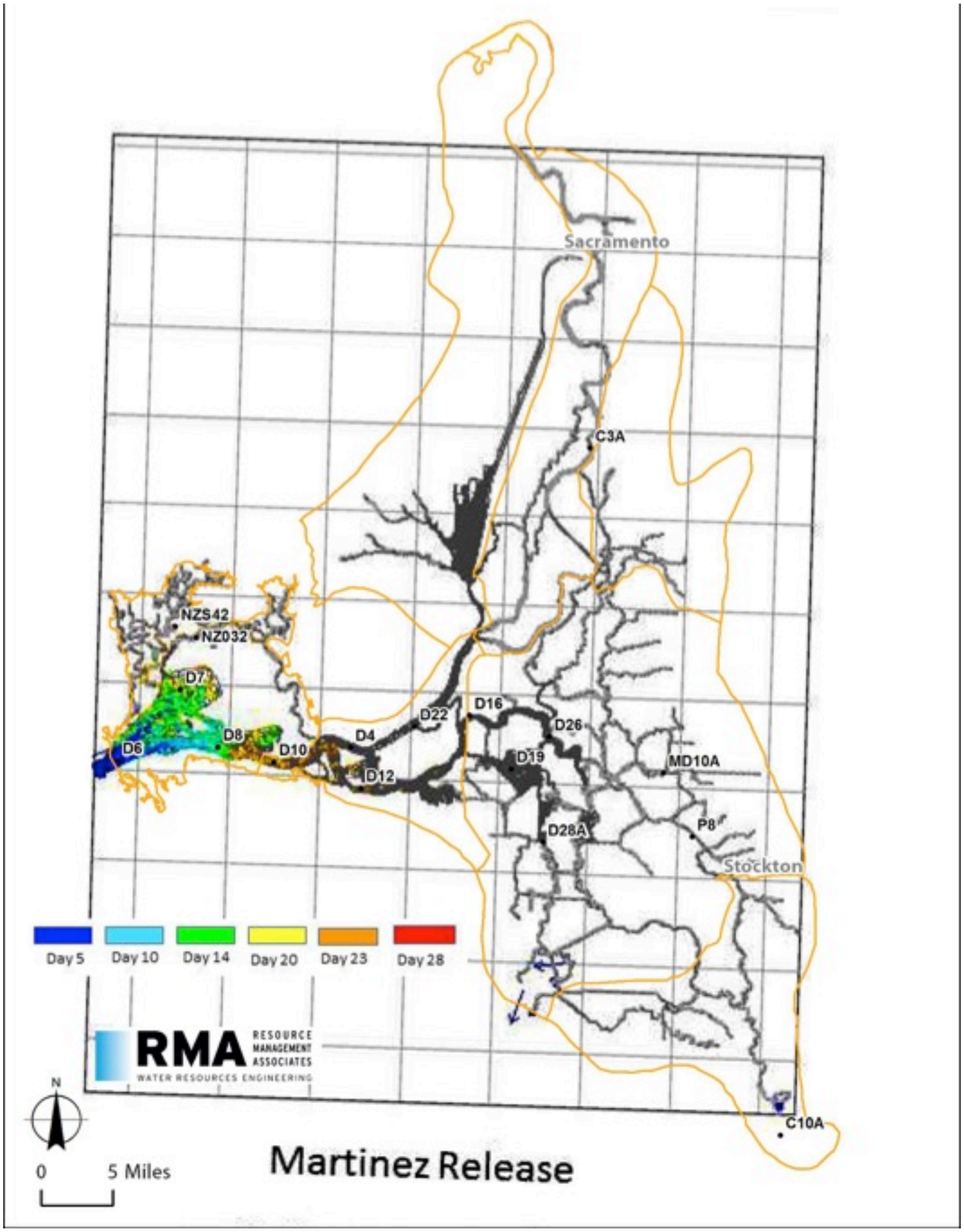

Figure 6.5.Water parcel "age" modeling can be applied to evaluate residence time and source mixing in different flow scenarios. This type of modeling is based on the DSM2 model and visualizes the simulated dispersion of water parcels, based on the tracking of virtual tracer particles over time from the point of their release. The colors in the map represent the "age" of water parcels. The simulations are for 28 days (representing late summer/early fall conditions in a year with average flow) and for releases from three different points: Freeport (a), Vernalis (b), and Martinez (c). The "youngest" particles are those that have been most recently released just before the simulation ended and represent shorter residence and/or travel times. The "oldest" particles are those that have been released at the beginning of the simulation and represent longer residence and/or travel times.

7. Summary

The primary purpose of this project was to identify options for optimizing the design of a status and trends nutrient monitoring program for the Delta. Specific goals were to:

1. Summarize, compare, and recommend potential subregions to be used for monitoring and assessing nutrients in the Delta;
2. Investigate spatial and temporal patterns in nutrient trends and potential drivers of these patterns relative to proposed subregions;
3. Evaluate if the current nutrient monitoring design is sufficient to characterize nutrient status and trends in proposed subregions; and
4. Assess the current monitoring coverage of different aquatic habitat types within each of the proposed subregions.

This work was conducted under the assumption that a status and trends monitoring program for nutrients in the Delta should cover all distinct subregions and be able to detect trends of ecological and management interest. Based on this assumption, the report contains detailed options for improving the nutrient monitoring program based on a careful review of the existing data and monitoring networks. The options are meant to be useful information to managers for continuous improvement, not to prescribe changes to long-running, successful programs. Implementation of any changes to existing monitoring programs will depend on the priorities and constraints of managers.

What are potential subregions for monitoring and assessing nutrients in the Delta?

Seven subregions appear to be sufficient to represent areas of different nutrient cycling in the Delta. The proposed subregions are shown in Figure 1.1. These subregions are (from north to south): Sacramento River, North Delta, Eastside, Suisun Bay, Central Delta, Confluence, and South Delta. The proposed subregions are derived from operational landscape units (OLUs), which are a newly developed planning tool for landscape-scale ecosystem restoration in the Delta (Grenier and Grossinger 2013). The OLU delineations are based on ecosystem functions and physical drivers such as water source and hydrology; therefore, there is a mechanistic linkage and scientific foundation for their use in the context of nutrient conditions and cycling. Our review also suggests that the proposed subregions are compatible with the DMS2 hydrologic model and are in general agreement with water quality regions used by major monitoring programs.

Are the dominant factors affecting nutrient concentrations similar within each subregion and distinct from those in other subregions?

The proposed subregions (Figure 3.1) are based on ecosystem functions and physical drivers; therefore, there is an underlying assumption that dominant factors affecting nutrient concentrations are similar within each subregion and distinct from those in other subregions. The results from the NMF analysis support the findings from a previous study (Novick et al. 2015), which suggest that there is significant heterogeneity in nutrient trends and their potential drivers *across* subregions (Figures 4.6 and 4.7). Two of the proposed subregions, Eastside and North Delta, could not be considered in this comparison because they represent data gaps.

Limited data availability also restricted the analysis of variability *within* subregions. The only two subregions with multiple DWR-EMP stations are the Suisun Bay and Central Delta subregions. Suisun Bay was found to be a rather homogeneous subregion, where potential drivers of nutrient trends and their relative influence are fairly consistent at different locations (Figures 4.6 and 4.7). On the other hand, results suggest that potential drivers of nutrient trends and their relative influence vary considerably at different monitoring locations in the proposed Central Delta region. As illustrated in Figures 4.6 and 4.7, dominant factors driving variability appear to be similar at stations D26 and D28A. However, the patterns observed at stations D26 and D28A (located in the inner Delta near the Confluence) are considerably different from those observed at stations MD10 (Disappointment Slough, near Eastside boundary) and P8 (San Joaquin River at Buckley Cove, near South Delta boundary). It is likely that different patterns in factors driving variability at these locations represent different peripheral influences, which is what hydrologic fingerprinting results presented in Novick et al. (2015) suggest. This observation raises the question whether the Central Delta should be further subdivided into smaller areas representing different peripheral influences. However, the patterns in nutrient variability observed at MD10 and P8 are at least in parts also driven by strong site-specific factors (Novick at al. 2016) and it is not certain how representative they are of surrounding areas. Moreover, the Central Delta is by definition a transition zone with various peripheral influences that vary inter-annually and seasonally in their strength and spatial extent, and a greater degree of heterogeneity is to be expected in this subregion. Additional data are needed (e.g, high-frequency mapping) to determine if dividing the Central Delta into more homogenous subdivisions would improve regional status and trends assessments and loads modeling

Within each subregion, is the current DWR-EMP monitoring design (number of stations, frequency, parameters) sufficient to characterize nutrient status and trends in the open channel habitats in response to loads?

A general insight is that the current DWR-EMP sampling does not cover all proposed subregions. Thus, the current spatial coverage is insufficient to characterize nutrient status and trends in all proposed subregions. There are currently no DWR-EMP sampling stations in the North Delta and the Eastside. The U.S. Geological Survey (USGS) has installed 5 moored sensors in the North Delta that have been generating data since August 2013. However, these sensors do not completely fill the gap, because they currently only measure nitrate and none of the other nutrient variables, such as ammonium or phosphate. Other programs are monitoring nutrients at stations located in the North Delta and Eastside, but their monitoring is currently not coordinated with the DWR-EMP in terms of parameters analyzed, frequency and timing of sampling, and comparability of data.

Co-locating discrete sampling stations with existing nutrient sensors in the North Delta would be a potential approach to fill the existing data gap for the North Delta subregion. In the Eastside subregion, a sensor/sampling station on the Mokelumne River located downstream of the confluence with the Cosumnes River (and upstream of the Delta Cross-Channel) could provide baseline information for this subregion.

The results from the power analysis suggest that the current DWR-EMP sampling can detect a 50% change over 10 years, or 4% per year change, for most subregions and parameters. Exceptions are ammonium in the Confluence and South Delta; and chlorophyll in the Confluence, Suisun Bay, and South Delta. Trend detection power for ammonium can be significantly improved by adding this analyte to two active DWR-EMP sampling sites (D12 and D22) that are currently not sampled for nutrients. For trend detection in chlorophyll, the analyses suggest that better utilization of sensors would be more beneficial than adding more discrete sampling points. The results from the power analysis suggest that continuous chlorophyll sensors maintained by the DWR-EMP may be able to detect a 10% decrease over ten years, or 1% per year change, in chlorophyll.

The results from the historic trends analyses and also from the power analysis suggest that adding more discrete sites could be beneficial for a few parameters and subregions to improve the ability to detect regional or subregional long-term trends of 50% decline over 10 years. In historic trend analyses, results were nearly identical for both test groups (active sites vs. active and discontinued sites combined) and there was no improvement in long-term trend detection by adding back in the discontinued stations. None of the trends detected in the combined data record of active and discontinued stations would have been missed by the active sites alone. However, the results from the power analysis suggest that adding back stations D12 and D22 is needed have sufficient power for trend detection for ammonia in the Confluence subregion.

The trend detection and power analyses conclude that strategically placed continuous sensors co-located with discrete sampling stations might be the best choice for improving the spatial and temporal coverage of monitoring (see Figure 7.1). Strategically placed high-frequency sensors more fully capture the range of variability encountered and at the same time provide better trend detection capability (Bergamaschi et al., in press). However, sensors do not capture all the variables of interest. Therefore, it might be desirable to co-locate discrete sampling at continuous sensor stations that are currently missing it. Modeling and advanced statistical analyses should be used to plan and optimize monitoring (i.e., inform where new or co-located stations would best be placed and how many there should be to capture the variability in a subregion).

Options for continuous monitoring of nutrients in the Delta with in-situ sensors will be presented in an upcoming report from USGS (Bergamaschi et al., in press). The recommendations from the upcoming report along with the results of the power analysis in this report should be considered together to develop recommendations for additional continuous monitoring in the Delta.

Within other habitats of the Delta, is the EMP nutrient monitoring program sufficient to characterize status and trends in nutrients and nutrient-related variables?

The analyses presented here reveal data gaps both in terms of spatial coverage and in terms of aquatic habitat coverage. In terms of habitats, there is a monitoring gap for wetlands. There is currently not any systematic nutrient monitoring for wetlands in the Delta. One potential approach for filling this gap would be a pilot study that builds on previous CalFed wetland mercury studies by strategically collecting nutrient data at the mouths of selected tidal marsh sloughs and selected outfalls from diked wetlands to develop the methodology and begin assessing the magnitudes of the tidal flux and discharge concentrations of nutrients.

Summary of Options for Improvements to Status and Trends Monitoring for Nutrients in the Delta

The options for improvements from this report were generated through careful review of existing data and monitoring designs. In order to make this information convenient and accessible to managers, all of the specific options identified in the report are listed below.

- The power analysis indicates that the current DWR-EMP monitoring network for nutrients provides sufficient statistical power to detect a 50% change over 10 years, or 4% per year change, for most subregions and parameters. Exceptions were ammonium and chlorophyll. The analysis suggests that current network provides insufficient statistical power to detect a 50% change over 10 years, or 4% per year change, in ammonium in the Confluence and South Delta, and in chlorophyll in the Confluence, South Delta, and Suisun Bay.
    a. In the Confluence, the statistical power to detect a 50% change over 10 years would increase from 68% to 99%, if ammonium measurements were resumed at stations D12 and D22.
    b. Resuming chl-a monitoring at D9 in Suisun Bay and resuming chl-a monitoring at one additional station in the Confluence (e.g. D11) would provide >80% statistical power to detect a 10-year change of 50% in these subregions.

- Results suggest that strategically placed continuous sensors would have potential for improving trend detection capabilities for those parameters for which they are available (nitrate and chlorophyll *a*). Discrete sampling sites should be co-located with sensors, because sensors do not capture all the variables of interest. Therefore, we recommend augmenting the existing monitoring network by
    a. Strategically placing co-located sensors and discrete sampling sites in currently under-monitored areas, such as the Eastside and the southern and eastern parts of the Central Delta;
    b. Adding discrete sampling to moored sensor sites that are currently missing it, such as the USGS nutrient sensors in the North Delta; and
    c. Augmenting the capabilities of existing moored sensor sites (i.e., USGS and DWR-EMP sensors) that are strategically located with additional sondes to expand the suite of parameters that can be continuously measured at each site. For example, nitrate sondes could be added to some of the existing chlorophyll sensors. Moreover, sensors for ammonium and phosphate are currently being tested and are expected to be available for routine deployment in the near future.
    d. Previous work (Senn and Novick 2014) suggests adding a new sensor station at Suisun Bay station D7 (Grizzly Bay), which was found to have consistently different conditions from stations D6 (Martinez) and D8 (Suisun Bay off Middle Point). There are plans for adding a USGS sensor station here in late summer 2016.

- Each subregion should have at least two stations in order to characterize heterogeneity both within and among subregions:

a. The Central Delta has proven to be particularly heterogeneous through the NMF analysis and we therefore recommend that at least four representative time-series stations be maintained there. The patterns in nutrient variability observed at the existing stations MD10 and P8 are at least in parts also driven by strong site-specific factors (Novick at al. 2016) and it is not certain how representative they are of surrounding areas. We therefore recommend adding two additional stations to the Central Delta. Potential locations include Little Potato Slough (MD7), Middle River at Union Point (P10A), San Joaquin River at Prisoner's Point (D29/existing DWR-EMP chlorophyll sensor), and Staten Island.
b. Confluence: potential locations include Deep Ship Channel near Antioch (D12/DWR-EMP chlorophyll sensor), Mallard Island (D10/DWR-EMP chlorophyll sensor), Sacramento River at Decker Island (USGS sensor DEC)/Emmaton (D22), Sacramento River at Rio Vista (D24), and San Joaquin River at Jersey Point (D15).
c. Eastside: potential locations include Mokelumne River at New Hope Road and Delta Cross-Channel.
d. North Delta: opportunities for co-locating discrete sampling sites with the existing USGS sensor stations include Cache Slough (CCH), Deep Water Shipping Channel (DWS), Liberty Cut (LCT), Liberty Island (LIB), and Toe Drain North of Stair Steps (TOE).
e. Sacramento River: potential locations include Freeport (USGS sensor and sampling station) and Walnut Grove (USGS sensor WGA)
f. South Delta: potential locations include San Joaquin River at Mossdale (P7, existing DWR-EMP chlorophyll sensor) and Old River near Tracy.

- Wetland areas, in particular, nutrient loading from Delta wetlands, are a data gap for the existing DWR-EMP monitoring program. One potential approach for filling this gap would be a pilot study that builds on previous CalFed wetland mercury studies by strategically collecting nutrient data at the mouths of selected tidal marsh sloughs and selected outfalls from diked wetlands to develop the methodology and begin assessing the magnitudes of the tidal flux and discharge concentrations of nutrients. The pilot study would also identify essential co-variants such as tidal prism and diked wetland discharge volumes and schedules. Assuming that the pilot indicates further monitoring is warranted, a comprehensive map of tidal and diked Delta wetlands would be needed as a sample frame to support a probabilistic regional sampling plan consistent with the proposed tidal wetland special study of the San Francisco Bay Regional Monitoring Program and the emerging plans for a Bay-Delta Wetlands Monitoring Program.

- Modeling, advanced statistical analyses, and targeted monitoring (e.g, high-frequency mapping) are recommended to determine:
  a. If dividing the Central Delta into more homogenous subdivisions would improve regional status and trends assessments and loads modeling; and
  b. Where new or co-located stations would best be placed and how many there should be to capture the variability in a subregion.

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