Appendix 3: Power Analysis of Nutrient Monitoring in the Delta

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1. Introduction

1.1. Motivation

An evaluation is needed whether the existing monitoring collects the appropriate data to determine 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 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 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 result in a nearly 95 percent reduction in ammonia discharged to the Delta by 2023 (Regional San 2016). The IEP-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 IEP-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.

1.2. Goals

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

1. Historic trend analysis: Estimate the power to detect long-term trends in nutrient concentrations in open water channels from existing IEP-EMP monitoring, 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 statistical analyses for both historic trend detection and forward-looking power analysis of trends tested the null hypothesis

H_0: trend = 0.

The alternate hypothesis

H_A: trend $\neq$ 0

was accepted when the probability that the alternate hypothesis is true was > 95% ($p < 0.05$).

2. Methods

Trend analysis was performed with the purpose to address three questions:

1. Are long-term trends at individual sites within a subregion consistent with each other?
2. Does the ability to detect long-term trends increase significantly, if additional stations are monitored?

3. Does the ability to detect long-term trends increase significantly, if the monitoring frequency is increased?

2.1. Historic Trend Analysis With Mann-Kendall Suite

Historic trends were analyzed on site-specific and subregional scales, using data from the IEP-EMP monthly sampling data over the longest uninterrupted period of record with an overlap of active and discontinued stations (1975–1995, see Table 1). The included variables were NH4, NO3, TN, PO4, TP, and chl-a. The long-term trend analyses were performed for all monthly data combined and for individual seasons. The individual seasons were spring (March, April, May), summer (June, July, August), fall (September, October, November), and winter (December, January, February)

Table 1. IEP-EMP stations and parameters that were included in the analysis. The table lists the stations, subregions, and total length of the data record for each parameter at each station.

Site Code	Location	Subregion	From	To (nh, nn, tn, p, tp)	To (chl)
C9	West Canal @ Clifton Court	Central Delta	Jan-75	Dec-95	Dec-95
D16	San Joaquin River @ Twitchell Island	Central Delta	Jan-75	Dec-95	Present
D19	Frank's Tract near Russo's Landing	Central Delta	Jan-75	Present	Present
D26	San Joaquin River @ Potato Slough	Central Delta	Jan-75	Present	Present
D28A	Old River @ Rancho Del Rio	Central Delta	Feb-75	Present	Present
MD7/MD7A	Little Potato Slough @ Terminous	Central Delta	Jan-75	Dec-95	Dec-95
MD10/MD10A	Disappointment Slough @ Bishop Cut	Central Delta	Jan-75	Present	Present
P8	San Joaquin River @ Buckley Cove	Central Delta	Feb-75	Present	Present
P10/P10A	Middle River @ Union Pt.	Central Delta	Mar-76	Dec-95	Dec-95
D4	Sacramento River above Point Sacramento	Confluence	Jan-75	Present	Present
D11	Sherman Lake near Antioch	Confluence	Jan-75	Dec-95	Dec-95
D12	San Joaquin River @ Antioch Ship Channel	Confluence	Jan-75	Dec-95	Present
D14A	Big Break near Oakley	Confluence	Jan-75	Dec-95	Dec-95
D15	San Joaquin River @ Jersey Point	Confluence	Jan-75	Dec-95	Dec-95
D22	Sacramento River @ Emmaton	Confluence	Jan-75	Dec-95	Present
D24	Sacramento River below Rio Vista Bridge	Confluence	Jan-75	Dec-95	Dec-95
C3/C3A	Sacramento River @ Hood	Sacramento River	Jan-75	Present	Present
C7	San Joaquin River @ Mossdale Bridge	South Delta	Jan-75	Dec-95	Dec-95
C10/C10A	San Joaquin River near Vernalis	South Delta	Jan-75	Present	Present
P12/P12A	Old River @ Oak Island	South Delta	Jan-75	Dec-95	Dec-95
D6	Suisun Bay @ Bulls Head nr. Martinez	Suisun Bay	Jan-75	Present	Present
D7	Grizzly Bay @ Dolphin nr. Suisun Slough	Suisun Bay	Jan-75	Present	Present
D8	Suisun Bay off Middle Point nr. Nichols	Suisun Bay	Jan-75	Present	Present
D9	Honker Bay near Wheeler Point	Suisun Bay	Jan-75	Dec-95	Dec-95

The 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). A chi-square test for homogeneity was performed to validate the use of the SKT/RKT test (Van Belle and Hughes 1984), since significant heterogeneity across seasons would negate the test results (Elridge et al. 2014). The chi-square test compared the SKT results (Kendall scores) of individual seasons (spring, summer, fall, winter) at individual sites. All data included in the analysis were adjusted for total river inflow using locally weighted scatterplot smoothing (LOWESS, Helsel and Hirsch 2002) with a span of 0.5 (Jassby 2008). The inflow-adjusted data consistently exhibited reduced coefficients of variance across all parameters and seasons compared to the original data.

2.2. Forward-looking Power Analysis

Based on the stated study objectives, we evaluated power using the different scenarios summarized in Table 2. 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 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 continuous data recorded between 7AM and 7PM (for chlorophyll at Antioch and Hood), or b) randomly selected from continuous data 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 2. Power analysis scenarios.

Design aspect	Evaluation	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	IEP-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); IEP-EMP discrete water quality data (2014-15) for C3. Parameter: NO3, chl-a	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.

3. Results

3.1. Historic trend analysis

3.1.1. Site-specific Trends

Figures 1 and 2 provide a visual summary of consistency in long-term trends detected in the time series from individual sites. For most of the nutrient variables, most of the sites had no detectable trends (i.e., no statistically significant trend); however, when long-term trends were detectable, the direction of trend was mostly consistent across the entire region. The exception was NH4, 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. Four sites in the Central Delta had detectable increasing trends for NH4, and one site (MD10) a detectable decreasing trend for NH4. 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).

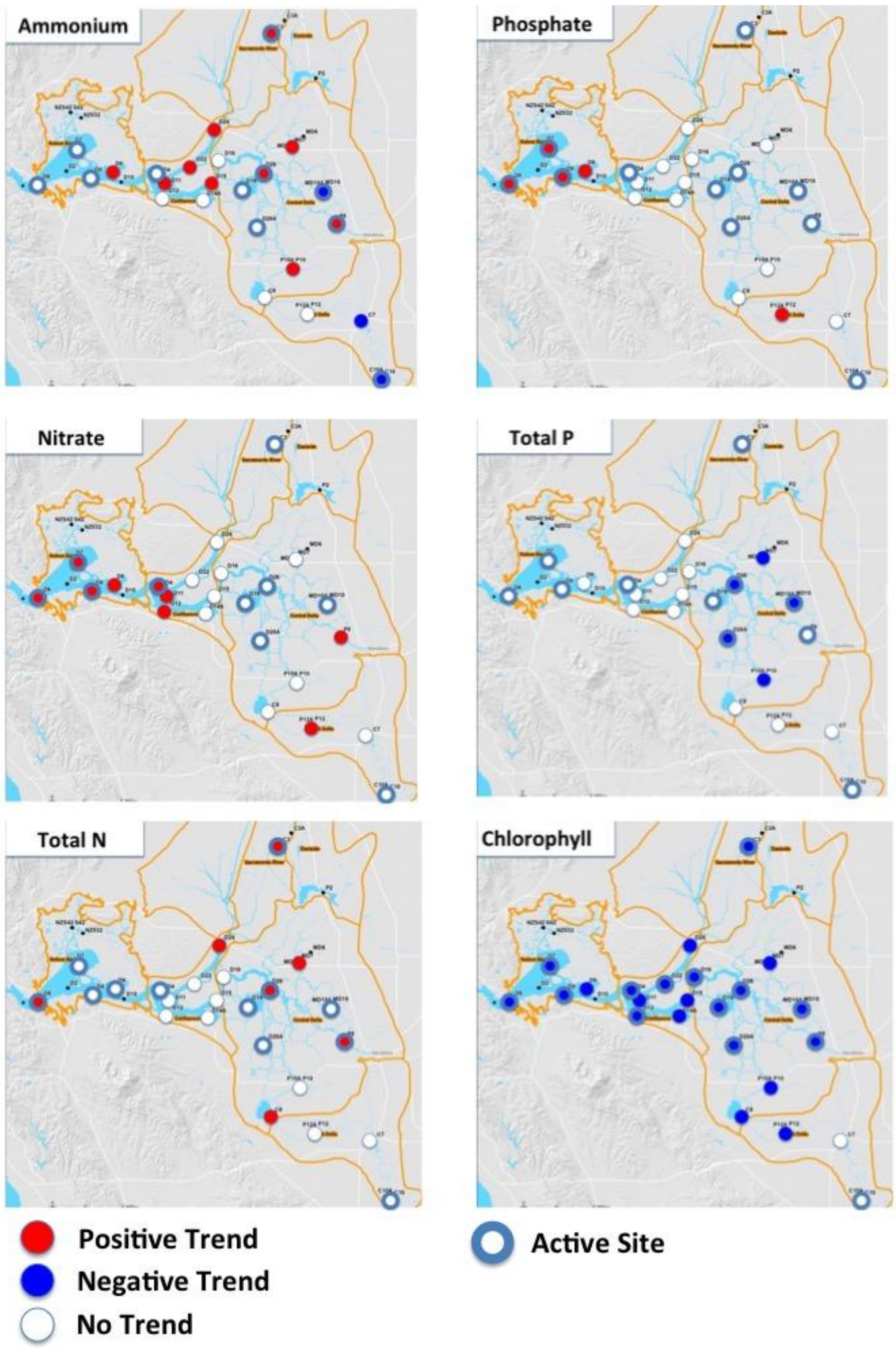

Figure 1. Site-specific detection of long-term trends at IEP-EMP stations, 1975-95 data (significance at $p \leq 0.05$).

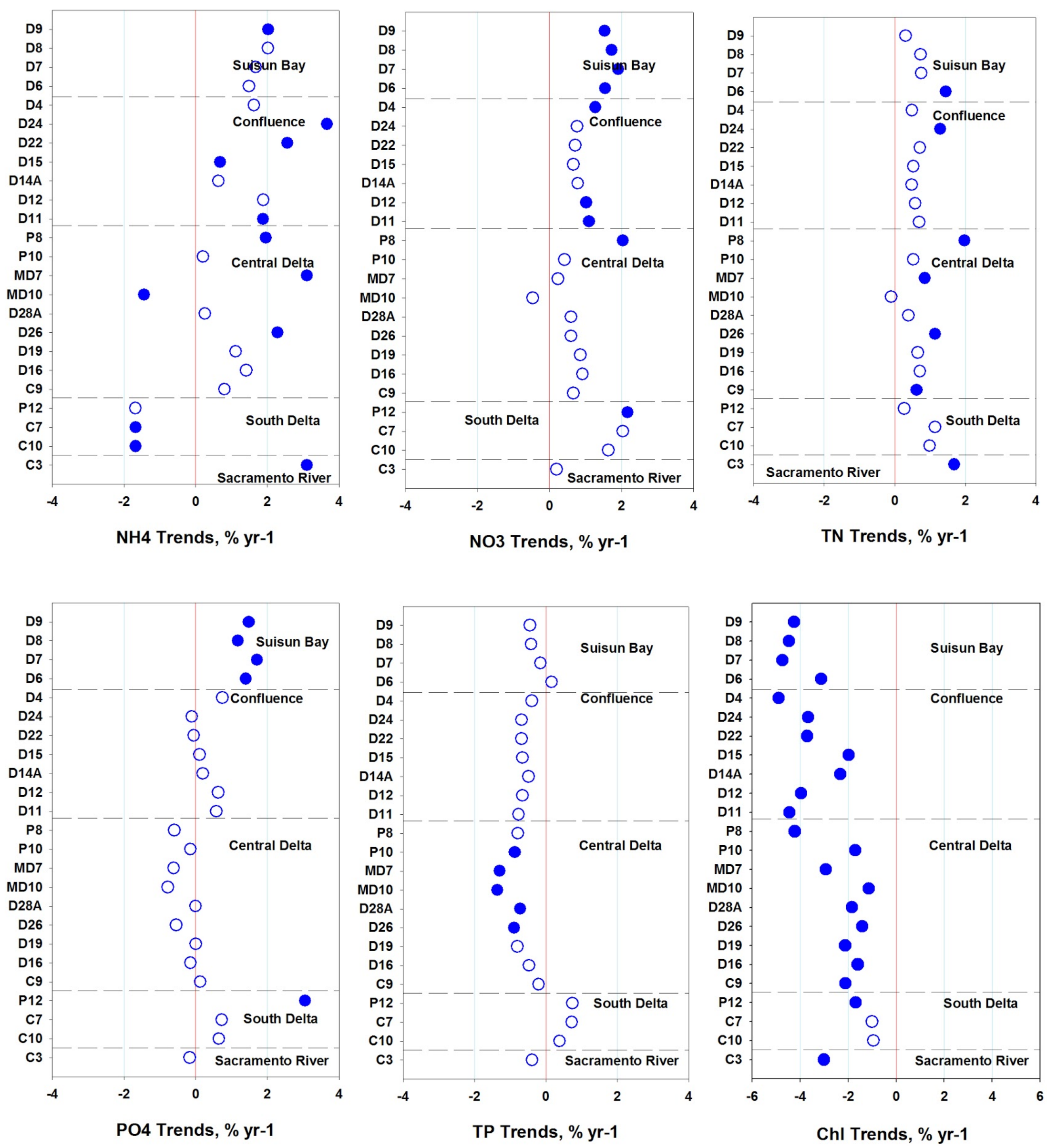

Figure 2. Magnitude (% change per year) of detected trends at DWR-EMP stations, 1975-95 data (significance at $p \leq 0.05$), for NH3, NO3, TN, PO4, TOP, and chl-a. Percent change per year is the ratio of the Sen slope to the long-term median for each variable.

3.1.2. Regional Trends

In subregions where there were multiple stations, we tested whether a regional trend test using all the historic stations would detect a different or clearer trend than the active stations alone. For most variables, there are currently only two subregions with multiple monitoring stations: Suisun Bay and Central Delta. Therefore, for most variables the analysis was limited to these two subregions. In the Central Delta, Stations MD10 and P8 were excluded from these analyses, because trends at MD10 were not consistent with those observed at other stations, and because P8 data for phosphate and total phosphorus did not pass the homogeneity test criterion for inclusion in the analyses.For chlorophyll, the Confluence has currently three active monitoring sites and was included in the trend analysis for chlorophyll.

The dark blue circles in Figure 3 represent the regional Kendall test results for regional trend detection in subregions based on active stations. The regional Kendall test detected significant increasing trends for NO3 and TN in both Central Delta and Suisun Bay, NH4 in Central Delta, and PO4 in Suisun Bay; and significant decreasing trends for chl-a in Central Delta, Confluence, and Suisun Bay.

The light blue circles in Figure 3 represent the regional Kendall test results for trend detection in subregions based on all stations combined (active and discontinued stations). There are four subregions with multiple monitoring stations, if the discontinued stations are included: Central Delta, Confluence, South Delta, and Suisun Bay. However, 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 test results do not suggest that adding back the same stations would significantly increase our ability to detect regional long-term trends. 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. This is consistent with the results at individual stations, because only one individual active site had a detectable trend (D6).

Separating the data by season may improve the ability to detect regional long-term trends for TP and TN. Significant decreasing trends in TP were detected for all subregions in the fall data that were not detected when combining data from all seasons (Compare Figure 3c with Figure 4d). Increasing trends in TN at the historic stations in Suisun Bay, the Confluence, and the South Delta were not significant in the combined data from all seasons but were significant in the separated winter data. Separating the data by season also increased the number of *individual* stations with detectable trends for 1) ammonium and total nitrogen in winter; 2) phosphate in summer, and 3) total phosphorus in fall. However, for ammonium and phosphate, separating the data by season did not increase trend detection in the combined results from multiple stations within subregions (compare Figure 3a with Figure 4a and Figure 3d with Figure 4c).

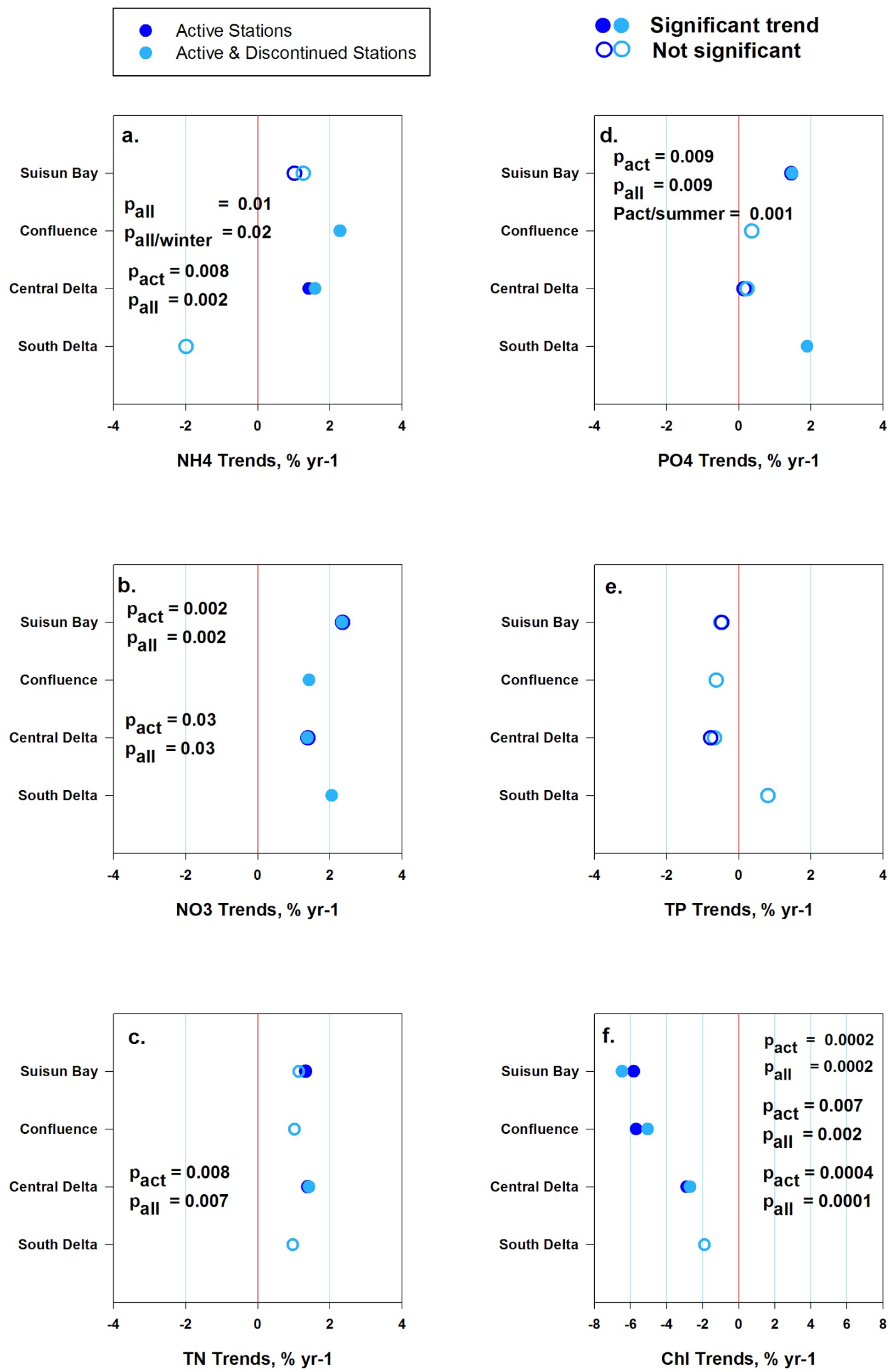

Figure 3. Comparison of detected trends using the RKT at active IE{-EMP stations and all stations (active plus discontinued), 1975-95 data (significance at $p \leq 0.05$), for NH3, NO3, TN, PO4, TP, and chl-a. Trends are expressed as the Sen slope divided by the long-term median for each subregion.

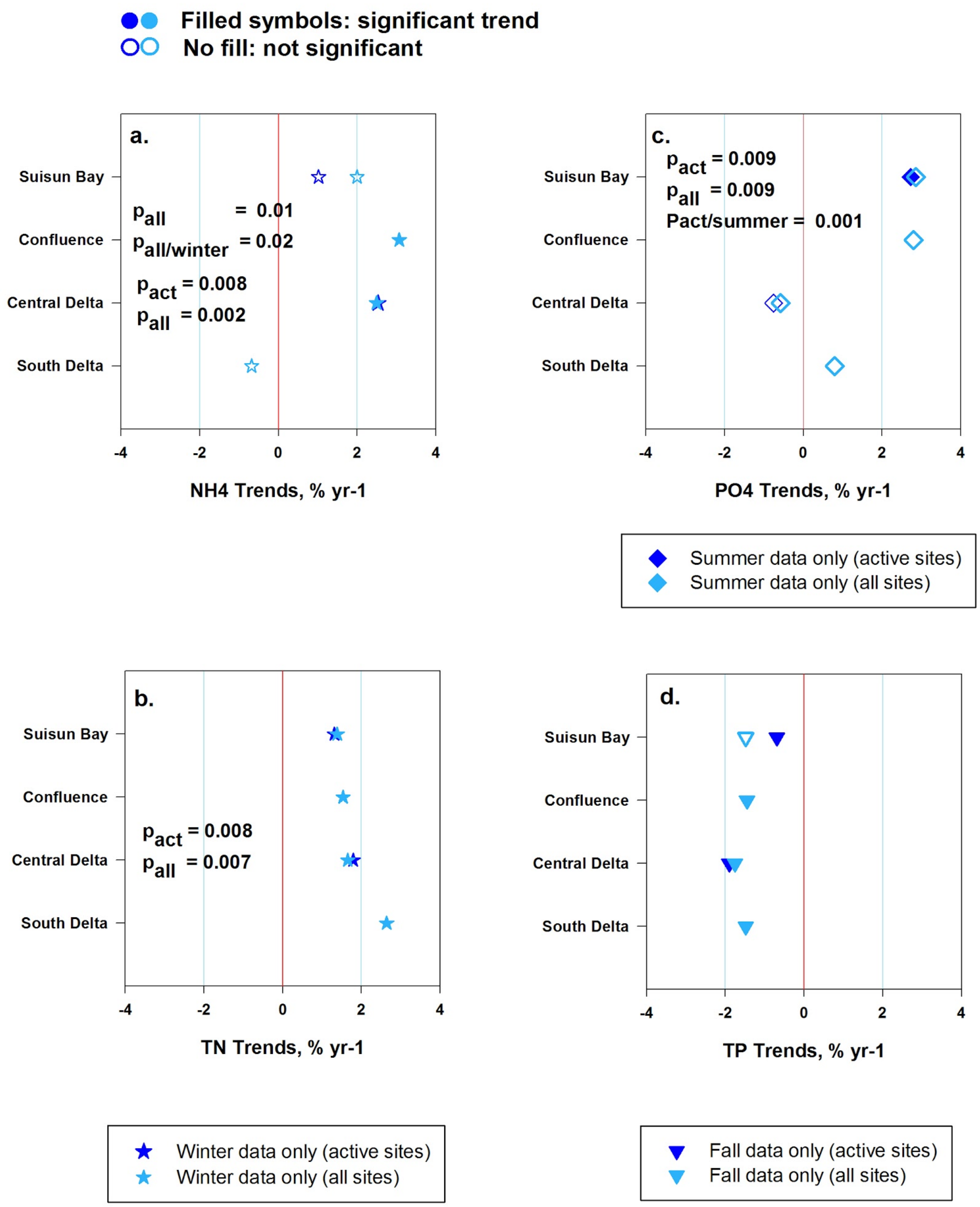

Figure 4. Comparison of detected trends using the RKT at active IEP-EMP stations and all stations (active plus discontinued), 1975-95 data (significance at $p \leq 0.05$), seasonally subsetted, for NH3, NO3, TN, PO4, TP, and chl-a. Trends are expressed as the Sen slope divided by the long-term median for each subregion.

3.2. Power Analysis

3.2.1. Spatial coverage

The power analysis indicates that the current IEP-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, with the exception of ammonium and chlorophyll (Tables 3-12).

For ammonium, the active monitoring stations provide less than sufficient statistical power to detect a 50% change over 10 years in the Confluence and South Delta subregions, both of which have currently only one active monitoring station. 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. D12 and D22 are active stations but are currently not monitored for ammonium or other nutrient variables. In the South Delta, resuming monitoring at discontinued stations would not significantly increase the statistical power for detecting trends in ammonium (Table 3).

For chlorophyll, the active monitoring stations provide less than sufficient statistical power to detect a 10-year change of 50% in the Suisun Bay, Confluence, and South Delta subregions (Table 12). The active monitoring stations provide 83% statistical power to detect a regional trend of 50% in the Central Delta only if MD10 and P8 are included. (These stations were not included in the power analyses for nutrient variables, because the detected trend for NH4 at MD10 was inconsistent with the regional trend for NH4, and because seasonal data for PO4 and TP at P8 did not meet the chi-square test criterion for homogeneity. However, the trend for chl-a at MD10 is consistent with the regional trends in chl, and seasonal data for chl-a at P8 meet the chi-square test criterion for homogeneity, and they were included in the power analysis for chl-a). 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. Resuming chl-a monitoring at discontinued stations in the South Delta would not significantly increase the statistical power for detecting long-term trends in chl-a in this subregion.

As quality control check on the power analysis, the magnitude of the actual trends detected in 1975-1995 were compared to what the power analysis would indicated to be the minimum detectable trends (Table 13). In theory, the actual detected trends in the past should be bigger than those predicted by the power analysis. The comparison shows the opposite which suggests that lower trends than predicted by the power analysis may be detectable by the existing network. A possible explanation is that the power analysis simulations used the standard error as a basis for simulating variance, which is a high estimate of variance.

Table 3. Power analysis results for detecting long-term trends in ammonium based on monthly discrete sampling by **IEP**-EMP**, using SKT for single and RKT for multiple stations.** Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay - Ammonium					
D6	5%	6%	17%	73%	**100%**
D6, D7	10%	16%	33%	83%	**99%**
D6, D7, D8	11%	20%	43%	**93%**	**100%**
D6, D7, D8, D9	14%	26%	58%	**98%**	**100%**
Confluence - Ammonium					
D4	4%	7%	15%	68%	**100%**
D4, D12, D22	14%	25%	57%	**99%**	**100%**
D4, D11, D12, D22	18%	31%	68%	**100%**	**100%**
D4, D11, D12, D14, D15, D22, D24	25%	50%	88%	**100%**	**100%**
Central Delta - Ammonium					
D19	6%	8%	22%	87%	**100%**
D19, D26	12%	23%	54%	**98%**	**100%**
D19, D26, D28	19%	33%	70%	**100%**	**100%**
D16, D19, D26, D28	20%	39%	79%	**100%**	**100%**
D16, D19, D26, D28, P10	22%	43%	84%	**100%**	**100%**
C9, D16, D19, D26, D28, P10	28%	52%	90%	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	29%	56%	**93%**	**100%**	**100%**
South Delta - Ammonium					
C10	6%	6%	11%	51%	**97%**
C7, C10	7%	9%	18%	64%	**97%**
C7, C10, P12	9%	10%	24%	76%	**99%**

Table 4. Power analysis results for detecting long-term trends in winter data (December, January, February) for ammonium, IEP-EMP, using SKT for single and RKT for multiple stations. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Ammonium/Winter					
D6	4%	6%	7%	30%	80%
D6, D7	11%	17%	28%	67%	**96%**
D6, D7, D8	16%	22%	38%	83%	**100%**
D6, D7, D8, D9	22%	31%	53%	**95%**	**100%**
Confluence – Ammonium/Winter					
D4	4%	4%	8%	29%	79%
D4, D12, D22	24%	30%	45%	91%	**100%**
D4, D11, D12, D22	29%	38%	59%	**97%**	**100%**
D4, D11, D12, D14, D15, D22, D24	37%	54	80%	**100%**	**100%**
Central Delta – Ammonium/Winter					
D19	4%	4%	11%	43%	**95%**
D19, D26	23%	33%	49%	94%	**100%**
D19, D26, D28	31%	43%	62%	**99%**	**100%**
D16, D19, D26, D28	35%	50%	72%	**100%**	**100%**
D16, D19, D26, D28, P10	37%	52%	76%	**100%**	**100%**
C9, D16, D19, D26, D28, P10	40%	58%	83%	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	46%	63%	88%	**100%**	**100%**
South Delta – Ammonium/Winter					
C10	5%	5%	5%	14%	52%
C7, C10	9%	13%	19%	43%	83%
C7, C10, P12	12%	14%	23%	54%	93%

Table 5. Power analysis results for detecting long-term trends in nitrate, based on monthly discrete sampling by IEP-EMP, using SKT for single and RKT for multiple stations. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Nitrate					
D6	4%	9%	27%	94%	**100%**
D6, D7	13%	27%	56%	**99%**	**100%**
D6, D7, D8	16%	36%	75%	**100%**	**100%**
D6, D7, D8, D9	23%	47%	87%	**100%**	**100%**
Confluence – Nitrate					
D4	7%	9%	30%	**97%**	**100%**
D4, D12, D22	23%	45%	86%	**100%**	**100%**
D4, D11, D12, D22	28%	56%	93%	**100%**	**100%**
D4, D11, D12, D14, D15, D22, D24	39%	70%	**99%**	**100%**	**100%**
Central Delta – Nitrate					
D19	5%	10%	24%	92%	**100%**
D19, D26	17%	27%	58%	**99%**	**100%**
D19, D26, D28	20%	38%	74%	**100%**	**100%**
D16, D19, D26, D28	24%	48%	86%	**100%**	**100%**
D16, D19, D26, D28, P10	28%	55%	93%	**100%**	**100%**
C9, D16, D19, D26, D28, P10	34%	62%	**97%**	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	35%	64%	**97%**	**100%**	**100%**
South Delta – Nitrate					
C10	5%	8%	25%	88%	**100%**
C7, C10	13%	21%	51%	**97%**	**100%**
C7, C10, P12	17%	32%	68%	**99%**	**100%**

Table 6. Power analysis results for detecting long-term trends in total nitrogen, based on monthly discrete sampling by IEP-EMP, using SKT for single and RKT for multiple stations. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Total Nitrogen					
D6	5%	13%	42%	**98%**	**100%**
D6, D7	15%	33%	72%	**100%**	**100%**
D6, D7, D8	22%	50%	89%	**100%**	**100%**
D6, D7, D8, D9	29%	65%	**97%**	**100%**	**100%**
Confluence – Total Nitrogen					
D4	8%	16%	59%	**100%**	**100%**
D4, D12, D22	34%	65%	**97%**	**100%**	**100%**
D4, D11, D12, D22	38%	73%	**99%**	**100%**	**100%**
D4, D11, D12, D14, D15, D22, D24	54%	90%	**100%**	**100%**	**100%**
Central Delta – Total Nitrogen					
D19	6%	13%	40%	**99%**	**100%**
D19, D26	16%	33%	79%	**100%**	**100%**
D19, D26, D28	26%	53%	92%	**100%**	**100%**
D16, D19, D26, D28	34%	65%	**97%**	**100%**	**100%**
D16, D19, D26, D28, P10	38%	72%	**99%**	**100%**	**100%**
C9, D16, D19, D26, D28, P10	46%	80%	**100%**	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	49%	83%	**100%**	**100%**	**100%**
South Delta – Total Nitrogen					
C10	5%	11%	35%	**98%**	**100%**
C7, C10	18%	32%	72%	**100%**	**100%**
C7, C10, P12	24%	45%	88%	**100%**	**100%**

Table 7. Power analysis results for detecting long-term trends in winter data (December, January, February) for total nitrogen, based on monthly discrete sampling by IEP-EMP. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Total Nitrogen/Winter					
D6	5%	6%	15%	60%	**100%**
D6, D7	12%	19%	36%	88%	**100%**
D6, D7, D8	18%	30%	58%	**99%**	**100%**
D6, D7, D8, D9	24%	39%	67%	**100%**	**100%**
Confluence – Total Nitrogen/Winter					
D4	5%	7%	17%	57%	**100%**
D4, D12, D22	26%	42%	65%	**100%**	**100%**
D4, D11, D12, D22	28%	43%	68%	**100%**	**100%**
D4, D11, D12, D14, D15, D22, D24	39%	61%	89%	**100%**	**100%**
Central Delta – Total Nitrogen/Winter					
D19	4%	5%	12%	48%	**96%**
D19, D26	20%	23%	40%	89%	**100%**
D19, D26, D28	29%	35%	57%	**97%**	**100%**
D16, D19, D26, D28	31%	41%	69%	**99%**	**100%**
D16, D19, D26, D28, P10	34%	47%	77%	**100%**	**100%**
C9, D16, D19, D26, D28, P10	41%	54%	83%	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	42%	58%	87%	**100%**	**100%**
South Delta – Total Nitrogen/Winter					
C10	5%	5%	9%	40%	91%
C7, C10	13%	17%	38%	83%	**100%**
C7, C10, P12	16%	27%	51%	**96%**	**100%**

Table 8. Power analysis results for detecting long-term trends for phosphate, based on monthly discrete sampling by IEP-EMP. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yrDecline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Phosphate					
D6	7%	13%	45%	**100%**	**100%**
D6, D7	10%	23%	58%	**99%**	**100%**
D6, D7, D8	10%	30%	75%	**100%**	**100%**
D6, D7, D8, D9	11%	36%	83%	**100%**	**100%**
Confluence – Phosphate					
D4	6%	15%	50%	**100%**	**100%**
D4, D12, D22	13%	40%	88%	**100%**	**100%**
D4, D11, D12, D22	16%	51%	94%	**100%**	**100%**
D4, D11, D12, D14, D15, D22, D24	28%	73%	**99%**	**100%**	**100%**
Central Delta – Phosphate					
D19	7%	14%	49%	**100%**	**100%**
D19, D26	13%	30%	79%	**100%**	**100%**
D19, D26, D28	17%	39%	88%	**100%**	**100%**
D16, D19, D26, D28	20%	50%	94%	**100%**	**100%**
D16, D19, D26, D28, P10	25%	63%	**98%**	**100%**	**100%**
C9, D16, D19, D26, D28, P10	32%	71%	**99%**	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	35%	75%	**99%**	**100%**	**100%**
South Delta – Phosphate					
C10	6%	9%	24%	92%	**100%**
C7, C10	12%	18%	44%	**96%**	**100%**
C7, C10, P12	12%	24%	56%	**99%**	**100%**

Table 9. Power analysis results for detecting long-term trends in summer data (December, January, February) for phosphate, based on monthly discrete sampling by IEP-EMP. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr-Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Phosphate/Summer					
D6	4%	5%	10%	49%	**98%**
D6, D7	4%	8%	15%	73%	**100%**
D6, D7, D8	5%	9%	22%	90%	**100%**
D6, D7, D8, D9	5%	10%	28%	**96%**	**100%**
Confluence – Phosphate/Summer					
D4	5%	7%	14%	59%	**100%**
D4, D12, D22	5%	12%	36%	**98%**	**100%**
D4, D11, D12, D22	6%	16%	45%	**99%**	**100%**
D4, D11, D12, D14, D15, D22, D24	9%	25%	73%	**100%**	**100%**
Central Delta – Phosphate/Summer					
D19	5%	6%	13%	59%	**99%**
D19, D26	5%	8%	21%	88%	**100%**
D19, D26, D28	6%	11%	30%	**95%**	**100%**
D16, D19, D26, D28	6%	14%	39%	**98%**	**100%**
D16, D19, D26, D28, P10	8%	15%	45%	**100%**	**100%**
C9, D16, D19, D26, D28, P10	8%	18%	54%	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	9%	20%	61%	**100%**	**100%**
South Delta – Phosphate/Summer					
C10	4%	5%	11%	44%	88%
C7, C10	5%	6%	14%	65%	**100%**
C7, C10, P12	5%	8%	18%	81%	**100%**

Table 10. Power analysis results for detecting long-term trends for total phosphorus, based on monthly discrete sampling by IEP-EMP, using SKT for single and RKT for multiple stations. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Total Phosphorus					
D6	6%	10%	30%	**95%**	**100%**
D6, D7	5%	6%	17%	70%	**100%**
D6, D7, D8	4%	7%	18%	85%	**100%**
D6, D7, D8, D9	4%	10%	29%	**96%**	**100%**
Confluence – Total Phosphorus					
D4	4%	10%	26%	94%	**100%**
D4, D12, D22	6%	10%	37%	**99%**	**100%**
D4, D11, D12, D22	6%	12%	45%	**100%**	**100%**
D4, D11, D12, D14, D15, D22, D24	8%	22%	77%	**100%**	**100%**
Central Delta – Total Phosphorus					
D19	7%	17%	53%	**100%**	**100%**
D19, D26	7%	11%	37%	**97%**	**100%**
D19, D26, D28	5%	16%	52%	**100%**	**100%**
D16, D19, D26, D28	7%	19%	64%	**100%**	**100%**
D16, D19, D26, D28, P10	7%	25%	74%	**100%**	**100%**
C9, D16, D19, D26, D28, P10	8%	28%	79%	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	10%	31%	84%	**100%**	**100%**
South Delta – Total Phosphorus					
C10	5%	9%	26%	92%	**100%**
C7, C10	4%	8%	24%	87%	**100%**
C7, C10, P12	6%	9%	31%	**96%**	**100%**

Table 11. Power analysis results for detecting long-term trends in fall data (September, October, November) for total phosphorus, based on monthly discrete sampling by IEP-EMP, using SKT for single and RKT for multiple stations. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Total Phosphorus/Fall					
D6	3%	6%	11%	51%	**98%**
D6, D7	5%	6%	16%	70%	**100%**
D6, D7, D8	4%	7%	18%	85%	**100%**
D6, D7, D8, D9	4%	10%	29%	**96%**	**100%**
Confluence – Total Phosphorus/Fall					
D4	3%	6%	8%	28%	77%
D4, D12, D22	6%	10%	37%	**99%**	**100%**
D4, D11, D12, D22	6%	12%	45%	**100%**	**100%**
D4, D11, D12, D14, D15, D22, D24	8%	22%	77%	**100%**	**100%**
Central Delta – Total Phosphorus/Fall					
D19	4%	8%	22%	85%	**100%**
D19, D26	7%	11%	37%	**97%**	**100%**
D19, D26, D28	5%	16%	52%	**100%**	**100%**
D16, D19, D26, D28	7%	19%	64%	**100%**	**100%**
D16, D19, D26, D28, P10	7%	25%	74%	**100%**	**100%**
C9, D16, D19, D26, D28, P10	8%	28%	79%	**100%**	**100%**
C9, D16, D19, D26, D28, MD7, P10	10%	31%	84%	**100%**	**100%**
South Delta – Total Phosphorus/Fall					
C10	5%	5%	9%	39%	91%
C7, C10	4%	8%	24%	87%	**100%**
C7, C10, P12	6%	9%	31%	**96%**	**100%**

Table 12. Power analysis results for detecting long-term trends for chlorophyll, based on monthly discrete sampling by IEP-EMP, using SKT for single and RKT for multiple stations.. Results are based on estimated seasonal and inter-annual variability for each parameter and station, and assumed trends. Red text represents the current monitoring network, and the blue areas highlight results that are ≥ 80% power. Results ≥ 95% are bold-faced.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
	Trend - Annual Decline				
	0.5%	**1%**	**2%**	**4%**	**7%**
Suisun Bay – Chlorophyll					
D6	5%	7%	14%	67%	**100%**
D6, D7	6%	8%	18%	68%	**97%**
D6, D7, D8	8%	9%	22%	78%	**99%**
D6, D7, D8, D9	6%	9%	26%	**84%**	**100%**
Confluence – Chlorophyll					
D4	4%	6%	10%	49%	**97%**
D4, D12, D22	7%	12%	24%	75%	**100%**
D4, D11, D12, D22	6%	13%	26%	**83%**	**100%**
D4, D11, D12, D14, D15, D22, D24	11%	17%	44%	**95%**	**100%**
Central Delta – Chlorophyll					
D19	4%	6%	13%	55%	**99%**
D19, D26	7%	6%	11%	37%	84%
D19, D26, D28	8%	9%	13%	57%	**97%**
D16, D19, D26, D28	7%	11%	19%	71%	**99%**
D16, D19, D26, D28, P10	8%	11%	24%	77%	**100%**
D19, D26, D28, MD10, P8[1]	8%	12%	26%	83%	**100%**
C9, D16, D19, D26, D28, P10	8%	12%	29%	84%	**100%**
C9, D16, D19, D26, D28, MD7, P10	8%	14%	33%	89%	**100%**
South Delta – Chlorophyll					
C10	5%	6%	14%	67%	**99%**
C7, C10	7%	9%	14%	52%	**91%**
C7, C10, P12	8%	9%	19%	71%	**99%**

[1] MD10 and P8 were only included in the simulations for chlorophyll.

Table 13. Comparison of detected historic trends (1975 - 1995 data), expressed as the Sen slope divided by the long-term median (%/yr) with predicted trend thresholds at 80% statistical power, expressed as annual percent change.

	Trend	NH4	NO3	TN	PO4	TP	Chl
Suisun Bay							
Single station: D6	Historic - 20yr	ND	1.5%	1.5%	1.4%	ND	-3.1%
	Simulated -10yr	5.6%	4.1%	3.8%	3.7%	4.1%	6.1%
	Simulated - 20yr	-	3.5%	3.3%	2.0%	3.3%	4.1%
Active stations: D6, D7, D8	Historic - 20yr	ND	2.4%	1.3%	1.5%	ND	-5.8%
	Simulated -10yr	4.0%	2.6%	1.8%	2.6%	4.5%	4.9%
	Simulated - 20yr	-	-	-	-	-	-
All historic stations D6, D7, D8, D9	Historic - 20yr	ND	2.3%	ND	1.5%	ND	-6.5%
	Simulated -10yr	3.5%	1.9%	1.5%	2.0%	4.1%	4.5%
	Simulated - 20yr	-	-	-	-	-	-
Confluence							
Single station/ active station: D4	Historic - 20yr	ND	1.3%	ND	ND	ND	-4.9%
	Simulated -10yr	5.9%	4.0%	3.4%	3.6%	4.1%	6.9%
	Simulated - 20yr	-	3.1%	-	-	-	4.5%
Active stations (only Chl): D4, D12, D22	Historic - 20yr	-	-	-	-	-	-5.8%
	Simulated -10yr	3.5%	1.9%	1.5%	1.9%	3.9%	5.4%
	Simulated - 20yr	-	-	-	-	-	-
All historic stations: D4, D11, D12, D14, D15, D22, D24	Historic - 20yr	ND	2.3%	ND	1.5%	ND	-6.5%
	Simulated -10yr	1.9%	1.4%	0.9%	1.3%	2.4%	3.9%
	Simulated - 20yr	-	-	-	-	-	-
Central Delta							
Single station: D19	Historic - 20yr	ND	ND	ND	ND	ND	-2.1%
	Simulated -10yr	4.4%	4.1%	3.8%	3.6%	3.6%	6.6%
	Simulated - 20yr	-	-	-	-	-	4.3%
Active stations: D19, D26, D28	Historic - 20yr	1.4%	1.4%	1.4%	ND	ND	-2.9%
	Simulated -10yr	3.0%	2.7%	1.8%	1.9%	3.6%	6.7%
	Simulated - 20yr	-	-	-	-	-	-
Historic stations[2]: C9, D16, D19, D26, D28, MD7, P10	Historic - 20yr	1.6%	1.4%	1.4%	ND	ND	-2.7%
	Simulated -10yr	1.7%	1.6%	1.0%	1.3%	2.0%	4.2%
	Simulated - 20yr	-	-	-	-	-	-
South Delta							
Single station/active station: C10	Historic - 20yr	-1.7%	ND	ND	ND	ND	ND
	Simulated -10yr	4.4%	4.2%	3.8%	3.6%	3.6%	6.6%
	Simulated - 20yr	4.3%	-	-	-	-	-
All historic stations: C7, C10, P12	Historic - 20yr	ND	2.1%	ND	1.9%	ND	ND
	Simulated -10yr	5.2%	3.0%	1.9%	3.5%	4.0%	5.8%
	Simulated - 20yr	-	-	-	-	-	-

[2] 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.

3.2.2. *Sampling frequency*

Due to the scarcity of readily comparable and sufficiently long and overlapping datasets, the sampling frequency analysis was limited to a comparison of the statistical power for trend detection by continuous and by discrete monitoring at three stations, where moored NO3 and chl-a sensors are co-located with discrete sampling locations for these parameters. The three sampling locations are Sacramento River at Freeport (FPT), Sacramento River at Hood (C3), and Sacramento River at San Joaquin River (D12).

A power analysis of sampling frequency (continuous vs. discrete) was conducted using NO3 data from the Freeport moored sensor. The Freeport and Vernalis moored sensors are currently the only two moored NO3 sensors in the Delta that are co-located with active nutrient grab sample monitoring sites. The Freeport sensor was chosen for this analysis, because it was established on August 30, 2013 and has a slightly longer period of record than the Vernalis sensor, which was established on January 21, 2015. The period of record considered for the analysis was a two-year period ranging from January 1, 2014, to December 31, 2015. Although grab samples are collected at this site (see red dots on Figure 5), there are gaps in the record. Therefore, both continuous data and monthly grab samples at high slack tide were simulated using the variance in the daily means from measured continuous data at this site (Figure 5). The variances calculated from the continuous data are similar to the variance of the actual grab samples, as shown by the virtually identical interquartile ranges of the grab samples, raw continuous data, and daily means calculated from continuous data (Figure 6). As would be expected, there are fewer outliers outside the interquartile range (the whiskers in Figure 6 extend to 1.5x the interquartile range) for the grab samples and the observed daily means compared to the raw continuous data. The assumed variance in the Monte Carlo simulations was the standard deviation of daily mean concentrations from all days with data during each season (winter, spring, summer, fall), relative to the seasonal means for these data. To simulate a continuous data series, ~30 daily mean concentrations were randomly generated from the seasonal distribution for each month. To simulate a grab sampling data series, 1 daily mean concentration was randomly generated from the seasonal distribution for each month. A linear trend was superimposed on these random points (see Figure 7).

Table 14 and Figure 8 provide a summary of the results of this analysis. The results suggest that continuous data has much higher power to detect trends because of the larger sample size. For nitrate, the continuous sensor data has sufficient statistical power to detect a 10% decrease over 10 years, compared to very low statistical power (6%) to detect the same trend with discrete monthly grab samples. However, this result has to be viewed with caution, because of the short data record on which the simulation was based. The data used to estimate the variance for this simulation only span two years, which were also both drought years and therefore less likely to represent the interannual data variance that would be expected over a longer period of time with a wider range of conditions. In addition, it is likely that the short period of record of discrete data inflated the variance in the simulated grab data.

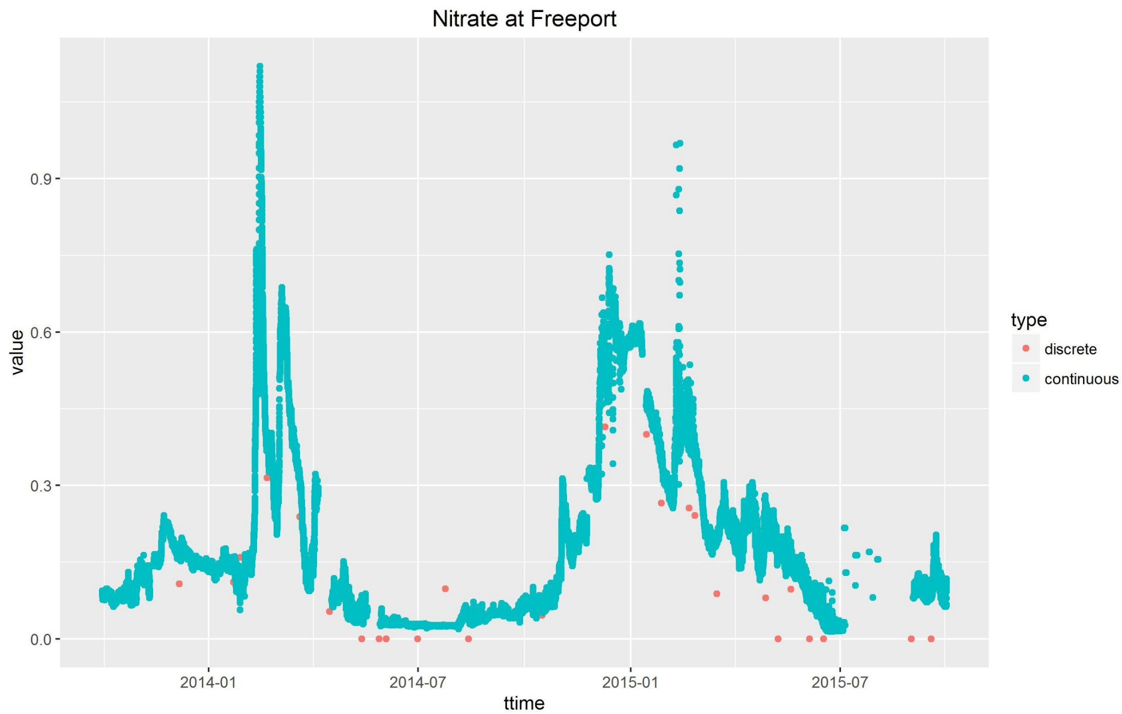

Figure 5. Time series for discrete (monthly sampling) and continuous (daily means) NO3 data (mg/L as N) collected at Sacramento River at Freeport.

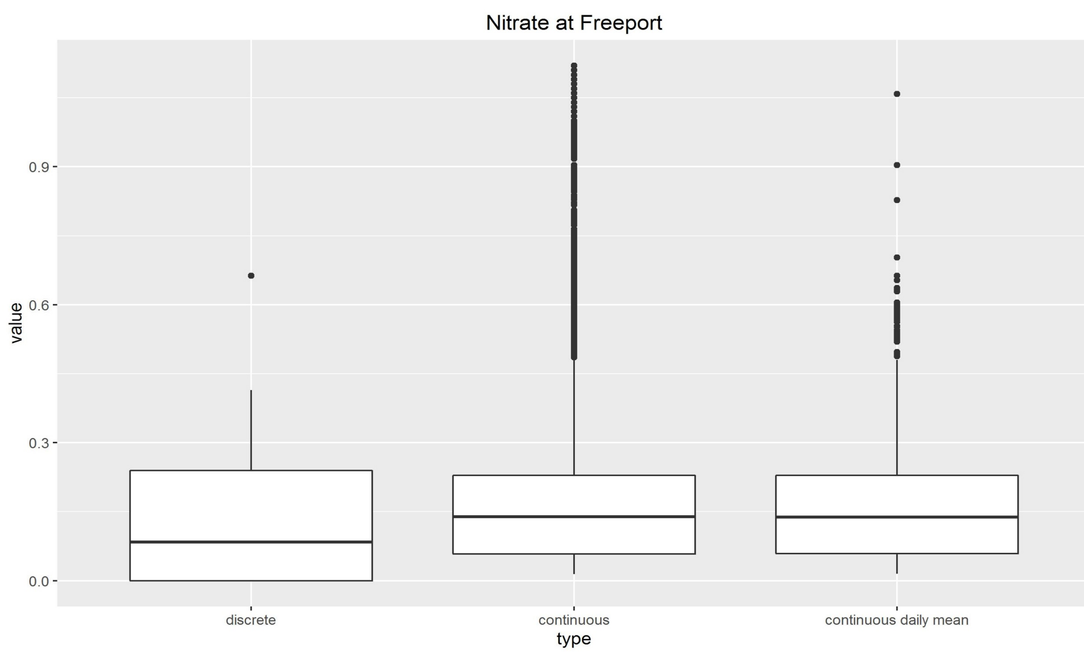

Figure 6. Boxplots of NO3 concentrations at Freeport (2014-15): a) monthly grab samples, b) continuous moored sensor data, and c) daily means of the continuous data. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Outliers are shown as dots.

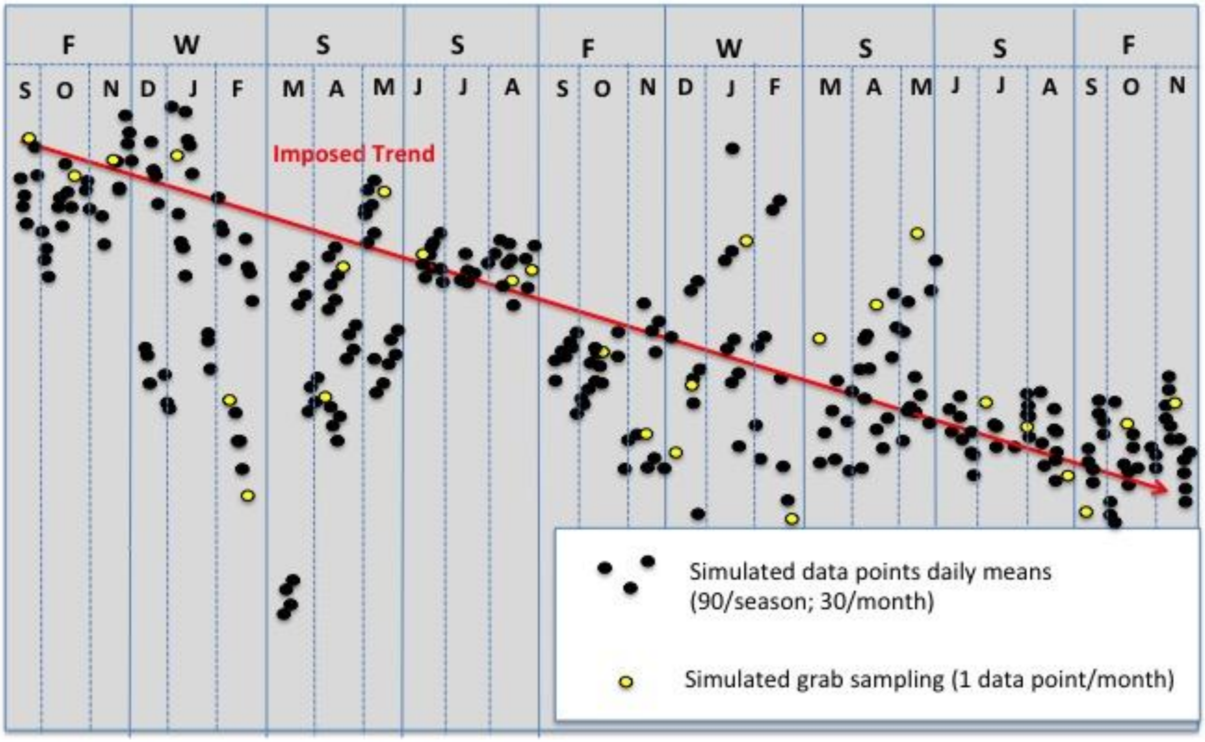

Figure 7. Conceptual representation of the Monte Carlo simulations used to study the effects of sampling frequency on the statistical power of trend detection. In a continuous data series, ~30 daily mean concentrations were randomly generated from the seasonal distribution for each month (90 data points per season). To simulate a grab sampling data series, 1 daily mean concentration was randomly generated from the seasonal distribution for each month. A linear trend was superimposed on these random points.

Table 14. 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.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
Simulations based on data for Oct 2014 – Sep 2015:*	**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.

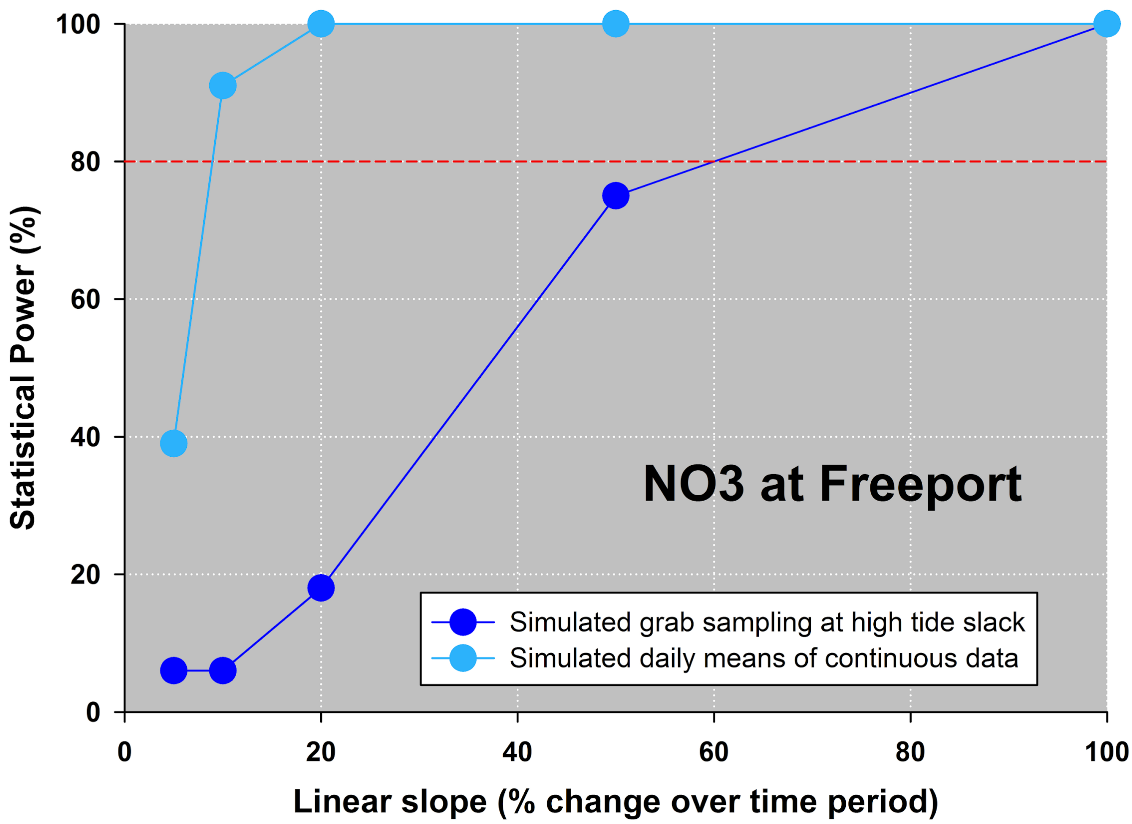

Figure 8. Power curves for the detection of long-term trends in nitrate from a) daily means and b) monthly grab samples collected at high slack tide, each simulated from continuous data recorded by the USGS sensor at Sacramento River at Freeport (FPT). The red dotted line represents 80% power.

Results from the power analysis of chlorophyll data confirm the general finding that continuous data provide greater statistical power for detecting long-term trends than discrete sampling data (Table 15 and Figure 9). The power analyses for chl-a data are based on a longer period of record (November 13, 2008 to June 30, 2015) and consist of a three-way comparison between a) daily means simulated from continuous data, b) monthly grab sampling simulated from continuous data, and c) monthly grab sampling from monthly grab sampling data. At Hood, the continuous data provide sufficient statistical power to detect a 20% decline over 10 years, compared to insufficient statistical power for the monthly data simulated from continuous data and grab samples. At Antioch, the continuous data provide sufficient statistical power to detect a 10% decline over 10 years, compared to insufficient statistical power for the monthly data simulated from continuous data and grab samples.

Table 15. 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.

	Trend - 10yr Decline				
	5%	**10%**	**20%**	**50%**	**100%**
Simulations based on data for Nov 2008 – Jun 2015:*	**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.

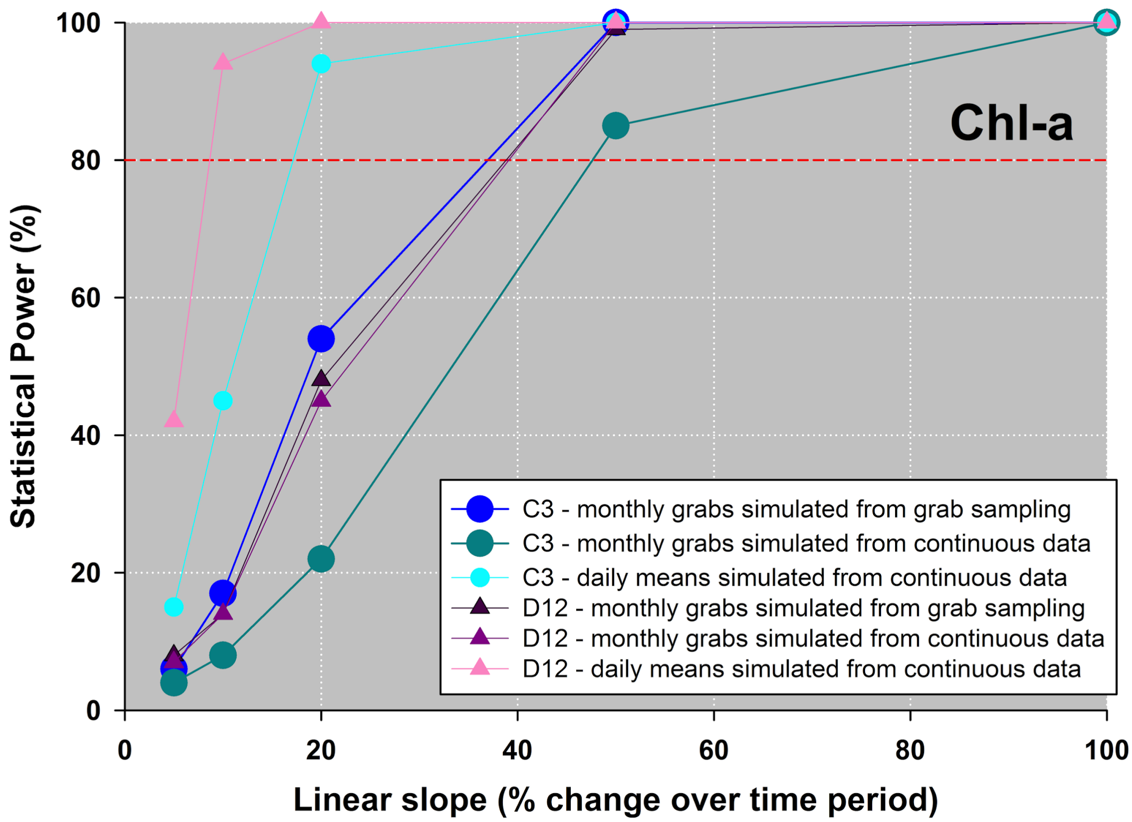

Figure 9. Power curves for the detection of long-term trends in chlorophyll from a) daily means simulated from continuous data b) monthly grab samples simulated from continuous data, and c) monthly grab samples simulated from grab sample data. The data are from two IEP-EMP monitoring stations that are 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.

4. Discussion

For the period of record analyzed and for most of the nutrient variables, most of the sites had no detectable trends (i.e., no statistically significant trend); however, when long-term trends were detectable, the direction of trend was mostly consistent across the entire region. The exception was NH4, 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 site. As discussed in Section 2, the Central Delta subregions 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.

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, provided there is consistency in trends. Moreover, trend analysis for combined sites will help discerning subregional trends from localized trends at individual sites. Therefore, it is generally preferable in trend analysis to have datasets from multiple sites within a given subregion that represent replicates of a subregional mean.

The results from the historic trends analyses and also from the power analysis suggest that adding more discrete sites is only needed for a few parameters and subregions to improve the ability to detect regional or subregional long-term trends. 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 would improve trend detection for some subregions and some parameters. Specifically, the power analyses suggest that adding back discontinued stations in the Confluence and Suisun Bay subregion would increase the statistical power for trend detection in ammonium and chlorophyll. By resuming ammonium monitoring at stations D12 and D22 in the Confluence subregion, the statistical power for detecting trends in ammonium would increase the power to detect a 50% decrease over 10 years from 68% to 99%, and thus increase the sensitivity of trend detection from 7% annual decline to a 4% annual decline. Sampling stations D12 and D22 are currently monitored for chlorophyll but not for ammonium.

The benefits of adding back more discrete sampling points for improving statistical power for trend detection in chlorophyll are marginal. Adding back station D11, which is no longer visited, would increase the power to detect a 50% decrease in chlorophyll (4% annual change) from 75% to 83% (80% is considered a threshold level for statistical power in trend detection). In Suisun Bay, adding back station D9 would increase the power to detect a 50% decrease in chlorophyll (4% annual change) from 78% to 84%.

Results suggest that strategically placed continuous sensors would have potential for improving trend detection capabilities. 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. 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%. 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.

The power analysis estimates for continuous data need to be viewed with caution, because of the limited data record that was available to estimate the variance in sensor measurements. Another source of potential bias in the simulations is that daily means were simulated rather than continuous data. This was done because the required simulations of continuous 15 min data combined with the desired sampling scenarios (e.g. every high tide slack occurring over the next 10 years between 7am and 7pm) were impractical.

At this time, nutrient sensors provide limited spatial coverage of the Delta (see Figure 17 in Appendix 1) and the only nutrient parameter currently measured at these sensors is NO3. However, chlorophyll fluorescence is measured at a total of 9 DWR-EMP continuous stations in 5 subregions (3 in Confluence, 2 each in Central Delta and South Delta, 1 in Sacramento River, and 1 in Suisun Bay). USGS is currently developing and testing NH4 and PO4 sensors for deployment at moored stations.

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.

5. References

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