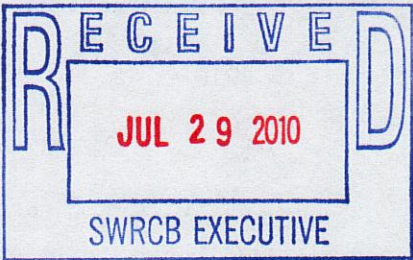




8/3/10 Bd Mtg Item 12  
Delta Flow Criteria  
Deadline: 7/29/10 by 12 noon



Technology in balance with nature

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July 29, 2010

**Sacramento Regional Wastewater Treatment Plant**  
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Jeanine Townsend  
Clerk to the Board  
State Water Resources Control Board  
1001 I Street, 24th Floor  
Sacramento, CA 95814

*Via Email and First Class U. S. Mail*  
[commentletters@waterboards.ca.gov](mailto:commentletters@waterboards.ca.gov)

**Subject: Sacramento Regional County Sanitation District's Comments on the DRAFT Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem (7/20/10)**

**Board of Directors**  
Representing:

- County of Sacramento
- County of Yolo
- City of Citrus Heights
- City of Elk Grove
- City of Folsom
- City of Rancho Cordova
- City of Sacramento
- City of West Sacramento

Dear Ms. Townsend:

Sacramento Regional County Sanitation District (SRCSD) submits the following comments on the State Water Resources Control Board's (State Water Board) *Draft Report on the Development of Flow Criteria for the Sacramento-San Joaquin Delta System* (Draft Report). In general, SRCSD supports the Draft Report's recommendations for further study of ammonia and nutrients in the Delta and to address "other stressors," as appropriate, based on the results of current and future scientific studies. SRCSD has been working with the Central Valley Regional Water Quality Control Board (Regional Water Board) to investigate the role of nutrients and potential "other stressors" in the Delta and to develop a regional monitoring program to help address many of the water quality questions in the Delta.

SRCSD has the following specific concerns and suggests language changes to address those concerns:

- Mary K. Snyder  
District Engineer
- Stan R. Dean  
Director of Policy and Planning
- Prabhakar Somavarapu  
Director of Operations
- Marcia Maurer  
Chief Financial Officer
- Claudia Goss  
Director of Communications

- Hypotheses asserting SRCSD's discharge is the root cause of the pelagic organism decline.
- Misinterpretations of the Draft Report's conclusions regarding ammonia from SRCSD's discharge.

As the State Water Board knows, investigations of potential “other stressors” have been undertaken by the National Academy of Sciences (NAS) Review Panel, the Bay Delta Conservation Plan, and the Bay Delta Science Program. In the meantime, the State Water Board also received written testimony and exhibits, and conducted a panel during the informational proceeding related to other stressors. While SRCSD supports further investigation, we do not believe the Draft Report fully reflects the information presented by Delta scientists during the proceedings. In particular, certain hypotheses and arguments advocated by specific parties were not supported by others, including renowned scientists who have dedicated their professional lives to studying the Sacramento-San Joaquin Delta.

Section 3.3.3, Contaminants (pages 35-36) and Section 4.3.3, Water Quality and Contaminants (page 93) of the *Draft Delta Flow Criteria Report*, overall reflect the state of scientific understanding relative to ammonia and nutrients. However, it is unclear why a San Francisco Bay Regional Water Quality Control Board staff letter to the Central Valley Regional Water Quality Control Board staff is referenced, especially since the letter does nothing more than refer to studies already discussed in this section and the San Francisco Regional Water Board did not participate in the proceeding. Moreover, the inclusion in Sections 3.3.3 and 4.3.3 of a “third, newer hypothesis” promoted by Dr. Patricia Glibert that Delta food web impacts have been caused by changes in nitrogen to phosphorus ratios is inappropriate and scientifically suspect as stated. Dr. Glibert presented her arguments as a witness for the export contractors at the informational proceeding, and they were not well-supported then, or in recent weeks before the NAS Review Panel. While her paper on these subjects was released and heavily promoted after the informational proceeding, it remains true that the conclusions are predicated upon correlation analyses and ecological assumptions that are inappropriate and have been questioned by Delta scientists. (See SRCSD’s June 30 letter addressed to the State Water Board, and attached memoranda.)

Our concern is that the Draft Report or portions of the Draft Report could be misinterpreted, or taken out of context as currently drafted, to mean that the State Water Board has taken a position supporting hypotheses that conclude SRCSD’s discharge is the overwhelming cause of the pelagic organism decline. It appears that your own staff has misgivings about these currently unsupported hypotheses and tends to agree that, at minimum, more studies would be necessary to confirm or deny them. To that end, and to provide additional clarification, SRCSD requests the following language changes to the Draft Report (additions are underscored and deletions are in strikeout):

**Section 3.3.3 (page 36)**

“Ammonia has emerged as a contaminant of special concern in the Delta. Recent hypotheses are that ammonia is causing toxicity to delta smelt, other local fish,

and zooplankton, and is reducing primary production rates in the Sacramento River below the Sacramento Regional Wastewater Treatment Plant (SRWTP) and in Suisun Bay. A third, newer, hypothesis is that ammonia and nitrogen to phosphorus ratios have altered phytoplankton and fish population abundance. As described below, none of these hypotheses have been confirmed.”

“The SRWTP is the primary source of ammonia to the Delta (Jassby 2008). The SRWTP has converted the lower Sacramento River Delta from a nitrate to an ammonia dominated nitrogen system (Foe et. al. 2010).”

“Ammonia concentrations are higher in the Sacramento River below the SRWTP than in Suisun Bay. The findings in Suisun Bay led to a hypothesis that ammonia might be inhibiting nitrate uptake and reducing primary production rates in the Sacramento River and downstream Delta. Experimental results for the Sacramento River are more ambiguous than for Suisun Bay (Parker et al. 2010). Experiments conducted on Sacramento River water demonstrate no consistent differences above and below the SRWTP. However, in one bench-top experiment, effluent dosed into upstream Sacramento River water at environmentally realistic concentrations ~~does~~ showed conflicting data that may indicate an increase or decrease in primary production at environmentally relevant concentrations. Elevated ammonia concentrations consistently decrease nitrate uptake in bottle experiments. Whether a shift in nitrogen utilization indicates that different algal species are beginning to grow in the ammonia rich water in the estuary is not known. Finally, a recent paper by Glibert (2010) theorizes demonstrates significant relationships between the form and concentration of nutrients discharged by SRWTP, and changes in phytoplankton, zooplankton and fish abundance in the Delta. This hypothesis has been questioned and its acceptance remains an uncertainty.”

#### **Section 4.3.3 (page 93)**

“Ammonia has emerged as a contaminant of special concern in the Delta. Recent hypotheses are that ammonia is causing toxicity to delta smelt, other local fish, and zooplankton and is reducing primary production rates in the Sacramento River below the Sacramento Regional Wastewater Treatment Plant and in Suisun Bay. A newer hypothesis is that ammonia and nitrogen to phosphorus ratios have altered phytoplankton species composition and these changes have had a detrimental effect on zooplankton and fish population abundance (Glibert 2010). These hypotheses have been questioned and more experiments are needed to evaluate ~~the effect of whether~~ nutrients, including ammonia, affect primary production and species composition and fish population abundance in the Sacramento River and Delta.”

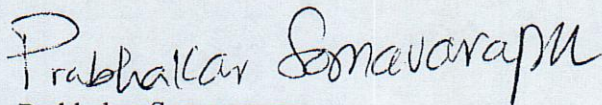
State Water Resources Control Board  
Re: SRCSD Comment Letter – Draft Delta Flow Criteria Report  
July 29, 2010  
Page 4

**Section 4.4 (page 97)**

Lastly under the discussion of Sacramento Valley Unimpaired Total Outflow the first sentence should be changed to “Estimates of the unimpaired Sacramento Valley outflow were computed as the sum of estimates from 11 sub-basins in the watershed and are understood to represent the flow natural unimpaired streamflow that would occur on the Sacramento River at approximately Freeport.” This would clarify the basis for baseflow determinations.

We appreciate the work done by the State Water Board on the Draft Report and we look forward to working with all appropriate agencies in the future to address the questions on the role of contaminants in the Delta. Please contact Linda Dorn at [dornl@sacsewer.com](mailto:dornl@sacsewer.com) or 916-876-6030 to discuss this further.

Sincerely,



Prabhakar Somavarapu  
Director of Policy and Planning

Attachments: LWA July 29, 2010 Comments for Consideration by the State Water Resources Control Board Regarding the Scientific Article *Long-term Changes in Nutrient Loading and Stoichiometry and their Relationships with Changes in the Food Web and Dominant Pelagic Fish Species in the San Francisco Estuary, California* by Patricia Glibert”;

CH2MHill July 29, 2010 Comments for Consideration by the State Water Resources Control Board Regarding *Long-term Changes in Nutrient Loading and Stoichiometry and their Relationships with Changes in the Food Web and Dominant Pelagic Fish Species in the San Francisco Estuary, California* by Patricia Glibert - pre-print copy (May 17<sup>th</sup>, 2010).

cc: Stan Dean, District Engineer  
Terrie Mitchell, Manager Legislative and Regulatory Affairs

# Memorandum

DATE: July 29, 2010

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TO: Stan Dean, District Engineer  
Sacramento Regional County Sanitation  
District  
10060 Goethe Road  
Sacramento, CA 95827

CC: Linda Dorn, SRCSD  
Terrie Mitchell, SRCSD  
Prabhakar Somavarapu, SRCSD

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SUBJECT: Comments for Consideration by the State  
Water Resources Control Board Regarding  
the Scientific Article *Long-term Changes  
in Nutrient Loading and Stoichiometry and  
their Relationships with Changes in the  
Food Web and Dominant Pelagic Fish  
Species in the San Francisco Estuary,  
California* by Patricia Glibert

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L A R R Y  
W A L K E R



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A pre-print of a scientific article authored by Patricia Glibert (University of Maryland Center for Environmental Sciences) entitled "*Long-term changes in nutrient loading and stoichiometry and their relationships with changes in the food web and dominant pelagic fish species in the San Francisco Estuary, California*", scheduled for publication in *Reviews in Fisheries Science*, was publicly released on May 17, 2010. In the article, Glibert uses a calculation termed CUSUM to transform long-term datasets for nutrient concentrations and abundances of phytoplankton, three copepod species, the invasive clam *Corbula amurensis*, and several fish species (including Delta smelt and longfin smelt). In brief, the CUSUM transformation converts time series of measured values into series of cumulative standardized deviations from a long-term mean (or other constant). The resulting time series of CUSUM values exhibit features and patterns which diverge in several important ways from those of the underlying measured data - some of which are useful for detecting change points in time series which contain a lot of seasonal or interannual variation.

In Glibert's study, the transformed data ("CUSUM values") were used in two ways: (1) displayed as time series to detect potential change points in underlying measured data, and (2) used in linear regressions by pairing CUSUM values for different environmental parameters. Based on visual inspection of CUSUM time series and linear regressions between CUSUM values for selected

pairings of nutrient or biological parameters, Glibert concludes that changes in nutrient ratios (which she attributes primarily to changes in ammonia and phosphorus concentrations in the discharge from the Sacramento Regional Wastewater Treatment Plant) have driven changes in abundance and composition of organisms higher in the estuarine food web, such as phytoplankton, copepods, invasive clams, and pelagic and littoral zone fishes.

The route by which Glibert arrives at her conclusions raises concerns from both technical and ecological standpoints. The correlation approach used by Glibert (using CUSUM values instead of measured values) violates assumptions for linear regression, and can produce spurious relationships between variables that are unsupported by the underlying data. Although she analyzed chemical and plankton data from only one station in the freshwater Delta (Sacramento River at Hood), and two stations in Suisun Bay, Glibert generalizes her results to the whole of the upper San Francisco Estuary (SFE). Although they are not well articulated in the article, a number of problematic ecological assumptions are required to infer cause and effect from her correlation analysis. Key analyses that are necessary to support her conceptual model are missing from the publication. Many well-known alternative hypotheses for the observed changes in plankton composition and fish abundance in the SFE (and in estuaries, generally) - which would have been testable using her CUSUM methodology - were omitted from the analysis and from discussion in the article. Finally, owing to the peculiarity of the CUSUM transformation, it is likely that a wide variety of non-nutrient environmental factors (essentially any factors which have trended over time in the SFE in concert with changes in fish abundance) could be shown as highly correlated with pelagic fish abundance using CUSUM correlations. As an example included in Section 1 of this memo, it is shown that when subjected to the same analysis used in Glibert's paper, annual water exports perform as well as ammonia concentrations in explaining trends in the summertime abundance of Delta smelt.

At the end of the methods section of her paper, Glibert cautions against using CUSUM correlations as evidence of cause and effect, as follows:

"Relationships between CUSUM trends for different nutrients or between different components of the food web, as shown herein, allow investigators to infer mechanistic relationships supported by known physiological or trophic relationships, or can lead to further testable hypotheses of the relationships between trophic components. It is in this context that they are used here. As with all correlations, the variables may have a cause-and-effect relationship or both may be related to another variable." (emphasis added)

Unfortunately, the CUSUM correlations presented in Glibert's paper were not ultimately placed in such context. Instead, they were used to make unwarranted, overly simplistic conclusions regarding the food web of upper SFE.

The contents of this memo are organized as follows:

1. Concerns with the Statistical Analysis
2. Concerns with Underlying Ecological Assumptions
3. Alternative Hypotheses which are Unaddressed
4. Inconsistencies

## 1. Concerns with the Statistical Analysis

The type of correlation analysis used in Glibert's paper violates the underlying assumptions for linear regression and can produce misleading results. Other concerns include the limited geographic extent of the data, possible improper subsampling of CUSUM time series, nontransparent data reduction, and omissions of key analyses which would support alternative hypotheses.

**Geographic Coverage.** Sweeping generalizations are made regarding the estuarine food web and the Pelagic Organism Decline (POD) using data from only 1 station in the Freshwater Delta (Hood, IEP station C3) and 2 stations in Suisun Bay (IEP stations D8 and D7).

**Violation of Statistical Assumptions.** Glibert admits that the CUSUM approach mutes seasonal or other short-term variation in a time series. Also, Glibert admits that CUSUM series exaggerate shifts in the underlying raw data. These features of CUSUM are useful for pinpointing change points in inherently variable time series, or for exploring whether change points coincide for different factors. In the statistical literature, CUSUM is primarily used to create charts for single variables that allow the user to detect change points or determine whether deviations from control points are random or signal a trend. However, the characteristics of CUSUM that lend it to change-point analysis and quality control make it completely inappropriate to evaluate relationships between variables (such as CUSUM  $\text{NH}_4^+$  vs CUSUM fish abundance) by conducting standard linear regression using CUSUM values (taken out of sequence from their time series) as independent or dependent variables.

The simple CUSUM correlations that represent the basis for the author's conclusions violate virtually every assumption of a standard correlation analysis. CUSUM series are inherently serially correlated, heteroscedastic and non-normally distributed, and the residuals of CUSUM correlations are non-independent. The CUSUM transformation is similar to a long-term moving average in that they both tend to smooth short-term variability and are inherently serially auto-correlated. However, CUSUM transformation is much more extreme in this regard and erases or obscures variability and relationships among data points in a series. Additionally, because they are *cumulative* sums of deviations, the variance structure of a CUSUM series changes throughout a time series. The values at the beginning of a CUSUM series are influenced by fewer preceding values than values at the end of the series. This means that values at the end of the series are more highly auto-correlated than values at the beginning of the series. The increasing serial correlation within CUSUM series increases the chances of violating the assumption of homoscedasticity (equal variance) for correlation analysis. Based on violations of several of the underlying assumptions of a traditional correlation analysis, the results and subsequent conclusions drawn by the author which rely on the CUSUM correlations presented should be considered invalid.

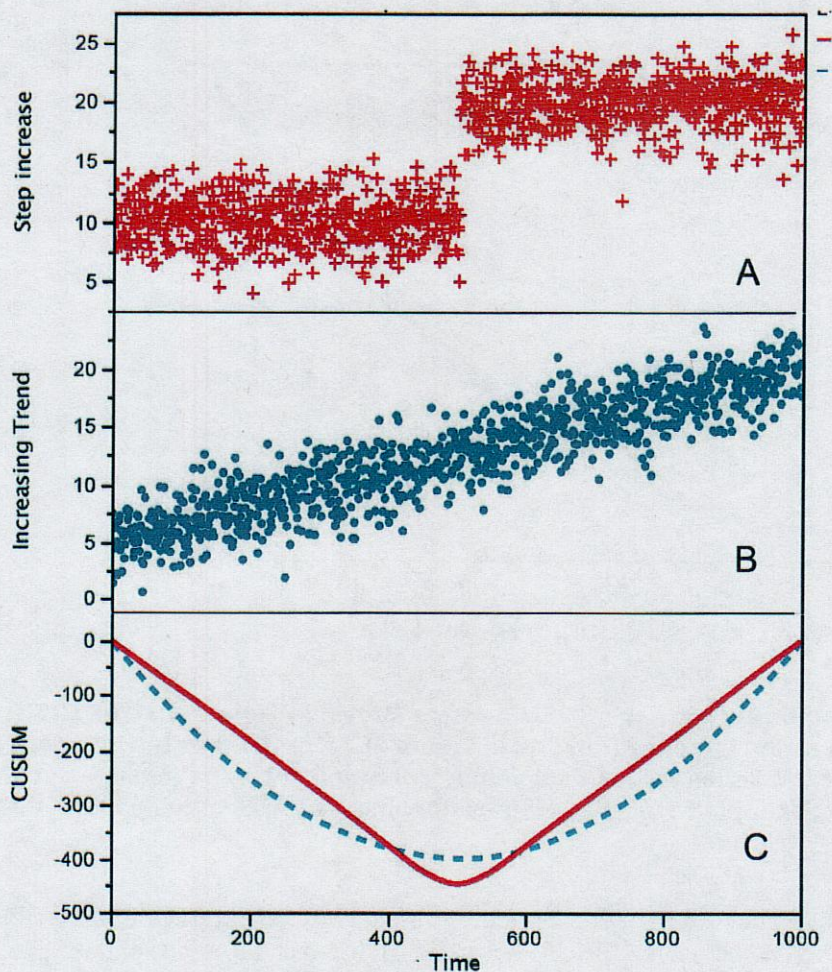
In addition to issues surrounding Glibert's uncustomary use of CUSUM values for correlation analysis, not all of the datasets used by Glibert were appropriate for customary CUSUM change point analysis. Autoregressive time series such as flow data are not appropriate for CUSUM change-point analysis. CUSUM change point analysis also assumes that underlying data are homoscedastic and often assumes that data are normally distributed. In the article, Glibert acknowledges that data were not tested for autocorrelation prior to the CUSUM transformation; tests regarding normality and equal variance were apparently also omitted.

**Artificial Relationships and Inflated  $R^2$  Values.** Another problematic characteristic of the CUSUM transformation is that it results in a very limited range of serially correlated data structures. Owing to the dependence of CUSUM on the long-term mean of the time series, most CUSUM series of normally distributed data automatically begin near zero and end near zero (as is evident from many of Glibert's time series graphs of CUSUM values). Consequently, real trends or patterns in the data are obscured or inverted, and portions of a time series with no trend can produce a series of increasing or decreasing CUSUM values, depending on the relationship between the actual measurements and the population mean, and where they occur in the longer time series. For example, short-lived perturbations can cause trends in CUSUM values that persist for years (or decades) after underlying data return to normal ranges. This feature of CUSUM is well illustrated by the CUSUM series for  $\text{NO}_3:\text{NH}_4$  in Glibert's Figure 4. Figure 4 (panels B and C) shows that  $\text{NO}_3:\text{NH}_4$  ratios were intermittently anomalously high in Suisun Bay during about 5 years starting in 1987, but occupied similar ranges of lower values during most of the years prior and afterward. Inflections in the CUSUM charts in Figure 4 are useful for illustrating the beginning and end of this perturbation. However, owing to the perturbation in the longer time series, CUSUM values follow a conspicuous declining trajectory from 1994 onward, despite the fact that underlying data for that period are not trending up or down.

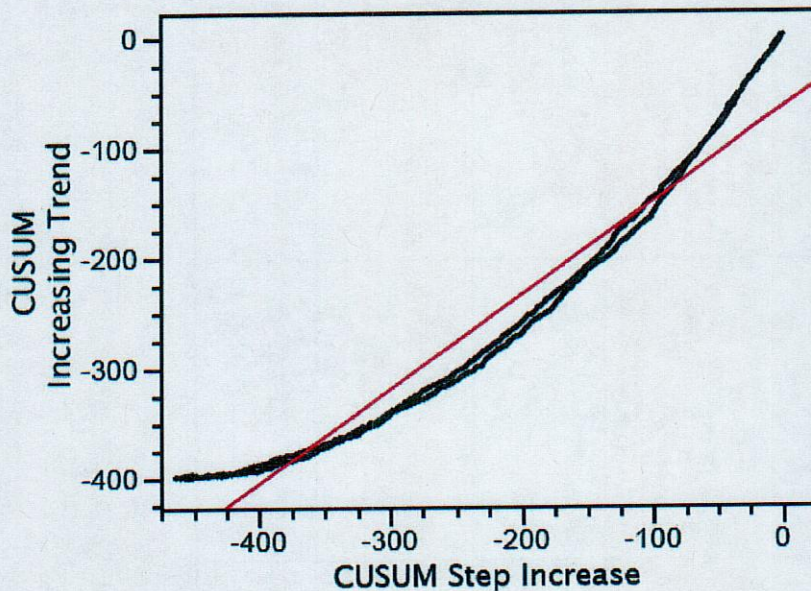
Such features of CUSUM generate artificial patterns in the data and can produce statistically significant relationships between independent and dependent variables for which no relationship can be derived using real-world concentrations or abundances. The result of the limitations of CUSUM data structure is that they generate "correlations" with impressively inflated  $R^2$  values that are largely artificial and can't be interpreted in the same way as standard parametric correlation or regression analysis. Equally important, statistically significant relationships that *are* present in underlying data can be disguised when CUSUM time series are compared instead of real world measurements.

An example of a misleading result from CUSUM correlations is illustrated in Figure 1 below. For this figure, two contrasting synthetic time series were produced: one in which there was a step change in a time series (a doubling; red series, panel A) but no other trend, and another in which values gradually increased over time, with no step increase (blue series, panel B). The time series with the step change generates a CUSUM series that is nearly identical in structure to the CUSUM series for the monotonic increasing data (panel C). Although there is no abrupt change in the monotonic trend, the CUSUM calculation forces an inflection point midway through the time series of CUSUM values (the bottom of the blue trough in panel C). And although there is no feature of the monotonic trend which coincides with the step increase in the other parameter, the CUSUM series for both datasets are similar and highly "correlated" (Figure 1C, Figure 2). A similar misleading result would occur if the introduction of a non-native species was treated like a step change - with many years (or decades) of zero abundance included in the time series for an invasive species prior to its establishment. Such an approach appears to have been used by Glibert when comparing the CUSUM time series of ammonia and the invasive clam *Corbula amurensis*.





**Figure 1. Comparison of CUSUM charts for contrasting underlying time series. Upper panels show hypothetical time series featuring a step increase (A), and a monotonic increase over time (B). Lower panel compares the resulting CUSUM charts for the step increase (red line) and the monotonic increase (blue line).**



**Figure 2.** Correlation between the CUSUM series shown in Figure 1C. The CUSUM series for the data with a step increase (red line in Figure 1C) was used as the independent variable; the CUSUM series for the data with a monotonic increase (blue line in Figure 1C) was used as the dependent variable. Regression line (red) was significant ( $p < 0.0001$ ,  $R^2 = 0.94$ ).

**Issues Created by Breaking Up Time Series.** Another requirement of CUSUM analysis is that time series being compared using CUSUM must start and stop at the same point in time. Data series do not have to have the same number of observations, but the CUSUM series must be generated for the same time period for each variable. If variables cover two different but overlapping time periods, valid comparisons of trends must be made with CUSUM series calculated only for the common overlapping period. It is not clear from Glibert's methods section whether CUSUM series were appropriately recalculated for each correlation analysis. If this was not done, the comparisons are essentially meaningless. For example:

1. In Figure 13, Glibert included *Corbula* abundance values of zero from the period prior to its establishment (1975-1986) to generate the CUSUM series for the whole period 1975-2005. However, the caption for Table 1 states that correlation analysis between CUSUM-*Corbula* and CUSUM-X2 was performed using CUSUM values for 1987-2005 only. Were separate CUSUM time series (not presented in the article) generated for both variables using data only for 1987-2005 before running this correlation?
2. In Figure 8, were separate CUSUM series generated for flow and nutrient parameters for pre-POD and POD periods before  $R^2$  values were generated for the partial time series?
3. In Figure 19, CUSUM values for *Pseudodiaptomus* and *Limnoithona* for 1987-2005 were apparently used as independent variables. Were these CUSUM values extracted from the CUSUM series generated using copepod data from all years (1974-2006, see Fig. 11), or

were CUSUM series *recalculated* for fish and copepods for the years 1987-2005 before linear regression was performed?

***Non-transparent Data Reduction.*** Glibert does not reveal how she aggregated raw data or CUSUM values for variables that were measured monthly (such as nutrients, phytoplankton, zooplankton) or daily (such as Delta outflow or X2) in order to pair them with annual fish abundance indices (such as Summer Townet survey or Fall Midwater Trawl indices). Were monthly or daily data aggregated prior to CUSUM transformation? If so, how did the averaging periods relate to timing of fish surveys? Summer Townet indices are derived from June-August fish catch; Fall Midwater Trawl indices are derived from Sept-Dec. fish catch. Were monthly nutrient or copepod data averaged for periods preceding or overlapping the fish catches? If so, how long were the averaging periods? Were they ecologically relevant averaging periods?

***Questionable Ecological Relevance of CUSUM Values.*** CUSUM values at any single point in a time series are affected by all the values that precede them. The Delta time series used by Glibert extend over decades. This raises the question whether comparison of CUSUM values for nutrients and plankton are ecologically meaningful if the underlying ambient concentrations or organism counts don't covary in a meaningful way. Use of CUSUM values as independent or dependent variables in a regression analysis implies that the values have inherent meaning when taken out of sequence from their time series. Raw CUSUM values calculated using decades-long datasets might have some inherent meaning for long-lived organisms whose biological state (size, fecundity, physiological condition) can be affected by cumulative exposure to environmental conditions over years or decades. However, phytoplankton and zooplankton populations respond to short-term phenomena on scales of days to weeks. For short-lived organisms such as phytoplankton (days) and copepods (weeks) - or even Delta smelt and longfin smelt which live 1-2 years - it does not seem ecologically meaningful or valid to use CUSUM values derived over decades of observations for uses *other* than change point identification.

***Omitted CUSUM Correlations.*** Several obvious pairings of environmental variables are omitted from Glibert's portfolio of CUSUM correlations. Some of the omitted analyses are needed to make the claim (using Glibert's approach) that the bottom two tiers of her conceptual model (nutrient ratios and phytoplankton taxa, Fig. 23) are statistically related. In addition, several widely hypothesized *non*-nutrient drivers of plankton composition or fish abundance (such as clam abundance, turbidity, or water exports) are not used as independent variables for CUSUM analysis in Glibert's study, although publicly available data would lend them easily to the same treatment. Because changes in ambient ammonia concentrations in Suisun Bay have coincided with changes in other environmental factors, it is likely that several non-nutrient factors would perform similarly as nutrients in CUSUM correlations with phytoplankton, copepods, or fish abundance. Examples of omitted analyses are discussed below.

***Fall abundance of Delta smelt is not compared to nutrient or copepod trends.*** Glibert shows that the CUSUM values for the Summer Townet Index for Delta smelt are correlated with CUSUM values for copepods (Fig. 18) and NH<sub>4</sub> (Fig. 20). Why aren't analogous results presented using CUSUM values for the Fall Midwater Trawl index for Delta smelt?

Trends in nutrient ratios were not directly compared to trends for organisms at the base of the planktonic food web. Several of Glibert's conclusions rely on the premise that changes in nutrient ratios (TN:TP, NO<sub>3</sub>:NH<sub>4</sub>, DIN:DIP) have driven observed changes in phytoplankton composition. The only CUSUM correlations she presents for nutrient parameters vs phytoplankton taxa are in Figure 10: [NH<sub>4</sub>] vs. five broad taxonomic categories of phytoplankton. CUSUM regressions between nutrient ratios (TN:TP, NO<sub>3</sub>:NH<sub>4</sub>, or DIN:DIP) and phytoplankton indices (chl.a or individual taxonomic groups) are omitted from the paper. CUSUM trends in nutrient ratios are also not directly compared to those for copepod abundance. NO<sub>3</sub>:NH<sub>4</sub> trends are not compared to any of the biological trends (phytoplankton, copepods, clams, or fish); they are only compared to trends in Delta outflow. As a consequence, the current publication does not provide evidence that nutrient ratios and phytoplankton composition are statistically related. Thus it is debatable whether the findings presented by the author support the conclusion that "...that nutrient form is related to the "quality" of phytoplankton," as is claimed on page 26.

Corbula abundance is not tested as an independent variable. Glibert does not use her statistical approach to test obvious top-down hypotheses regarding the widely acknowledged role of *Corbula* as an ecosystem engineer in the brackish Delta. The tight relationship between CUSUM for NH<sub>4</sub> and *Corbula* (Fig. 14) strongly suggests that if *Corbula* were substituted for NH<sub>4</sub> as an independent variable (i.e., used as the x-axis), *Corbula* trends might be significantly correlated with those of the phytoplankton groups shown in Fig. 10, or those of fish species shown in Figs 20-21. In her summary, Glibert concludes that fish species could be divided into two groups: (1) those whose CUSUM trends were positively correlated with trends in abundance of *Eurytemora* and negatively correlated with *Pseudodiaptomus* and *Limnoithona*, and (2) those whose long-term CUSUM trends were negatively correlated with *Eurytemora* and positively correlated with *Pseudodiaptomus* and *Limnoithona*. Her thesis is that nutrient-driven changes in phytoplankton "quality" ultimately explain these patterns. However, the change point dividing these two copepod "regimes" (at least in the brackish Delta) coincides well with the establishment of *Corbula*, and the near elimination of (overall) phytoplankton biomass in Suisun Bay (see Fig. 9A).

Turbidity is not tested as an independent variable. A long-term decline in turbidity in the estuary has occurred since 1975, associated with several factors including upstream sediment trapping by dams, a gradual decrease in the sediment available downstream for resuspension and transport, washout during El Nino floods, and sediment trapping by submerged aquatic vegetation<sup>1,2</sup>. Because turbidity is required by Delta smelt for successful foraging and predator avoidance, this long-term trend is considered a credible contributor to population declines for the species. The decline in turbidity has occurred over the same time frame as increases in ammonia in Suisun Bay. Consequently, CUSUM correlations between Delta smelt abundance and turbidity are as likely to be as statistically significant (and equally invalid) as those using ambient ammonia concentrations as the independent variable.

Trends in export volumes are not evaluated. Although Glibert uses the results of her nutrient-related CUSUM analysis to argue that water management strategies have less influence than nutrients on population trends for fish, she does not acknowledge that water management strategies

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<sup>1</sup> Jassby A.D., J.E. Cloern, and B.E. Cole. 2002. Annual primary production: Patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnol. Oceanogr.* 47:698-712.

<sup>2</sup> Nobriga, M.L., T.R. Sommer, F. Feyrer, and K. Fleming. 2008. Long-term trends in summertime habitat suitability for Delta smelt (*Hypomesus transpacificus*). *San Francisco Estuary & Watershed*, Feb. 2008.

have allowed increases in seasonal and annual export volumes over the same time period that nutrient concentrations were evaluated. Glibert does not derive CUSUM scores for water exports in order to test alternative hypotheses related to the direct or indirect effects of exports on fish abundance. However, when subjected to the same analysis that Glibert uses in her paper, annual water exports perform as well as Suisun Bay ammonia concentrations in CUSUM correlations with summertime Delta smelt abundance. In Figure 3 below, CUSUM values for annual water exports volumes (summed for prior-year September through current-year August) are compared to CUSUM values for the Delta smelt Summer Towntnet index (STN). The overall relationship is statistically significant ( $p < 0.0001$ ) and the  $R^2$  value (0.42) is identical to that obtained when CUSUM for Suisun Bay ammonia was used as the independent variable (see Glibert Figure 18; also provided below as Figure 4).

Such omissions reveal the incomplete nature of the hypothesis testing provided by Glibert's study. CUSUM correlations are likely to be significant for any number of paired time series of environmental parameters from the Delta, provided the individual time series include an overall increasing or decreasing trend. However, all CUSUM correlations must be regarded as statistically flawed, and hypothesis testing using this approach is to be avoided. While CUSUM correlations between fish abundance and ammonia are convenient for focusing attention on ammonia (as opposed to other potential drivers of the food web or the POD), they ultimately signify little with respect to the relative importance of multiple environmental factors which have changed over recent decades in the San Francisco Estuary.

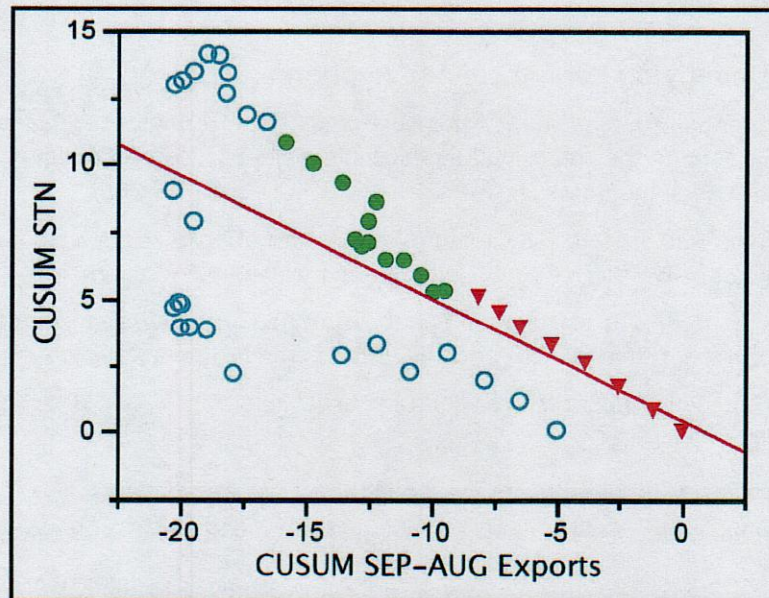
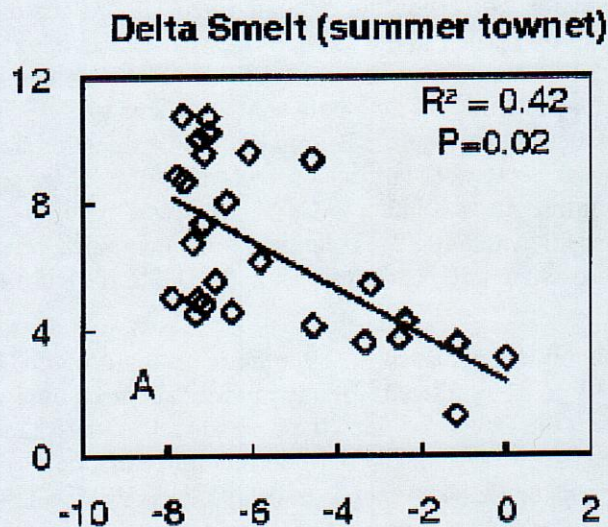


Figure 3. Relationship between CUSUM values for annual water exports (x-axis) and CUSUM values for the Delta smelt Summer Towntnet Index (y-axis). The Summer Towntnet Index for each year (a proxy for June-August abundance) was paired with cumulative export volume for the 12-month period preceding the final summer townet (i.e. previous-year September through current-year August). Data for water exports were the combined export volumes (MAF) for the SWP, CVP and Contra Costa Canal computed from daily Dayflow model output. CUSUM series were calculated for the period 1959-2007 for both parameters. Regression line (red line) was significant ( $P < 0.0001$ ;  $R^2 = 0.42$ ). Color coding is as follows: open blue circles for pre-*Corbula* years (1956-1986), solid green circles for post-*Corbula* years 1987-1999, red triangles for POD years 2000-2007.



**Figure 4. Correlation between CUSUM for ammonium concentrations in Suisun Bay (IEP station D8) on the x-axis and CUSUM for the Delta smelt summer tow net index on the y-axis, from Figure 20 in Glibert 2010. CUSUM series were calculated using data for 1975-2005.**

## 2. Problems with Underlying Ecological Assumptions

Many ecological assumptions are required to infer cause and effect from the correlations presented in Glibert's paper, or to support the conceptual model she developed. Several assumptions are problematic for reasons which include:

- Not New, but Not Well Tested. The assumption is a part of "prevailing wisdom" for the Delta, but may not be well tested or well supported by available research.
- New, but Unsupported. The assumption is not part of prevailing wisdom for the Delta, but no published or unpublished work is cited by Glibert which supports the assumption.
- Contradicted/Bounded. Other research contradicts the assumption, or places boundaries on its applicability.
- Logically Flawed. The assumption is not logical.

A few examples of problematic assumptions are provided below, with brief explanations.

**Assumption:** *Ammonium places diatoms at a competitive disadvantage compared to other kinds of phytoplankton* (Contradicted/Bounded)

As revealed by SFSU research in 2008-2009,<sup>3,4</sup> phytoplankton biomass and growth rates in the Sacramento River do not respond to ammonium or  $\text{NO}_3:\text{NH}_4$  ratios in the ways that were

<sup>3</sup> Parker A.E., R.C. Dugdale, F.P. Wilkerson, A. Marchi, J. Davidson-Drexel, J. Fuller, and S. Blaser. 2009. *Transport and Fate of Ammonium Supply from a Major Urban Wastewater Treatment Facility in the Sacramento River, CA*. 9th Biennial State of the San Francisco Estuary Conference, Oakland, CA, September 29-October 1, 2009.

predicted by short-term bottle experiments conducted by R. Dugdale (SFSU) and colleagues using water from Suisun Bay and points westward in the estuary.<sup>5,6</sup> Based on the performance of the >5 µm size range of Sacramento River phytoplankton (a presumed proxy for diatoms) in a variety of nutrient addition experiments and several detailed longitudinal surveys of nitrogen and carbon uptake rates (from above Sacramento into Suisun Bay), it does not appear from the recent SFSU research that elevated ammonium or low NO<sub>3</sub>:NH<sub>4</sub> ratios place diatoms at a competitive disadvantage compared to other phytoplankton taxa in the Sacramento River. Until analogous research is conducted in the interior Delta, the same caveat is reasonably applied to other freshwater Delta locations dominated by flows diverted from the Sacramento River. This means that Glibert cannot apply her conceptual model to the freshwater Delta without contradicting available research.

**Assumption:** *Diatoms are vastly preferable as food for calanoid copepods, or at least for Eurytemora (Not New, but Not Well Tested)*

Non-diatom classes of phytoplankton include species which are perfectly good food for zooplankton - to such an extent that they are commonly used to culture zooplankton in the lab. Examples are *Cryptomonas* (a cryptophyte genus) and *Scenedesmus* spp. (a green genus), which are both used to rear zooplankton in laboratories. Both *E. affinis* and *P. forbesi* were more successfully cultured in the lab when fed the motile cryptophyte alga *Cryptomonas* than when fed the diatom *Skeletonema* or the green alga *Scenedesmus* suggesting these calanoid copepods might prefer motile prey.<sup>7</sup> Significant grazing on heterotrophic ciliates (non-phytoplankton) has been observed for both of the calanoid copepods included in Glibert's analyses: *P. forbesi* and *E. affinis*.<sup>8</sup> In feeding experiments using natural plankton assemblages from the SFE, another calanoid copepod (*Acartia*) grazed heterotrophic ciliates at higher rates than diatoms.<sup>9</sup> In addition the large diatom *Aulacoseira* (formerly *Melosira*) *granulata*, which is one of the more abundant taxa in blooms in the freshwater Delta, may not be very nutritious for zooplankton.<sup>10</sup> Ongoing research in the low salinity zone (LSZ) of the estuary indicates that bacteria and small-sized phytoplankton contribute to a complicated food web with many trophic levels between bacteria and the copepod prey favored by pelagic fish.<sup>11</sup>

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<sup>4</sup> Parker, A.E., A.M. Marchi, J. Drexel-Davidson, R.C. Dugdale, and F.P. Wilkerson. 2010. Effect of ammonium and wastewater effluent on riverine phytoplankton in the Sacramento River, CA. Draft Final Report, submitted to the Central Valley Regional Water Quality Control Board, March 17, 2010.

<sup>5</sup> Dugdale, R. C., F. P. Wilkerson, V. E. Hogue, and A. Marchi. 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. *Estuar. Coast. Shelf Sci.* 73: 17-29.

<sup>6</sup> Wilkerson, F.P., R.C. Dugdale, V.E. Hogue, and A. Marchi. 2006. Phytoplankton blooms and nitrogen productivity in San Francisco Bay. *Estuaries Coasts* 29: 401-416.

<sup>7</sup> Hall, C., and A. Mueller-Solger. 2005. Culturing delta copepods. *IEP Newsletter.*, Vol. 18, No. 3, Summer 2005.

<sup>8</sup> Bouley, P., and W.J. Kimmerer. 2006. Ecology of a highly abundant, introduced cyclopoid copepod in a temperate estuary. *Mar. Ecol. Prog. Ser.* 324:219-228.

<sup>9</sup> Gifford, J.M., G. Rollwagen-Bollens, and S.M. Bollens. 2007. Mesozooplankton omnivory in the upper San Francisco Estuary. *Mar. Ecol. Prog. Ser.*, 348:33-46.

<sup>10</sup> Orsi, J.J. 1995. Food habits of several abundant zooplankton species in the Sacramento-San Joaquin estuary. Interagency ecological program for the San Francisco Bay-Delta Estuary Technical Report 41.

<sup>11</sup> Kimmerer, W.J., SFSU, 2009, personal communication.

**Assumption:** *Calanoid copepods have decreased in abundance in the Delta because they are food limited (Not New, but Not Well Tested).*

Kimmerer et al. (2005)<sup>12</sup> measured egg production by the calanoid copepod *Acartia* on several occasions during 1999-2002, and discovered that egg production during most of the year was below that observed during month-long spring phytoplankton blooms. However, similar data for the calanoid copepods *Eurytemora* and *Pseudodiaptomus* have not been reported. Direct mortality of copepod nauplii from entrainment by filtering clams was shown to be a better explanation than food limitation for declines in three species of estuarine copepods after the arrival of *Corbula amurensis*.<sup>13</sup> Chlorophyll-a levels below 10 µg/L are frequently cited as evidence that zooplankton in the Delta are food limited. However, this threshold is based on growth experiments conducted with a single cladoceran zooplankton species (*Daphnia magna*)<sup>14</sup> and it is unclear whether this threshold is appropriately applied to copepods in this system.

**Assumption:** *Fish which have increased during the POD (largemouth bass, inland silversides, threadfin shad, sunfish) receive an advantage from the current nutrient/plankton regime. (New, but Unsupported; Logically Flawed)*

Glibert cites no ecological information from the Delta or other estuaries to support the hypothesis that largemouth bass, inland silversides, threadfin shad, or sunfish would thrive in an estuary populated with the copepod *Limnoithona* but not one populated with *Eurytemora* or *Pseudodiaptomus*. Also, largemouth bass and sunfish are associated with submerged aquatic vegetation (they aren't pelagic fish) and a credible hypothesis which has been advanced by Delta fisheries experts is that habitat changes (increasing lake-like conditions and proliferation of aquatic weeds) have allowed largemouth bass and sunfish to proliferate in the Delta.<sup>15,16</sup>

**Assumption:** *Fish which have increased during the POD (largemouth bass, inland silversides, threadfin shad, sunfish) were disadvantaged by the previous nutrient/plankton regime (New, but Unsupported; Logically Flawed)*

As indicated above, Glibert implies that largemouth bass, inland silversides, threadfin shad, and sunfish have recently increased in the estuary because the current plankton regime favors them. To be logically consistent, one must conclude that the *previous* plankton regime was unfavorable for them. There is no reason to believe that the prior diatom/calanoid copepod regime would have provided a competitive *disadvantage* for these species prior to the POD.

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<sup>12</sup> Kimmerer, W.J., N. Ferm, M.H. Nicolini, and C. Penalva. 2005. Chronic food limitation of egg production in populations of copepods of the genus *Acartia* in the San Francisco Estuary. *Estuaries* 28:541-550.

<sup>13</sup> Kimmerer, W.J., E. Gartside, and J.J. Orsi. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Mar. Ecol. Prog. Ser.* 113:81-93.

<sup>14</sup> Müller-Solger, A.B., A.D. Jassby, and D. C. Müller-Navarra. 2002. Nutritional quality of food resources for zooplankton (*Daphnia*) in a tidal freshwater system (Sacramento-San Joaquin River Delta). *Limnol. Oceanogr.* 47: 1468-1476.

<sup>15</sup> Brown, L.R. and D. Michniuk. 2007. Littoral fish assemblages of the alien-dominated Sacramento-San Joaquin Delta, California, 1980-1983 and 2001-2003. *Estuaries and Coasts* 30:186-200.

<sup>16</sup> Moyle, P.B., W.A. Bennett, W.E. Fleenor, and J.R. Lund. 2010. Habitat variability and complexity in the upper San Francisco Estuary. Written Testimony submitted for the SWRCB Informational Proceeding to Develop Flow Criteria. Avail. at [http://www.waterboards.ca.gov/waterrights/water\\_issues/programs/bay\\_delta/deltaflow/entity\\_index.shtml](http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/entity_index.shtml)



**Assumption:** *Corbula* are favored by the current phytoplankton assemblage. (New, but Unsupported; Contradicted).

Glibert cites no evidence from the literature that would support her theory that *Corbula* fare better when filtering the current plankton assemblage, compared to prior assemblages. As explained below in one of the alternative hypotheses, there is evidence that the reverse is true: benthic grazing may influence phytoplankton composition in a top-down manner.

### 3. Alternative Hypotheses Regarding Trends in Plankton and Fish Abundance which are Unaddressed

Glibert's conclusions ultimately rely on the basic premises that (1) temporal shifts in the relative abundance of phytoplankton taxa were caused by changes in nutrient ratios, and (2) shifts in zooplankton abundance were caused by changes in the taxonomic composition of phytoplankton. There are credible alternative hypotheses for observed temporal shifts in the relative abundance of phytoplankton, zooplankton, and fish taxa which are not acknowledged in Glibert's article. In addition there is a credible alternative hypothesis for the timing of *Corbula*'s establishment in the estuary (to contrast with Glibert's suggestion that the establishment of *Corbula* was ammonia driven). Below are several examples of alternative hypotheses related to community composition in the Delta which have been discussed in the literature and at recent Delta forums.

**Alternative Hypothesis 1:** *Selective grazing by clams and copepods can influence the species composition of phytoplankton - and may contribute to the occurrence of Microcystis.*

Clam grazing selectively removes larger particles from the water column;<sup>17</sup> clams may consume a larger fraction of diatoms than smaller plankton taxa such as flagellates. Kimmerer (2005)<sup>18</sup> used long-term dissolved silica dynamics, corrected for mixing in the low salinity zone, as an indicator of diatom productivity in the northern SFE. He showed that there was a step decrease in annual silica uptake after 1986, which he attributed to efficient removal of diatoms by *Corbula amurensis* after its introduction in 1986. Grazing by *Corbicula fluminea* can cause shallow habitats in the freshwater Delta to serve as a net sink for phytoplankton;<sup>19,20</sup> it is possible that diatoms are differentially affected by benthic grazing (e.g., compared to motile or buoyant taxa) in both the brackish and freshwater Delta. In fact, benthic grazing has been implicated as a factor favoring *Microcystis* over other phytoplankton, as explained in the CalFed expert panel's "Ammonia Framework:"

"However, in places where filter-feeding mussels and clams overlap with habitat suitable for *Microcystis* (i.e., low salinity), the presence of these invertebrates might enhance bloom formation by selectively rejecting large *Microcystis* colonies. That grazer selectivity can give *Microcystis* a grazer-resistant, competitive advantage over

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<sup>17</sup> Werner, I., and J.T. Hollibaugh. 1993. *Potamocorbula amurensis*: Comparison of clearance rates and assimilation efficiencies for phytoplankton and bacterioplankton. *Limnol. Oceanogr.* 38: 949-964.

<sup>18</sup> Kimmerer, W.J. 2005. Long-term changes in apparent uptake of silica in the San Francisco Estuary. *Limnol. Oceanogr.* 50: 793-798.

<sup>19</sup> Lopez, C.B., J.E. Cloern, T.S. Shraga, A.J. Little, L.V. Lucas, J.K. Thompson, and J. R. Burau. 2006. Ecological values of shallow-water habitats: implications for the restoration of disturbed ecosystems. *Ecosystems* 9: 422-440.

<sup>20</sup> Parchaso F., and J. Thompson. 2008. *Corbicula fluminea* distribution and biomass response to hydrology and food: A model for CASCade scenarios of change. CALFED Science Conference, Sacramento, CA., October, 2008. Avail at <http://cascade.wr.usgs.gov/CALFED2008.shtm>

other phytoplankton, as Vanderploeg et al. (2001) reported for zebra mussels (*Dreissena polymorpha*) in the Great Lakes.” (Meyer et al. 2009)<sup>21</sup>

In addition to mussels and clams, zooplankton can exert a top-down effect on phytoplankton composition; the literature regarding selective feeding by zooplankton is impractical to review herein. However, in a particularly pertinent example, selective grazing by the Delta copepod *Pseudodiaptomus forbesi* was recently demonstrated as a viable mechanism for encouraging *Microcystis* blooms.<sup>22</sup>

**Alternative Hypothesis 2:** *Benthic grazing caused the crash in abundance of the copepod *Eurytemora affinis* in 1987.*

Direct mortality of copepod nauplii from entrainment by filtering clams was shown to be a better explanation than food limitation for declines in three species of estuarine copepods, including *Eurytemora affinis*, after the arrival of *Corbula*.<sup>23</sup>

**Alternative Hypothesis 3:** *Residence time and other physical factors influence phytoplankton composition in estuaries.*

Physical factors (such as temperature, current speed, residence time, turbulent mixing, stratification, light penetration) may be strongly affecting competitive outcomes between diatoms and other phytoplankton taxa in the Delta, irrespective of (or in combination with) nutrient concentrations or ratios. The influence of flows and residence time on phytoplankton assemblages in estuaries is well-acknowledged in other regions. For example, hydrologic perturbations, such as droughts, floods, and storm-related deep mixing events, overwhelm nutrient controls on phytoplankton composition in the Chesapeake Bay; diatoms are favored during years of high discharge and short residence time.<sup>24</sup> The role of flow and residence time in regulating estuarine microfloral composition was summarized by the expert panel convened by CalFed in March 2009 in their final “*Ammonia Framework*” document:

“Diatoms have fast growth rates and may be particularly good competitors during high flows with concomitant short residence times, when their fast growth rates can offset high flushing rates. In moderate flows, chlorophytes and cryptophytes become more competitive, whereas low flows with concomitant longer residence times allow the slower-growing cyanobacteria, non-nuisance picoplankton, and dinoflagellates to contribute larger percentages of the community biomass. These spatially and temporally-variable patterns of phytoplankton composition are typical of many estuaries [e.g., Chesapeake Bay, Maryland; Neuse-Pamlico Sound, North Carolina; Narragansett Bay, Rhode Island; Delaware Bay, Delaware].” Meyer et al. (2009)

The idea that flows influence diatom abundance is not new in the Delta. P. Lehman (DWR) associated a multi-decadal decrease in the proportional biomass of diatoms in the Delta and

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<sup>21</sup> Meyer, J.S., P.J. Mulholland, H.W. Paerl, and A.K. Ward. 2009. A framework for research addressing the role of ammonia/ammonium in the Sacramento-San Joaquin Delta and the San Francisco Bay Estuary Ecosystem. Final report submitted to CalFed Science Program, Sacramento, CA, April 13, 2009.

<sup>22</sup> Ger, K.A., P. Arneson, C.R. Goldman, and S.J.Teh. 2010. Species specific differences in the ingestion of *Microcystis* cells by the calanoid copepods *Eurytemora affinis* and *Pseudodiaptomus forbesi*. Short Communication. *J. Plankton Research*. doi: 10.1093/plankt/fbq071

<sup>23</sup> Kimmerer, W.J., E. Gartside, and J.J. Orsi. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Mar. Ecol. Prog. Ser.* 113: 81-93.

<sup>24</sup> Pearl, H.W., L.M. Valdes, B.L. Peierls, J.E. Adolf, and L.W. Harding, Jr. 2006. Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. *Limnol. Oceanogr.* 51(1, part 2): 448-462.

Suisun Bay to climatic influences on river flow.<sup>25,26</sup> The deep, pool-like bathymetry of the Stockton Deepwater Ship Channel is hypothesized by some investigators to function as a trap for diatoms in transport in the San Joaquin River.<sup>27</sup> The Central Valley Regional Board recently found that current speed in the Sacramento River was related to the difference in phytoplankton biomass between Freeport and Isleton.<sup>28</sup>

**Alternative Hypothesis 4: Non-nutrient-related factors are drivers of *Microcystis* blooms and toxicity.**

Although Glibert did not analyze data for *Microcystis* using CUSUM, she advances the hypothesis that nitrogen enrichment underlies its recent proliferation in the Delta. Available research from the Delta argues against a simplistic association between *Microcystis* and nutrient form or concentration. Studies conducted by Peggy Lehman (DWR)<sup>29,30</sup> and Cecile Mioni (UCSC)<sup>31</sup> in the Delta have found no apparent association between ammonium concentrations or  $\text{NH}_4^+:\text{P}$  ratios and either *Microcystis* abundance or toxicity. Instead, it appears from these studies that water temperature is strongly positively correlated with *Microcystis* abundance and toxicity and that water transparency, flows, and specific conductivity are also potential drivers of *Microcystis* blooms in the Delta. Indeed, spring-summer mean water temperature trended upward in the freshwater Delta between 1996-2005.<sup>32</sup> An association between water temperature and *Microcystis* blooms in the Delta would be consistent with observations from other estuaries. Increased residence time (e.g., during drought) and warmer temperatures are acknowledged as factors stimulating cyanobacterial blooms in other estuaries.<sup>33,34,35</sup> In addition, as noted above, differential grazing by the currently dominant calanoid copepod in the Delta

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<sup>25</sup> Lehman, P.W. 1996. Changes in chlorophyll-a concentration and phytoplankton community composition with water-year type in the upper San Francisco Estuary. (pp. 351-374) In Hollibaugh, J.T. (ed.) San Francisco Bay: the ecosystem. San Francisco (California): Pacific Division, American Association for the Advancement of Science.

<sup>26</sup> Lehman, P.W. 2000. The influence of climate on phytoplankton community biomass in San Francisco Bay Estuary. *Limnol. Oceanogr.* 45: 580-590.

<sup>27</sup> P. Lehman, DWR, Feb. 2009, personal communication.

<sup>28</sup> Foe, C., A. Ballard, and S. Fong. 2010. Nutrient concentrations and biological effects in the Sacramento-San Joaquin Delta. Central Valley Regional Water Quality Control Board, Draft Report, May 2010.

<sup>29</sup> Lehman, P.W., G. Boyer, M. Satchwell, and S. Waller. 2008. The influence of environmental conditions on the seasonal variation of *Microcystis* cell density and microcystins concentration in the San Francisco Estuary. *Hydrobiologia* 600: 187-204.

<sup>30</sup> Lehman, P.W., S.J. Teh, G.L. Boyer, M.L. Nobriga, E. Bass, and C. Hogle. 2010. Initial impacts of *Microcystis aeruginosa* blooms on the aquatic food web in the San Francisco Estuary. *Hydrobiologia* 637: 229-248.

<sup>31</sup> Mioni, C.E., and A. Paytan. 2010. *What controls Microcystis bloom & toxicity in the San Francisco Estuary? (Summer/Fall 2008 & 2009)*. Delta Science Program Brownbag Series, Sacramento, CA. May 12, 2010.

<sup>32</sup> Jassby, A. 2008. Phytoplankton in the Upper San Francisco Estuary: recent biomass trends, their causes and their trophic significance. San Francisco Estuary & Watershed Science, Feb. 2008.

<sup>33</sup> Pearl, H.W., K.L. Rossignol, S. Nathan Hall, B.L. Peierls, and M.S. Wetz. 2009. Phytoplankton community indicators of short- and long-term ecological change in the anthropogenically and climatically impacted Neuse River Estuary, North Carolina, USA. *Estuaries and Coasts*. DOI 10.1007/s12237-009-9137-0

<sup>34</sup> Paerl, H.W., and J. Huisman. 2008. Blooms like it hot. *Science* 320: 57-58. doi:10.1126/science.1155398

<sup>35</sup> Fernald, S.H., N.F. Caraco, and J. J. Cole. 2007. Changes in cyanobacterial dominance following the invasion of the zebra mussel *Dreissena polymorpha*: long-term results from the Hudson River Estuary. *Estuaries and Coasts* 30: 163-170.

(*Pseudodiaptomus forbesi*) and by the non-native clams *Corbula amurensis* and *Corbicula fluminea* potentially confer a competitive advantage for *Microcystis* over other phytoplankton taxa.

**Alternative Hypothesis 5:** A period of low outflow and high X2 created favorable conditions for *Corbula* establishment in Suisun Bay after 1987.

Salinity gradients are known to affect *Corbula* physiology, grazing rate, and settlement success.<sup>36</sup> A prolonged period of abnormally low Delta outflow from 1987-1992 is believed to have assisted the rapid establishment of *Corbula* in Suisun Bay after its introduction.<sup>37</sup> This seems a more plausible view of events than Glibert's hypothesis that *Corbula* was present in the estuary at undetectable levels for years or decades and then received a sudden advantage of some kind beginning in 1987 from changes in the nutrient-phytoplankton regime.

**Alternative Hypothesis 6:** Physical characteristics of Liberty Island explain its current role as a Delta smelt refugium.

On page 27, Glibert proposes that the apparent role of Liberty Island, in the Cache Slough area, as a recent year-round Delta smelt refugium is likely explained by lower  $\text{NH}_4^+$  levels (compared to the Sacramento River) and more abundant diatoms (no data are presented to support this hypothesis in her article). However, other features of this habitat are seriously considered by Delta scientists as explanations for its above-average suitability for Delta smelt: (1) it is the remaining area within the Delta containing numerous dead-end sloughs (which were characteristic of the pre-settled Delta and which are believed to create opportunities for tide-induced retention of organic matter and suspended sediment),<sup>38</sup> (2) it has not become choked with invasive aquatic weeds, and (3) owing to wind-driven resuspension of sediment in shallow water and enhanced flood tide currents, it has higher levels of suspended sediment (needed by Delta smelt for predator avoidance and successful foraging) compared to the adjacent Delta.<sup>39</sup>

**Alternative Hypothesis 7.** Water exports affect the food web.

Water exports affect residence time in the interior Delta and directly remove phytoplankton and zooplankton biomass from productive areas of the freshwater Delta. A carbon budget for the Delta indicates that water exports remove more phytoplankton carbon from the freshwater Delta than is contained in net Delta outflow.<sup>40</sup> Consequently, water exports effect the quantity - and likely the quality - of planktonic food resources transported through the Delta to Suisun Bay.<sup>41</sup>

<sup>36</sup> Stillman, J. 2010. Metabolic responses to environmental salinity in the invasive clam *Corbula amurensis*. Interagency Ecological Program (IEP) Annual Workshop, Sacramento, CA, May 25-26, 2010.

<sup>37</sup> Moyle, P.B., W.A. Bennett, W.E. Fleenor, and J.R. Lund. 2010. Habitat variability and complexity in the upper San Francisco Estuary. Written Testimony submitted for the SWRCB Informational Proceeding to Develop Flow Criteria. Avail. at [http://www.waterboards.ca.gov/waterrights/water\\_issues/programs/bay\\_delta/deltaflow/entity\\_index.shtml](http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/entity_index.shtml)

<sup>38</sup> Whipple, A. 2010. Historical ecology of the Delta: Habitat characteristics of a fluvial-tidal landscape. Interagency Ecological Program (IEP) Annual Workshop, Sacramento, CA, May 25-26, 2010.

<sup>39</sup> King, T. 2010. Sedimentation processes and turbidities favoring endangered fish in the northern Sacramento-San Joaquin River Delta. Interagency Ecological Program (IEP) Annual Workshop, Sacramento, CA, May 25-26, 2010.

<sup>40</sup> Jassby, A.D., J.E. Cloern, and B.E. Cole. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnol. Oceanogr.* 47: 698-712.

<sup>41</sup> Baxter, R., R. Breuer, L. Brown, M. Chotkowski, F. Freyer, M. Gringas, B. Herbold, A. Müller-Solger, M. Nobriga, T. Sommer, and K. Souza. 2008. Pelagic organism decline progress report: 2007 synthesis of results. Interagency Ecological Program for the San Francisco Estuary.

Glibert suggests that water management strategies have not prevented pelagic fish declines because they are over-riden by nutrient-related processes. Unfortunately, Glibert does not subject data for water exports to CUSUM analysis, nor does she acknowledge that water management strategies have been accompanied by increases over time in seasonal and annual export volumes from the Delta. As shown above in Section 1, water exports perform as well as ambient ammonia concentrations in CUSUM correlations with Delta smelt summer abundance data.

***Alternative Hypothesis 8. Aquatic weeds encourage non-native fishes.***

Glibert does not acknowledge that the rise of non-native, non-pelagic fishes (such as largemouth bass, sunfish species, and Mississippi silversides) is attributed in large part to the proliferation of invasive submerged aquatic vegetation (SAV) in the Delta.<sup>42</sup>

#### **4. Inconsistencies**

*Pseudodiaptomus as prey.* *Pseudodiaptomus forbesi* is widely touted as an important prey item for Delta smelt and other pelagic fish. Enough so that (1) the water agencies have gone to lengths to argue at recent venues that ammonia must be behind the recent decline in *Pseudodiaptomus*<sup>43</sup> and (2) the Central Valley Regional Board is funding ammonia toxicity tests using *Pseudodiaptomus*. However in Fig. 18, Glibert's CUSUM analysis suggests that Delta smelt and longfin smelt trend in opposite directions from *Pseudodiaptomus*. This is an example where a CUSUM correlation produces a result which contradicts our understanding of fish feeding ecology. In an environment of food scarcity, Delta smelt should be closely tracking their remaining food resources, unless sources of mortality other than food shortages are driving population trends.

Flows effect on  $\text{NO}_3:\text{NH}_4$ . Figure 8E in Glibert's paper shows an inverse relationship between outflow and  $\text{NO}_3:\text{NH}_4$  in Suisun Bay prior to 2000, but a positive relationship after 2000. Glibert contends that  $\text{NH}_4$  in Suisun Bay is controlled by effluent- $\text{NH}_4$  delivered to Suisun Bay via the Sacramento River (Fig. 7B). Higher levels of  $\text{NH}_4$  would result in lower  $\text{NO}_3:\text{NH}_4$  ratios, and vice versa (provided nitrate inputs are reasonably constant, see Fig. 6B). If so, why would flow (which presumably diluted effluent ammonia throughout the time record) have an opposite relationship with  $\text{NO}_3:\text{NH}_4$  during two different portions of the time series? The relationship prior to 2000 is inconsistent with a premise that ammonium from the SRWTP, diluted and delivered via the Sacramento River, controls the  $\text{NO}_3:\text{NH}_4$  ratio in Suisun Bay. The results suggest an incomplete understanding about the extent to which ammonium from SRWTP influences the  $\text{NO}_3:\text{NH}_4$  ratio downstream in the brackish estuary.

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<sup>42</sup> Brown, L.R. and D. Michniuk. 2007. Littoral fish assemblages of the alien-dominated Sacramento-San Joaquin Delta, California, 1980-1983 and 2001-2003. *Estuaries and Coasts* 30: 186-200.

<sup>43</sup> Written Testimony submitted for the SWRCB Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem on behalf of the San Luis & Delta-Mendota Water Authority, State Water Contractors, Westlands Water District, Santa Clara Valley Water District, Kern County Water Agency, and Metropolitan Water District of Southern California. Avail. at [http://www.waterboards.ca.gov/waterrights/water\\_issues/programs/bay\\_delta/deltaflow/entity\\_index.shtml](http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/entity_index.shtml)

**Comments for Consideration by the State Water Resources Control Board Regarding *Long-term Changes in Nutrient Loading and Stoichiometry and their Relationships with Changes in the Food Web and Dominant Pelagic Fish Species in the San Francisco Estuary, California* by Patricia Glibert - pre-print copy (May 17<sup>th</sup>, 2010).**

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A peer-reviewed paper by Dr. Patricia Glibert describes the relationships over time between nutrients (primarily ammonium, nitrate, and phosphorus) and the Delta food web (algae, zooplankton and POD fishes). This paper has been accepted by the journal *Reviews in Fisheries Science* and a pre-print copy was distributed by Dr Glibert's Center for Environmental Science at the University of Maryland. Comments describing the findings of this paper that relate to the Sacramento Regional Wastewater Treatment Plant (SRWTP) are provided below based on a limited review of the report because all of the supporting data were unavailable. Several issues and questions were identified during this review and the major topics are presented below. However, the subject of relationships between various physicochemical parameters and fish populations or phytoplankton community composition is complex and additional effort and evaluation would be needed to help to clarify and tease out the answers to some of these questions.

### **General Comments**

This paper presents a broad analysis of closely inter-correlated and auto-correlated variables (e.g., concentrations and flows are not independent) with an emphasis on time-series analysis. There are no direct comparisons (regressions or correlations) among parameters. Rather, the various parameters evaluated in this paper are compared indirectly through their variation from the average (i.e., increasing or decreasing trends) using the novel application of a statistical method used for control chart analyses. The cumulative sum (CUSUM) approach as applied to time series data is specifically designed to help elucidate

the points in time where changes have most likely occurred. It is a cumulative sum of differences between the running average and a given point in the data set. The author is correct that the CUSUM method shows inflection points; however, the technique does not infer causality. Instead, it merely suggests possible relationships that may merit further evaluation using other statistical approaches. The underlying relationships also need to be interpreted based on an understanding of the biological mechanisms at work, as indicated on page 12 (292-294).

The author recognizes that the Delta is a complex system (lines 205-206) but then fails to address many of the key factors associated with this complexity in her analysis (e.g., water clarity and temperature; lines 504-507). She further assumes that the mechanisms underlying the associations are understood and does not consider alternative possibilities. Her presentation of the Delta ecosystem is over simplistic. The Delta, as is any large ecosystem, is quite complex. As a result, the conclusions of the article exceed the evidence presented. By taking such a broad approach to the problem, the author has been able to selectively present data that seem to support the primary hypothesis that smelt are not influenced by flows (as inappropriately estimated by X2 position) but are strongly influenced by ammonium discharge (i.e., loads, and to a lesser degree by ambient ammonium concentrations).

To suggest that "a clear management strategy is the regulation of effluent N discharge through nitrification and denitrification." (lines 715-716) is not demonstrated by the data presented. Many would argue that the delta is not eutrophic, and that reducing nutrients would further reduce primary productivity.

The paper concludes by saying "Until such [nitrogen] reductions occur, other measures, including regulation of water pumping or manipulations of salinity, mass has been the current strategy, will likely show little beneficial effect. Without such action, the recovery of the endangered pelagic fish species is unlikely at best" (lines 716-718). The introduction also claims that there is a "high probability for success in restoring endangered pelagic fish." However, the confidence in any single environmental management decision to have a strong positive impact on the Delta is never high. At best, resource managers will have moderate confidence in any decision, because our understanding of the Delta processes with existing data are insufficient. For the author to claim that there is high confidence in a single resource management decision is not supported.

## Specific Comments

### Statistical Approach

- The author presents a relatively novel approach to analyze time-series data. There is nothing inherently wrong with this approach for identifying inflection points and for making limited interpretations, but the **conclusions assume a broad understanding of the Delta ecosystem and her interpretations are dependent on many assumptions.**
- A typical goal when applying CUSUM values to a time series is to quickly detect a change in the process mean (such as when applying the CUSUM values in a control chart). By keeping a cumulative total of deviations from the process mean, this

approach to temporal monitoring offers one method that may reveal small shifts in the data that might otherwise have been undetected. When evaluating these transformed CUSUM values, one typically seeks to determine if a substantial upward or downward trend develops in the plotted points.

- The application of CUSUM values in this report, however, goes beyond merely identifying temporal periods where an upward or downward trend occurs. CUSUM values were used to make correlations between various parameters. Such applications of CUSUM values may promote a greater focus on the impact of shifts in the parameters than on the actual magnitude of the values at any given time (or even the magnitude of values adjusted by some lag time to allow one parameter time to influence another). Whether this is a prudent approach is not clear. The author has not appeared to reference previous accepted applications of this correlation component of the approach (other than a single reference to another of her publications - in press). Thus, it is difficult to gauge the efficacy of using correlations between CUSUM values to understand relationships between parameters and **conclusions based on this novel statistical approach should be viewed with caution.**
- Correlation evaluations of raw data, lag-time adjusted data, etc. would help to offer alternative insights of the available data or help to infer causality. Therefore, alternative approaches and evaluations of the data are needed to fully evaluate the efficacy of the data analyses presented by Glibert.
- The literature describing CUSUM analysis does not appear to support or refute the statement that "The effect of such manipulation [summing CUSUM scores over time] is to filter the short term or seasonal variance, thereby revealing the long-term patterns in the data." **Whether CUSUM analysis serves to filter short-term variance and reveal long-term patterns is a novel interpretation of this analytical tool that is untested and has not been verified.** This claim, as it applies to the type of evaluation used in this manuscript, should be documented with references to other studies that have successfully used it. Otherwise, some of the conclusive statements in the report would appear to more appropriately slip into a language of unsettled hypotheses. A copy of the cited Glibert et al. (in review) may provide additional information about this approach, but was not available for review.
- Wastewater ammonium loads have shown steady increases over time that correlate with population increases in Sacramento County (Jassby 2008). Because CUSUMs are sensitive to the time period and average concentration that occurs during the selected period, it may be possible to identify different inflection points and make different interpretations using other timeframes. However, **any variables that have shown monotonic trends over recent years will, by definition, show positive CUSUM relationships to ammonium loading. Causality of the association cannot be inferred.**

#### Confidence in Conclusions and Recommended Actions

- **The confidence in conclusions and management decisions is overstated.** The author expresses very high confidence that the results of this analysis accurately explain the



cause of the POD and that the recommended resource management decisions (i.e., nitrification and denitrification at SRWTP) will solve the POD (e.g., lines 595-597). The perception that we understand the Delta sufficiently to have such confidence in the results from any one simple analysis based on limited data, or that such simple management decisions could address such a complex issue, suggests an over simplistic conceptual model of the Delta. Conclusions regarding the function of ecosystems are typically stated more cautiously, and resource management decisions affecting large and complex ecosystems, in general, can never be made with 'high' confidence.

### Limited Data

- **Few stations are evaluated when there are available data from many more.** The Delta has many monitoring stations and it is known that processes are not the same among all of them. For example, Parker et al. (2010) reported that algae in the Sacramento River respond differently to ammonium than algae in Suisun Bay (Dugdale et al. 2007). It is unclear whether data from the small selection of stations presented are representative of others in different areas of the Delta.
- **This analysis does not fully consider many factors that are considered important drivers in the POD, such as turbidity, *Microcystis*, Delta exports, contaminants, and invasive species (i.e., bivalves).** The absence of data evaluations for parameters that have been hypothesized and described by others as potentially important factors affecting the Delta food web adds significant uncertainty to the confidence in Glibert's conclusions that only ammonium has affected the Delta ecosystem. .
  - Turbidity has declined significantly over the past 30 years as flows have been controlled, submerged aquatic vegetation densities have increased, and bivalve densities have increased. Delta smelt respond directly to changes in turbidity (they prefer turbid waters where they are less likely to be eaten by predators) and there is a correlation between reduced turbidity and reduced delta smelt, yet this parameter is not considered in the Glibert analysis.
  - *Microcystis*, a blue-green algae (cyanobacteria) responsible for harmful algae blooms, has increased in recent years. Lehman (2008) conducted multivariate statistical analyses of multiple parameters potentially affecting Delta cyanobacteria and found that nutrients are not a driver for these harmful algae blooms, but flow has a significant influence. Recent data by Mioni (2010) supports the findings of Lehman. Despite referencing the Lehman (2008) paper, findings suggesting the influence of flow on harmful algae blooms are not mentioned in the Glibert paper (lines 559-561). Moreover, a reference to Lehman (2010) supports the ecological effects that cyanobacteria have on algae, zooplankton, and fish communities; although, Glibert again neglects to point out the influence of flow described therein.
  - Delta Exports have direct effects on fish survival/entrainment and algae losses that are not considered in this paper. Only delta flows and X2 are evaluated - which are measures of flow as waters exit the Delta - while exports are not

considered in the analysis of possible contributors to the POD. Therefore, conclusions that claim to identify potential causes of the POD are incomplete. Glibert states that "changes in flow are not correlated with all nutrients and nutrient ratios over the entire time series...although there were significant, but different, relationships for the pre-POD and POD years." (lines 597-599; Figure 8). Similar comparisons should be presented for other parameters (i.e., exports and fish, exports and phytoplankton abundance, flows and clam abundance, etc.) to complete the analyses.

- There is no consideration of the possible effects of contaminants on the POD. Recent studies indicate that the use of pyrethroid insecticides have resulted in ambient surface water concentrations that are toxic to sensitive invertebrates. Since the use of pyrethroids co-occurs with the POD (post-2000) there is reason to suspect that they have contributed to Delta ecosystem changes, yet they are not considered in the Glibert paper.
- Invasive clams have been the subject of compelling arguments showing their devastating impacts on Delta plankton (i.e., Kimmerer 1994). The potential influence, or relative proportion of these effects, is dismissed by Glibert despite the well understood ecological relationships supporting the role of invasive clams in reducing plankton. A statement (lines 445-446) claims that there were "no significant relationships between CUSUM trends in fish or clam abundance and the CUSUM of X2 (Table 1)." The analyses are incomplete without comparisons between clam abundance and fish abundance, or clam abundance and plankton abundance.
- **Ammonium trends in the San Joaquin River should be further evaluated and compared to Delta biota rather than ignored because they show trends that differ from those in the Sacramento River and Suisun Bay.** San Joaquin ammonium concentrations were relatively constant over time and decreased after 2000. This trend differs from the increasing trends in the Sacramento River and Suisun Bay (Figure 3; lines 328-332). The difference is used to support the hypothesis that the Sacramento River dominates the system and exclude any further analysis of the data from the San Joaquin River station. However, this difference should be used to evaluate plankton responses to ammonium in another part of the Delta and as a test case for the effects of nutrient removal (i.e., at the Stockton WWTP). The lack of further data analysis from the San Joaquin station is a potentially significant data gap.
- **It is surprising that large changes in fish, zooplankton, and algae can be attributed to very small changes in ammonium** (generally from 0.2 to 0.4 mg/L over 30 years) (Figure 3). The methods for data selection or data reduction is not entirely clear, since there are many more data points in Figure 3 than are presented in subsequent Figures. How the data are truncated (e.g., annual or monthly averages) should be explained and must make ecological sense. Plankton respond to local conditions on the timeframe of days to weeks. If comparisons are being made with annual averages it increases the uncertainty associated with any conclusions. These uncertainties should to be discussed.

### Assumed Relationships

- **Aquatic organisms respond to concentrations and not to loads (i.e., kg/day) or to trends.** Conclusions that ammonium has caused the POD are heavily weighted by comparisons between ammonium loading or effluent concentrations (441-444 and 579-582; Figure 6 and 22) and aquatic resources (i.e., algae, zooplankton, and fish). There is a fundamental problem with this concept, since aquatic organisms respond to concentrations, and any relationships assumed to exist between nutrient loading from SRWTP and plankton or fish are inappropriate.
  - The assumed relationship between loads and effects is clearly stated in the discussion: "The decline in diatoms, which began in 1982, was highly correlated with the increase in NH<sub>4</sub> loading." Many of the comments above apply to this statement (i.e., organisms respond to concentrations and not loads, other factors such as invasive clams significantly affected the phytoplankton communities in the mid-1980s, one station does not tell the story for the entire Delta. Despite what may appear to be similar trends between ammonium and algae it seems unlikely that the relatively small change in ammonium concentrations would have such a large impact.
  - Likewise, **ammonium concentrations in SRWTP effluent is not a surrogate for concentrations in the receiving water** (Figure 7 and 22), or in any part of the Delta where algae or fish are found. SRWTP effluent is diluted significantly by river flows and ambient concentrations are therefore dependent on those flows.
  - **Time lags between nutrients and algae and algae and zooplankton may be particularly important in determining causal relationships but are unexamined in this study.**
- POD species do not occur exclusively in Suisun Bay. Therefore, it is assumed that any relationships found between concentrations and responses in Suisun Bay also apply to the entire Delta. Existing data from Parker et al. (2010) show that this assumption is not true for phytoplankton responses to ammonium between Suisun Bay and the Sacramento River.
- **Step changes in phytoplankton that correspond with invasive clams in the mid 1980's are disregarded** in favor of a suggested "causation" due to similarly timed, but relatively small increases in ammonium (lines 534-536, 710-712). Glibert states that clams thrived because of nutrient loading, citing a correlation between the CUSUM of NH<sub>4</sub> (location not indicated) and the CUSUM of clam abundance. Correlation does not mean causation, as the author recognizes in the methods section. It is uncertain whether a correlation between trends (as indicated by correlating CUSUM values) has any environmental relevance. The correlation between invasive clam appearing in the Delta in 1986-1987 and a step decline in algae abundance (apparent in Figure 9a) has been reported by others as a clear cause and effect relationship that is not considered a possible contributor to the POD in Glibert's analysis.

- Likewise, a discussion of similar CUSUM trends between phytoplankton and NH<sub>4</sub> (lines 374-390; figure 10) focuses on data after 1984 when SRWTP began discharging combined treated wastewater for much of Sacramento County, but does not consider the effects of invasive clam grazing on phytoplankton in Suisun Bay that also began in 1987.
- **It is challenging to track the data presented among these figures and there appear to be inconsistencies that are not explained.** For example, CUSUM values for NH<sub>4</sub> at station D8 (Suisun Bay) are shown in Figure 3B and range from +30 to -30. Figures 20 and 21 show regressions between CUSUMs for fish abundance and nutrients (NH<sub>4</sub> and DIN:DIP). These nutrient data are said to be Station D8 (Suisun Bay), but the range of CUSUM values is only from -8 to 0, which do not correspond with the range of CUSUM values at Station D8. Likewise, CUSUM values for NH<sub>4</sub> are shown in figure 14 (comparison with CUSUM for *Corbicula* abundance) also only range from -8 to 0, and are inconsistent with the ambient data. However, the range of CUSUM values presented in these figures corresponds with the range of CUSUM values for NH<sub>4</sub> in wastewater discharge that are shown in Figure 22. These inconsistencies in the presented data need to be explained or corrected and may have significant impacts on the conclusions if relationships are based on loads and effluent concentrations and not ambient concentrations.
- **The response of delta smelt is emphasized over other fish with similar diets (plankton) that have opposite CUSUM responses over time.** Although the delta smelt and longfin smelt declines may support some kind of correlation between abundance CUSUMs and ammonium CUSUMs over time (Figure 20), largemouth bass, inland silversides, threadfin shad, and sunfish show stronger responses to the contrary (lines 419-434; Figure 21). Diets are generally considered similar among these POD species, but more detailed analysis is needed to tease out potential causal relationships. However, Glibert presents CUSUM analyses that are intended to suggest that these differences among fish species are related to changes in specific zooplankton species abundance (Figures 18 and 19). The degree of independence among these datasets is not clear when other factors (e.g., export flows) could be driving relationships. Further data evaluation is suggested to clarify the various related factors and their relative influences.
- **It is conceptually flawed to conclude that correlations between NH<sub>4</sub> concentrations in Suisun Bay and algae concentrations became more pronounced because the SRWTP came online in the mid 1980's** (lines 385-390). This temporal dissociation between pre- and post-SRWTP discharge is unfounded. Ammonium was constantly discharged into the Delta from multiple WWTPs prior to SRWTP combining many of these separate flows into one treatment facility and a single discharge point. The ammonium loads in treated wastewater are associated with population increases and not with operational changes.

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