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# Four decades of water quality change in the upper San Francisco Estuary

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<sup>3</sup> **Marcus W. Beck<sup>1</sup>, David Senn<sup>2</sup>, Phil Bresnahan<sup>2</sup>, Emily Novick<sup>2</sup>, James D. Hagy III<sup>1</sup>, Thomas Jabusch<sup>2</sup>, Phil Trowbridge<sup>2</sup>**

<sup>1</sup>USEPA National Health and Environmental Effects Research Laboratory  
Gulf Ecology Division, 1 Sabine Island Drive, Gulf Breeze, FL 32561

Phone: 850-934-2480, Fax: 850-934-2401

Emails: [beck.marcus@epa.gov](mailto:beck.marcus@epa.gov), [hagy.jim@epa.gov](mailto:hagy.jim@epa.gov)

<sup>2</sup>San Francisco Estuary Institute  
4911 Central Avenue, Richmond, CA 94804  
Phone: 510-746-7334, Fax: 510-746-7300

Emails: [davids@sfei.org](mailto:davids@sfei.org), [philb@sfei.org](mailto:philb@sfei.org), [emilyn@sfei.org](mailto:emilyn@sfei.org), [thomasj@sfei.org](mailto:thomasj@sfei.org)

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### Abstract

Recent methods for trend analysis have been developed that leverage the descriptive potential of long-term time series. Combined with these methods, multi-decadal datasets of water quality in coastal systems can provide valuable opportunities to gain insights into ecosystem properties and drivers of change. This study describes use of an estuarine adaptation of the Weighted Regressions on Time, Discharge, and Season (WRTDS) model to describe water quality trends over four decades in the Delta region of the San Francisco Estuary (SFE). This region is a complex mosaic of inflows that are primary sources of nutrients into the larger Bay. To date, a comprehensive evaluation of flow-normalized trends using the long-term monitoring dataset at multiple stations in the Delta has not been conducted despite the importance of nutrient transport from the region for water quality in the entire bay. The WRTDS technique is data-driven where the parameterization of the functional model changes smoothly over time following dynamic patterns of season and flow. Water quality trends that have not been previously quantified can be described, including variation in flow-normalized concentrations, frequency occurrence of extreme events, and response to historical changes in the watershed, all of which are important needs for understanding changes in the SFE. Model results from multiple stations in the Delta provided novel descriptions of historical trends and relationships between key species of dissolved inorganic nitrogen (ammonium, nitrate/nitrite, total). This variation was described in the context of varying contributions of input flows from the Sacramento and San Joaquin rivers, as well as tidal exchange with the central SFE. Conceptual relationships between water quality and drivers of change were used to generate and test hypotheses of mechanistic relationships using selected examples from the trend descriptions. Overall, this analysis provides an ecological and management-based understanding of historical trends in the SFE as a means to interpret potential impacts of recent changes and expected trends in this dynamic system. An argument is also made for more comprehensive evaluations of long-term monitoring datasets to understand relationships between response endpoints and causal mechanisms in coastal waters.

## 1 *Introduction*

1. How and why are trends interpreted - assessment of raw data, surrogates, various methods (kendall, GAM, WRTDS), what have been implications of using different approaches, see Kratzer USGS report <http://pubs.usgs.gov/sir/2010/5228/pdf/sir20105228.pdf> and data

35 http://pubs.usgs.gov/sir/2010/5228/, need to interpret eutrophication trends in estuaries - it's  
36 confusing ([Cloern and Jassby 2010](#))

37 2. WRTDS, original method ([Hirsch et al. 2010, 2015](#))

38 3. WRTDS application to Tampa Bay as test set ([Beck and Hagy III 2015](#)), further validation  
39 in Patuxent and other tidal waters [Beck et al. \(2015\)](#)

40 4. SF estuary, unique and prominent location, full story is complex (historical context and  
41 recent changes) ([Cloern and Jassby 2012](#)), why is the delta important (a vigorous  
42 biogeochemical reactor) ([Jassby and Cloern 2000, Jassby et al. 2002, Jassby 2008](#)), no one  
43 has empirically described the data in the delta using data-intensive methods

44 San Francisco Bay on the Pacific Coast of the United States is one of the most prominent  
45 estuaries in the western hemisphere. Background nutrient concentrations in the Bay often  
46 exceed those associated with excessive primary production, although eutrophication events  
47 have historically been infrequent. Recent changes in response to additional stressors (e.g.,  
48 variation in freshwater inputs/withdrawals, invasive species, climate change) suggests that  
49 Bay condition has not followed historical trajectories and more subtle spatial and temporal  
50 variation could provide clues that describe underlying properties of this system. The unique  
51 ecological and social context of the Bay, including a rich source of monitoring data from  
52 the last four decades, provides a valuable opportunity to gain insight into ecosystem  
53 properties of estuaries.

54 5. Study goal and objectives

- 55 • Provide a description of trends - annual, seasonal, spatial, response to flow, change by  
56 analytes
- 57 • Detailed description of selected sites in the context of conceptual relationships - 1)  
58 nonlinear or extreme quantile changes, site TBD, 2) P8 and WWTP improvements, 3)  
59 Suisun DIN, SiO<sub>2</sub>, Chla, and clams
- 60 • What this means for understanding other systems

61    **2 Methods**

62    **2.1 Study system**

63       The San Francisco Estuary (SFE) drains a 200 thousand km<sup>2</sup> watershed and is the largest  
64       bay on the Pacific coast of North America. The watershed provides drinking water to over 25  
65       million people, including irrigation for 18 thousand km<sup>2</sup> of agricultural land in the Central Valley.  
66       Water enters the Bay through the Sacramento and San Joaquin rivers that have a combined inflow  
67       of approximately 28 km<sup>3</sup> per year, with the Sacramento accounting for 84% of inflow to the  
68       Delta. The SFE system is divided into several sub-bays, including Suisun Bay immediately  
69       downstream of the Delta, San Pablo Bay to the north, South Bay, and the Central Bay that drains  
70       to the Pacific Ocean through the Golden Gate. Water dynamics in SFE are governed by inflows  
71       from the watershed, tidal exchange with the Pacific Ocean, and water withdrawals for municipal  
72       and agricultural use ([Jassby and Cloern 2000](#)). Seasonally, inflows into SFE peak in the spring  
73       and early summer from snowmelt in the upper watershed, whereas consumption, withdrawals,  
74       and export have steadily increased from 1960 to present but vary considerably depending on  
75       inter-annual climate effects ([Cloern and Jassby 2012](#)). The system is mixed mesotidal and  
76       significant exchange with the ocean occurs daily, although the extent of landward saltwater  
77       intrusion varies with inflow and annual water use patterns. Notable drought periods have occurred  
78       from 1976-1977, 1987-1992, and recently from 2013-2015 ([Cloern 2015](#)). Oceanic upwelling and  
79       climatic variation are also significant external factors that have influenced water quality dynamics  
80       in the Bay ([Cloern et al. 2007](#)).

81       Nutrient loading in SFE is comparable to other large estuaries that exhibit symptomatic  
82       effects of cultural eutrophication (e.g., Chesapeake Bay, [Kemp et al. 2005](#)). Orthophosphate  
83       ( $\text{PO}_4^{3-}$ ) and dissolved inorganic nitrogen (DIN) enter the Bay primarily through riverine sources  
84       in the north and municipal wastewater treatment plant (WWTP) inputs in the densely-populated  
85       area immediately surrounding SFE. Annual nutrient export from the Delta region has been  
86       estimated as approximately 30 thousand kg d<sup>-1</sup> of total nitrogen (varying with flow, [Novick et al.](#)  
87       2015), with 90% of ammonium ( $\text{NH}_4^+$ ) originating solely from the Sacramento Regional WWTP  
88       ([Jassby 2008](#)). Although nitrogen and phosphorus inputs are considerable, primary production is  
89       relatively low and not nutrient-limited ([Jassby et al. 2002](#), [Kimmerer et al. 2012](#)). The resistance

90 of SFE to the negative effects of eutrophication has historically been attributed to the unique  
91 physical and biological characteristics of the Bay, including strong tidal mixing that limits  
92 stratification (Cloern 1996, Thompson et al. 2008) and limits on phytoplankton growth from high  
93 turbidity and filter-feeding by bivalve mollusks (Thompson et al. 2008, Crauder et al. 2016).  
94 However, recent water quality trends have suggested that resistance of the system to nutrient  
95 inputs is decreasing given documented increases in chlorophyll biomass (Cloern et al. 2007),  
96 increased occurrence of hypoxic conditions (Sutula et al. in review), and increased abundance of  
97 phytoplankton species associated with harmful algal blooms (Lehman et al. 2005, 2010). These  
98 recent changes have been attributed to variation in global sea surface temperatures associated with  
99 climate change (Cloern et al. 2007), biological invasions (Cohen and Carlton 1998), and  
100 departures from the historical flow record (Enright and Culberson 2009, Cloern et al. 2012).

101 The Delta region is of particular interest for understanding historical patterns and potential  
102 trajectories of water quality response to nutrient inputs into the Bay. The Delta is a mosaic of  
103 linked channels or tracts that receive, process, and transport inflows from the Sacramento and San  
104 Joaquin rivers (Jassby and Cloern 2000, Jassby 2008, Novick et al. 2015). Quantitative  
105 descriptions of nutrient dynamics in the Delta are challenging given the numerous sources of  
106 nutrients and the volume of water that is exchanged through natural and anthropogenic processes.  
107 A comprehensive evaluation using mass-balance models to describe nutrient dynamics in the  
108 Delta demonstrated that nitrogen enters the system in different forms and is processed at different  
109 rates before export or removal (Novick et al. 2015). For example, a majority of ammonium  
110 entering the system during the summer is nitrified or assimilated, whereas a considerable  
111 percentage of total nitrogen load to the Delta is lost. Although, the focus of our analysis is not to  
112 quantify sources or sinks of nitrogen species, a quantitative evaluation of long-term trends will  
113 provide a more comprehensive historical interpretation to hypothesize the effects of future  
114 changes in the context of known dynamics. Nutrients in the Delta also vary with seasonal and  
115 annual changes in the delivery of water inflows, including water exports directly from the system  
116 (Jassby and Cloern 2000, Jassby 2008). Our analysis also explicitly accounts for the effects of  
117 flow changes on nutrient response to better understand variation both within the Delta and  
118 potential mechanisms of downstream transport.

119 **2.2 Data sources**

120 Multi-decadal time series of nutrients and flow records were used to develop a quantitative  
121 description of nitrogen trends in the Delta. The Interagency Ecological Program (IEP) is a  
122 consortium of state and federal agencies that have maintained the Environmental Monitoring  
123 Program (EMP) in the Delta region since 1975 ([IEP 2013](#)). The EMP collects monthly water  
124 quality samples at 19 stations in the Delta, Suisun Bay, and northeastern San Pablo Bay. Water  
125 samples were collected using a Van Dorn sample, a submersible pump, or a flow through system  
126 depending on site. All samples were processed with adequate QA/QC at the California  
127 Department of Water Resources Bryte Laboratory in Sacramento (references in [IEP 2013](#)).

128 Nutrient time series were obtained from the IEP website  
129 (<http://water.ca.gov/bdma/meta/Discrete/data.cfm>) at nine discrete sampling stations from 1976 to  
130 2012. Three representative stations from three locations in the Delta and Suisun Bay were used:  
131 Delta stations C3 (Sacramento inflow), C10 (San Joaquin inflow), P8; middle stations D19, D26,  
132 D28; and Suisun stations D4, D6, and D7. These stations were chosen based on the continuity of  
133 the water quality time series and geographic location for understanding trends. Data were  
134 minimally processed with the exception of averaging replicates that occurred on the same day.  
135 Detection limits throughout the period of record were obtained from the metadata, although few  
136 observations were censored (< 3%). The three nitrogen analytes that were evaluated were  
137 ammonium, nitrite/nitrate, and DIN (as the sum of the former two).

138 Daily flow estimates for the Delta region were obtained from the

139 **2.3 Analysis method and application**

140 nine discrete sampling stations with data from 1976 to 2012, DIN, ammonium, total  
141 nitrate, effects of different flow variables

142 **2.4 Time series modelling**

$$\ln(N) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) \quad (1)$$

143 Annual, seasonal trends of flow-normalized predictions

144 **2.5 Case studies**

145 These are science questions that are relevant outside of the region.

146 **2.5.1 Disaggregating observed nitrogen time series**

147 Hypothesis: Because multiple factors influence nutrient concentrations at different times,  
148 relationships between nutrients, time, and flow/salinity are non-linear and complex, so we expect  
149 1) annual trend independent of seasonal trend, 2) changes in seasonal amplitudes and quantile  
150 trends over time, 3) varying flow contribution, either as difference between  
151 predicted/flow-normalized results or changes in nutrient v flow scatterplots at different annual  
152 periods.

153 **2.5.2 Effects of wastewater treatment**

154 Hypothesis: Modal response of nutrient concentrations at P8 over time is result of WWTP  
155 upgrades, so we expect 1) a shift in load contributions before/after upgrade, 2) a flow-normalized  
156 annual trend at P8 to show a change concurrent with WWTP upgrades, and 3) different nitrogen  
157 species will have different changes depending on change in load outputs. See [here](#)

158 **2.5.3 Effects of biological invasions**

159 Hypothesis: Biological invasions by benthic filter feeders have shifted abundance and  
160 composition of phytoplankton communities in Suisun Bay, so we expect 1) decline in annual,  
161 flow-normalized chlorophyll concentrations over time coincident with increase in abundance of  
162 invaders, 2) changes in ratios of limiting nutrients (nitrogen, SiO<sub>2</sub>) suggesting different uptake  
163 rates with shift in community composition, and 3) seasonal shifts in limiting nutrients based on  
164 changes in community composition and relative abundances with seasonal succession.

165 **3 Results**

166 **3.1 Trends**

167 **3.2 Selected examples**

168 **3.2.1 Disaggregating observed nitrogen time series**

169 Fig. 3, Fig. 4

170 Emphasize the information the model provides relative to the observed time series. A  
171 distinct annual trend with a maximum in the middle of the time series is observed, with lower  
172 values at the beginning and end of the period. The seasonal patterns generally showed that DIN  
173 concentrations were highest in January with higher values at moderate to low flow rates  
174 depending on the year. Interestingly, summer and fall concentrations have showed a slight

increase later in the time series ( 2004-2009). The confounding effect of flow is also very apparent such that higher flows were associated with lower concentration. Dynaplot showed that there was always a negative association between the two (i.e., no modal response). The quantile distributions showed similar trends over time in both predicted values and flow-normalized predictions, although some exceptions were observed. In particular, high flow (1984, 2008) reduced concentrations of all quantiles but the magnitude of the effect increased at higher quantiles (i.e., the effect was disproportionate). The opposite was observed for low flow, i.e., the ninetieth percent showed the greatest increase for low flow.

Emphasize the summer/fall change in the 2000s, why is this? Check ([Cloern et al. 2007](#)), showed seasonal changes in early 2000s in chlorophyll (NE Pacific shifted to cool phase), is there a mechanism here with DIN? Relate to conceptual diagram.

### **3.2.2 Effects of wastewater treatment**

Overall reduction in total nitrogen load was observed as a result of reduction in ammonium (Fig. 5). Nitrate is the primary constituent of total nitrogen after 2007. Organic nitrogen is a larger percentage of the total after nitrification. What was reduction in ammonium starting in 2002?

Nitrogen trends at P8 shifted in response to upstream WWTP upgrades (Fig. 6), with ammonium showing the largest reduction. Interestingly, nitrite/nitrate concentrations also showed a similar but less dramatic decrease. Percent changes are shown in Table 2, where both nitrogen species shows large percent increases prior to WWTP upgrades followed by decreases after upgrades with ammonium showing the largest percentage. Seasonally, increases prior to upgrades were most apparent in the July-August-September (JAS) months for both analytes. Seasonal reductions post-upgrades were also largest in JAS for nitrite/nitrate, whereas percent reductions were similar across all monthly groupings for ammonium.

Relationships of nitrogen with flow showed the typical inverse flow/concentration dynamic with flushing at high flow, although patterns differed by nitrogen species. Seasonal variation was more apparent for ammonium, although both typically had the highest concentrations in the winter. Additionally, strength of the flow/nutrient relationship changed throughout the time series the year where the strongest relationship differed by analyte. Nitrite/nitrate typically had the strongest relationship flow later in the time series, whereas

205 ammonium had the strongest relationship with flow in the early 2000s.

206 **3.2.3 Effects of biological invasions**

207 Data from ([Crauder et al. 2016](#)), [Jassby \(2008\)](#) describes phytoplankton community  
208 changes in the upper estuary, including chlorophyll response to flow. Figure 10 in [Jassby \(2008\)](#)  
209 showed that chlorophyll generally decreased with flow in 1980 but increased with flow in 2000.

210 Note the decrease in *Potamocorbula* abundance in 2011, 2012. These are wet years where  
211 abundance/biomass of the clams is driven down by lower salinity. Contrased wtih the annual  
212 chlorophyll trends in the same years, the predicted values are above the flow-normalized trend  
213 suggesting an increase in chlorophyll with higher flow. The potential mechanism is therefore a  
214 decrease in clam abundance with high flow that releases phytoplankton from filtration pressure.  
215 This also explains the positive association of chlorophyll with flow in recent years (bottom right  
216 dynaplot).

217 Further, chlorophyll trends early in the time series generally show a decrease with high  
218 flow with a distinct maximum at moderate flow. This may suggest stratification events at  
219 moderate flow contributed to phytoplankton blooms early in the time series. Water withdrawals  
220 later in the time series could have also altered environmental conditions to reduce the frequency  
221 occurrence of stratification events. Look into this more...

222 What about biomass/density relationships for *Potamocorbula*? Although clam density  
223 increases throughout the period, What about initial decrease in chlorophyll prior to clam invasion?  
224 Is this related to water withdrawals (i.e., decrease in stratification events at moderate flow)?

225 [Fig. 7](#), [Fig. 8](#), [Table 3](#), [Table 4](#)

226 **4 Discussion**

227 Trends as percent change depend on the mean value, lower values will have larger percent  
228 changes.

229 Second case study showed typical inverse relationships between nutrients and flow, more  
230 flow means greater flushing and dilution of nutrient concentrations. Conversely, low flow means  
231 less flushing and higher nutrient concentrations, although this may not always be observed if the  
232 available nutrients are biologically available. Low-flow events during warmer months show the  
233 lowest ammonium concentrations, which corresponds to seasonal maxima in chlorophyll

concentration. A similar but weaker relationship was observed with nitrite/nitrate where increased flow was related to decreased concentration and lower concentrations overall were observed in the summer. However, low-flow events still had higher concentrations than high-flow events in July, as compared to ammonium which was low regardless of flow. This suggests that ammonium concentrations are driving phytoplankton production at P8. Annual trends in chlorophyll concentration (not shown) showed an overall decrease from the 1970s to present, although a slight peak is observed in the 2000s. This peak is likely related to the maximum ammonium concentration shown in Fig. 6. Moreover, flow/chlorophyll relationships have generally been constant throughout the period of record such that a change in flow has not been related to a change in phytoplankton production. This suggests that nutrient loads that contribute to production at P8 are primarily from point sources at WWTP outflows as a change in flow does not affect the load output. But what are watershed loads?

What do nitrogen trends mean? Have to interpret relative to trends in other variables. A decrease in nitrogen or constant nitrogen does not mean nitrogen inputs have stayed the same, they might actually be increasing if nitrogen. A change in chlorophyll relative to change in nitrogen could be informative, and even moreso, a change in silica relative to change in chlorophyll suggests diatom biomass has changed. However, there are mismatches in these trends that suggest other processes are at play, e.g., residence times and flow inputs, etc. Trends in Suisun relative to trends in Delta provide an example, e.g., Suisun is decrease in chlorophyll, increase in silica, increase in nitrogen, delta is decrease in silica, increase/decrease in DIN (depending on time period/season), decrease in chlorophyll, what's going on? See Senn slide 14 (from burial?). The WRTDS model lets us at least address trends in the context of season, time, and flow. This allows for more improved interpretation relative to observing raw data. Also explain more information by looking at ammonium, nitratative/nitrite, relative to DIN. What about other variables (light level as suspended particulate matter, temperature)?

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$$\ln(DIN) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) + \varepsilon$$

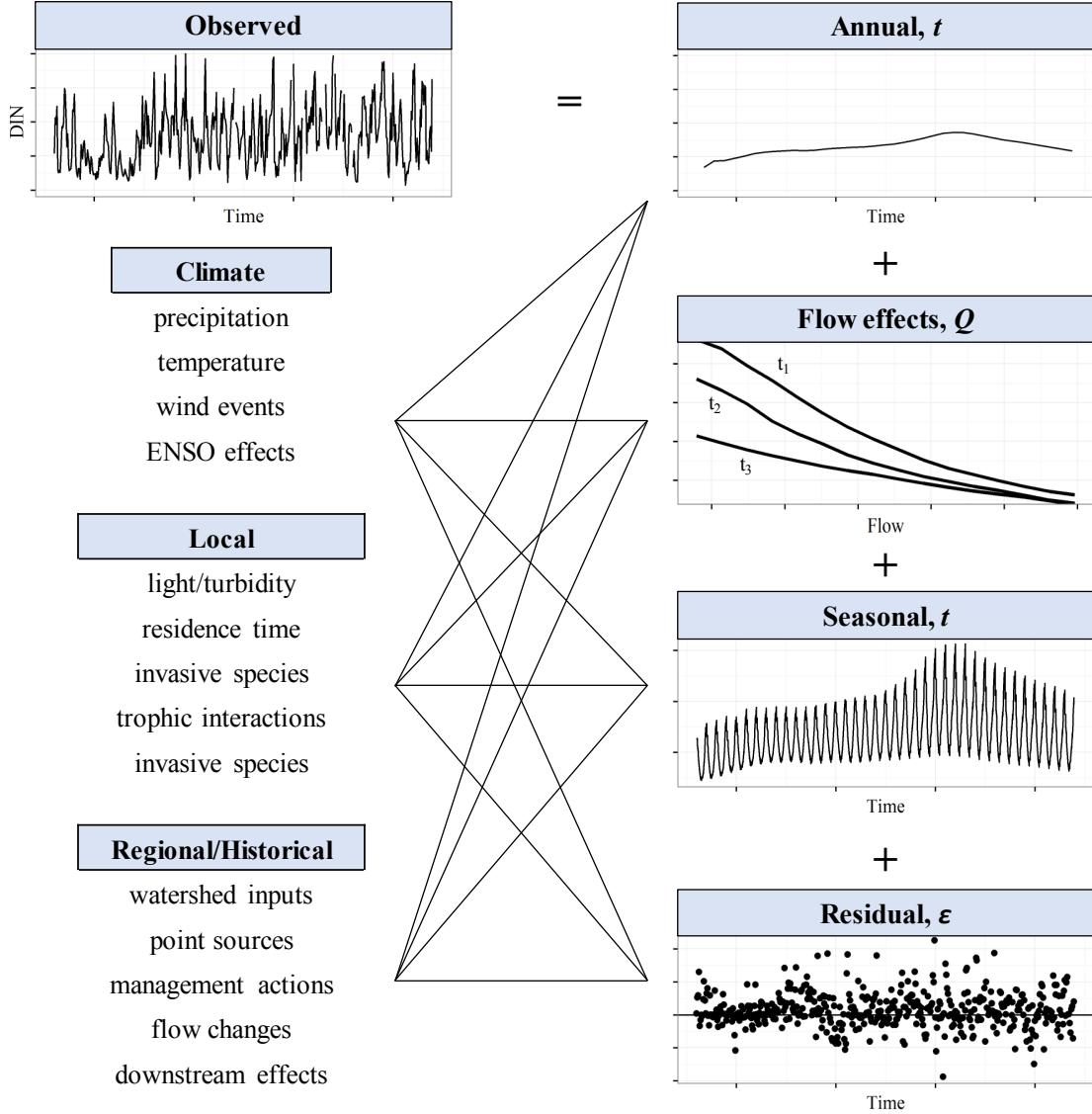


Fig. 1: Conceptual diagram illustrating use of WRTDS to decompose trends in observed nitrogen time series and potential forcing factors that can explain model output. Results from the model are described as annual and seasonal trends, changes in flow-nutrient dynamics for different time periods, and residual variation independent of time, flow, and season. Relationships between environmental factors (climate, local, regional/historical) and nitrogen trends are more easily related to the separate components of the observed time series using results from the model.

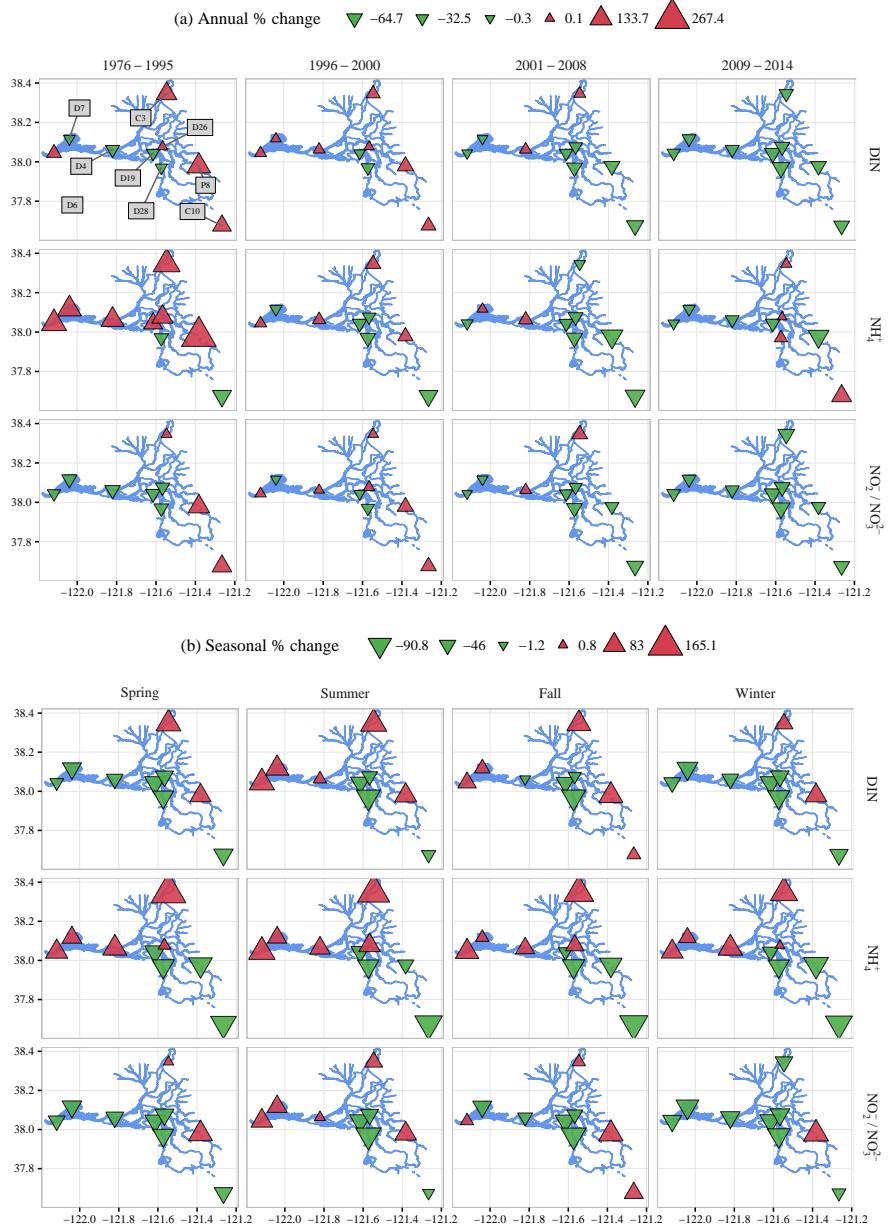


Fig. 2: Percent changes in nitrogen analytes for (a) annual and (b) seasonal (monthly) periods in the record. Changes are based on the difference between the ending and starting estimates for the flow-normalized estimates within each period. Points are colored for direction (red increasing, green decreasing) and sized for relative magnitude. Station names are shown in the top left panel. Months for each season are Spring: MAM, Summer: JJA, Fall: SON, Winter: DJF.

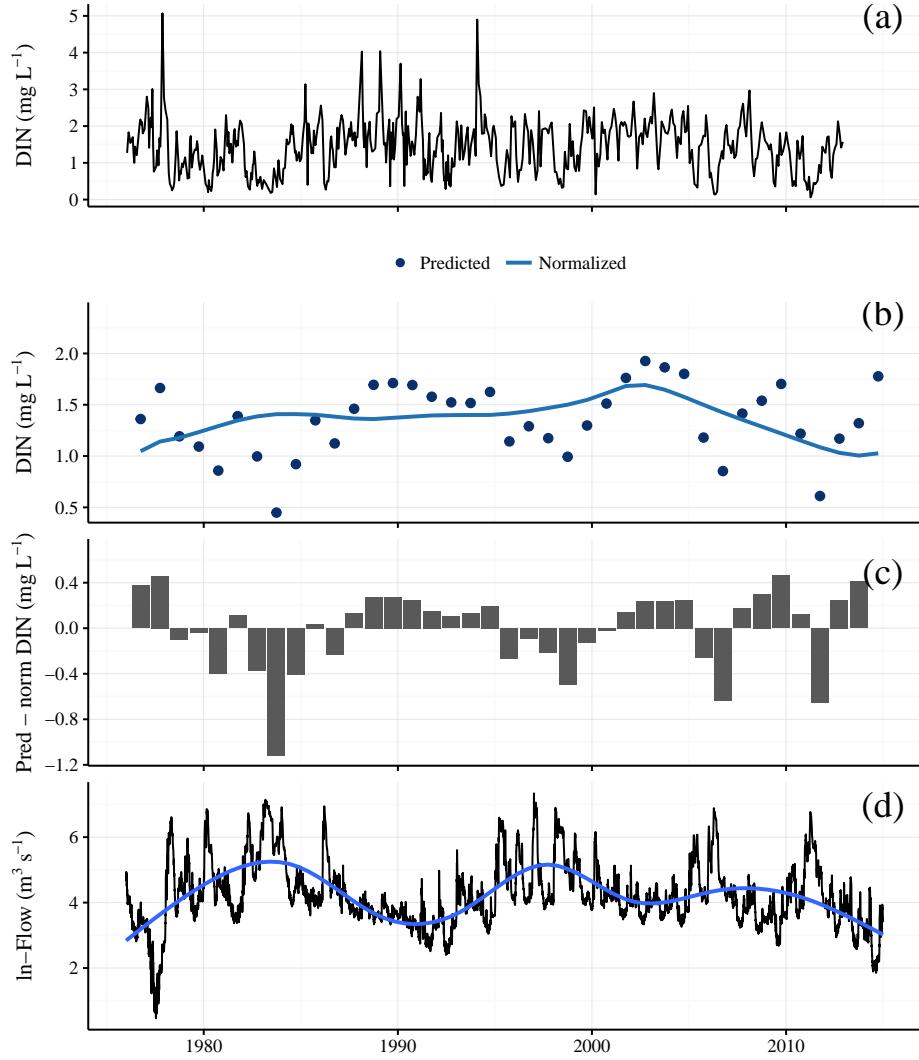


Fig. 3: Time series of DIN and flow at station C10. Subfigure (a) shows the observed DIN time series and subfigure (b) shows the annual (water year starting in October) predictions from WRTDS at different conditional quantiles ( $\tau = 0.1, 0.5, 0.9$ ). The points in subfigure (b) are predictions of observed DIN and the lines are flow-normalized predictions. Subfigure (c) shows the difference between the model predictions and flow-normalized predictions at the fiftieth conditional quantile. Subfigure (d) shows the flow time series of the San Joaquin River with a locally-estimated (loess) smooth to emphasize the long-term trend.

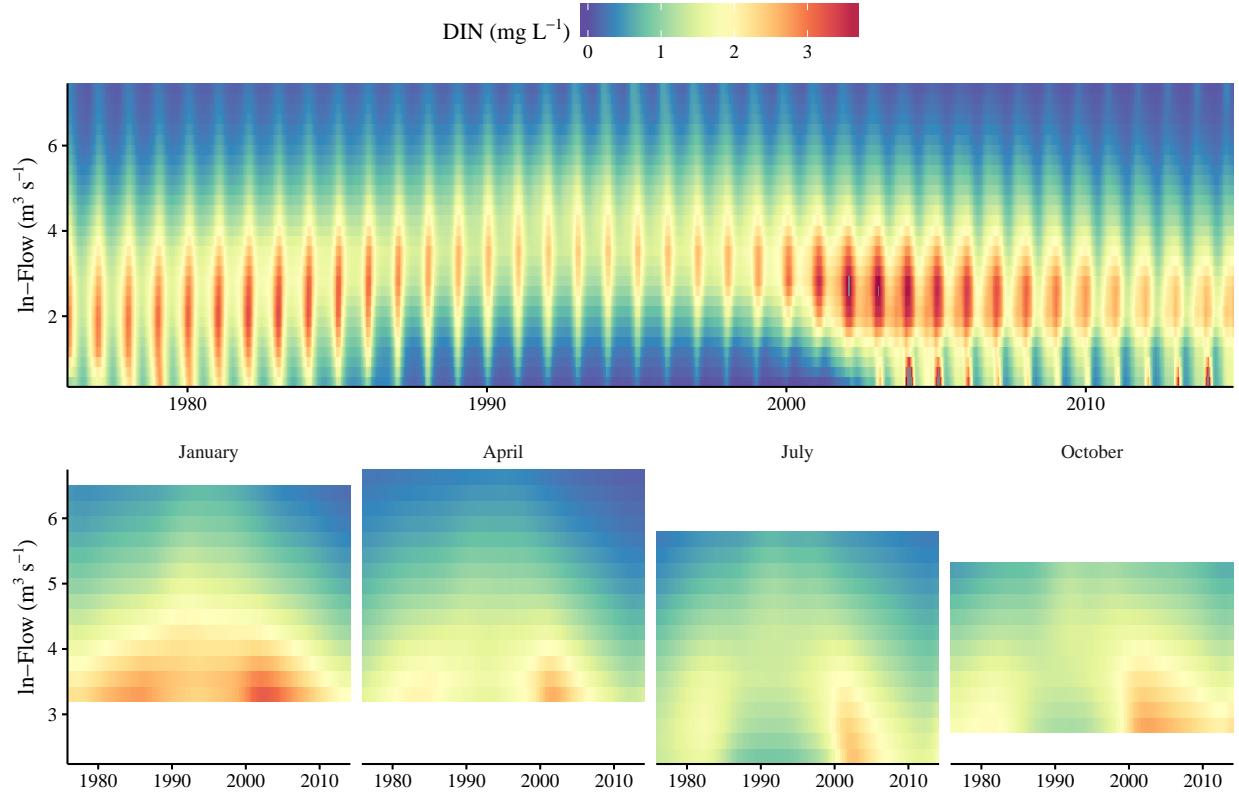


Fig. 4: Modelled relationships between DIN, flow, and time at station C10. The top figure shows the annual and seasonal variation over the entire time series and the bottom figure shows annual variation for selected months to remove seasonal variation. Warmer colors indicate higher DIN concentrations. The y-axis on the bottom figure is truncated by the fifth and ninety-fifth percentiles of flow within each month. Model results are for the fiftieth conditional quantile of DIN.

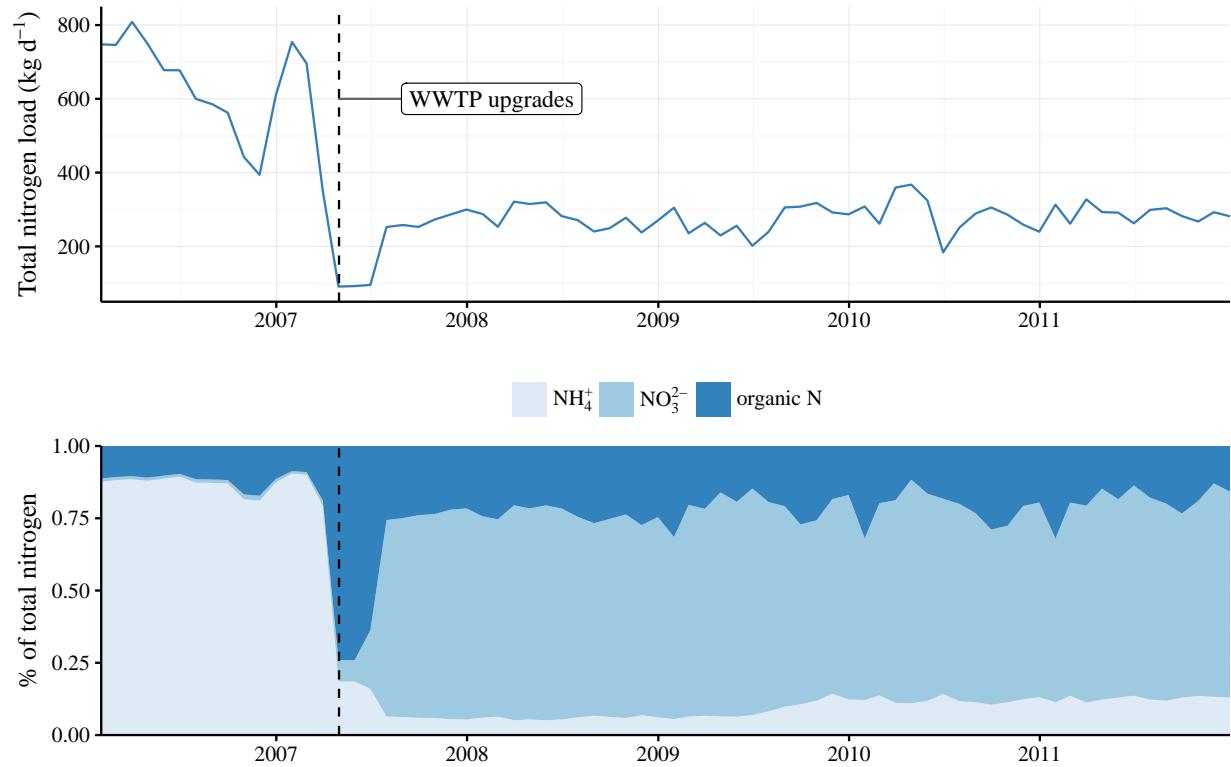


Fig. 5: Nitrogen load measurements ( $\text{kg d}^{-1}$ ) at the City of Tracy Wastewater Treatment Plant, San Joaquin County. Wastewater discharge requirements were implemented in May, 2007 to include nitrification/denitrification and tertiary filtration causing a reduction in total nitrogen effluent discharged to the Delta. Reductions were primarily observed for ammonium.

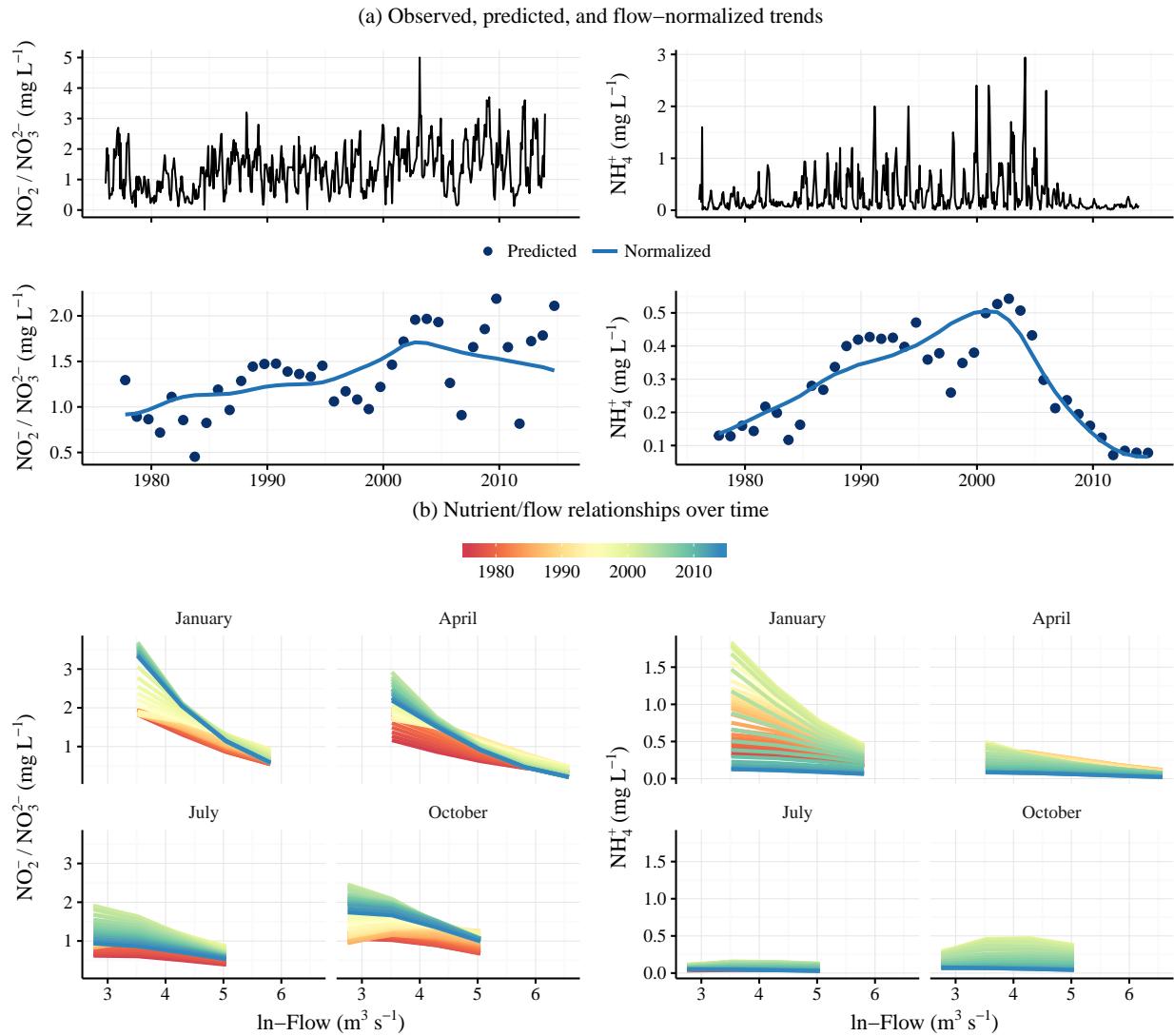


Fig. 6: Nitrogen trends at P8 as observed (a, top), predicted and flow-normalized estimates from WRTDS (a, bottom), and relationships with flow over time (b). Nitrite/nitrate trends are on the left and ammonium trends are on the right. Wastewater treatment plant upgrades at the City of Tracy (San Joaquin County), were completed in May 2007 (Fig. 5), coincident with a dramatic decrease in ammonium at P8.

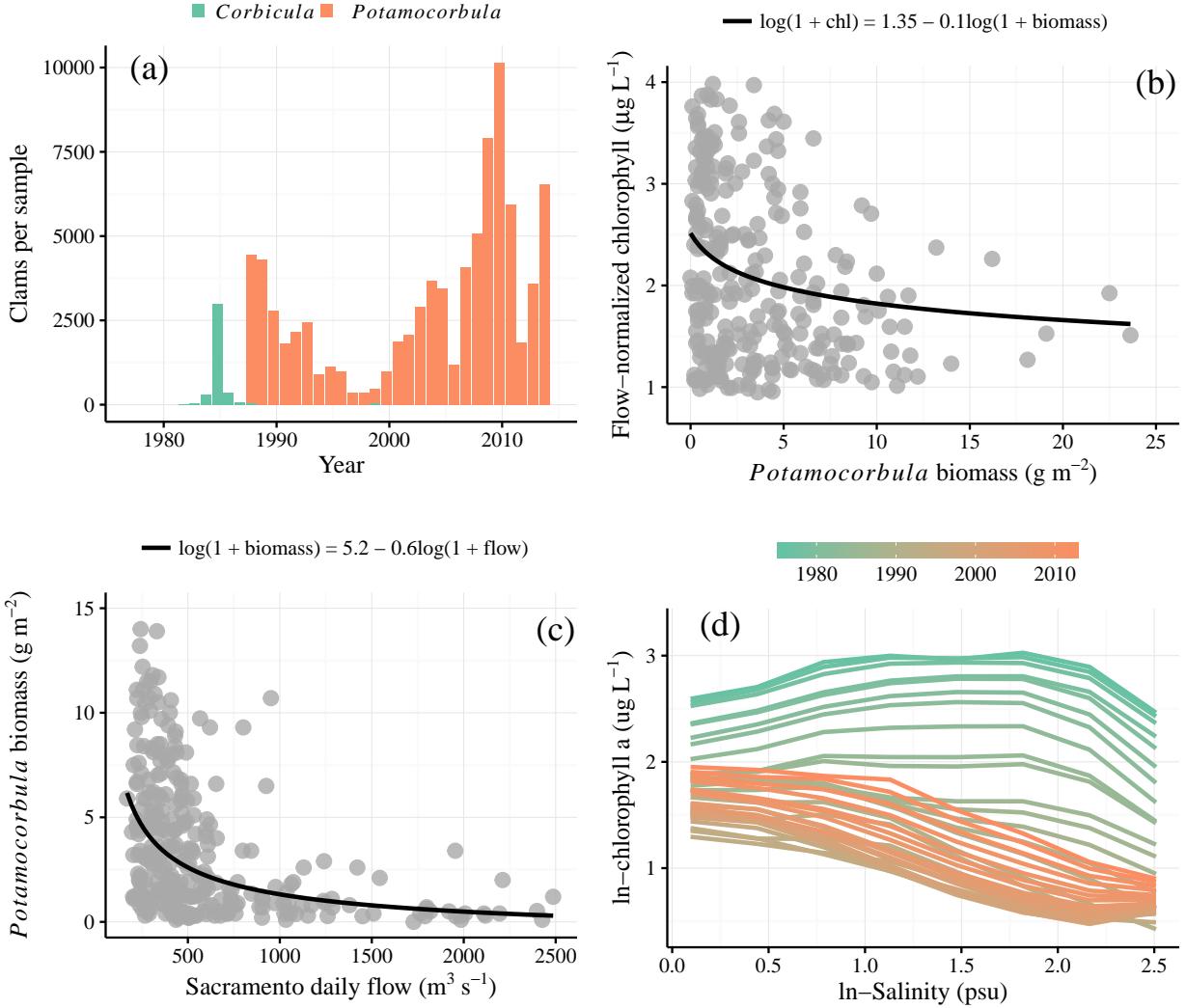


Fig. 7: Trends in clam abundance and chl-*a* concentration from 1976 to 2014 at station D7 in Suisun Bay. Invasion by *Potamocorbula amurensis* clams in the late 1980s and displacement of *Corbicula fluminea* was shown by changes in clam density (a, annual means). A coincident decrease in chl-*a* concentration was also observed (c). A weak but significant ( $p < 0.001$ ) relationship between clam biomass and chl-*a* concentration is shown in subfigure (b). Flow relationships with chl-*a* concentration have also changed over time (d, observations from June). Chlorophyll shows a slight positive then dominantly negative association with increasing flow (decreasing salinity) early in the time series, whereas the trend is reversed in recent years.

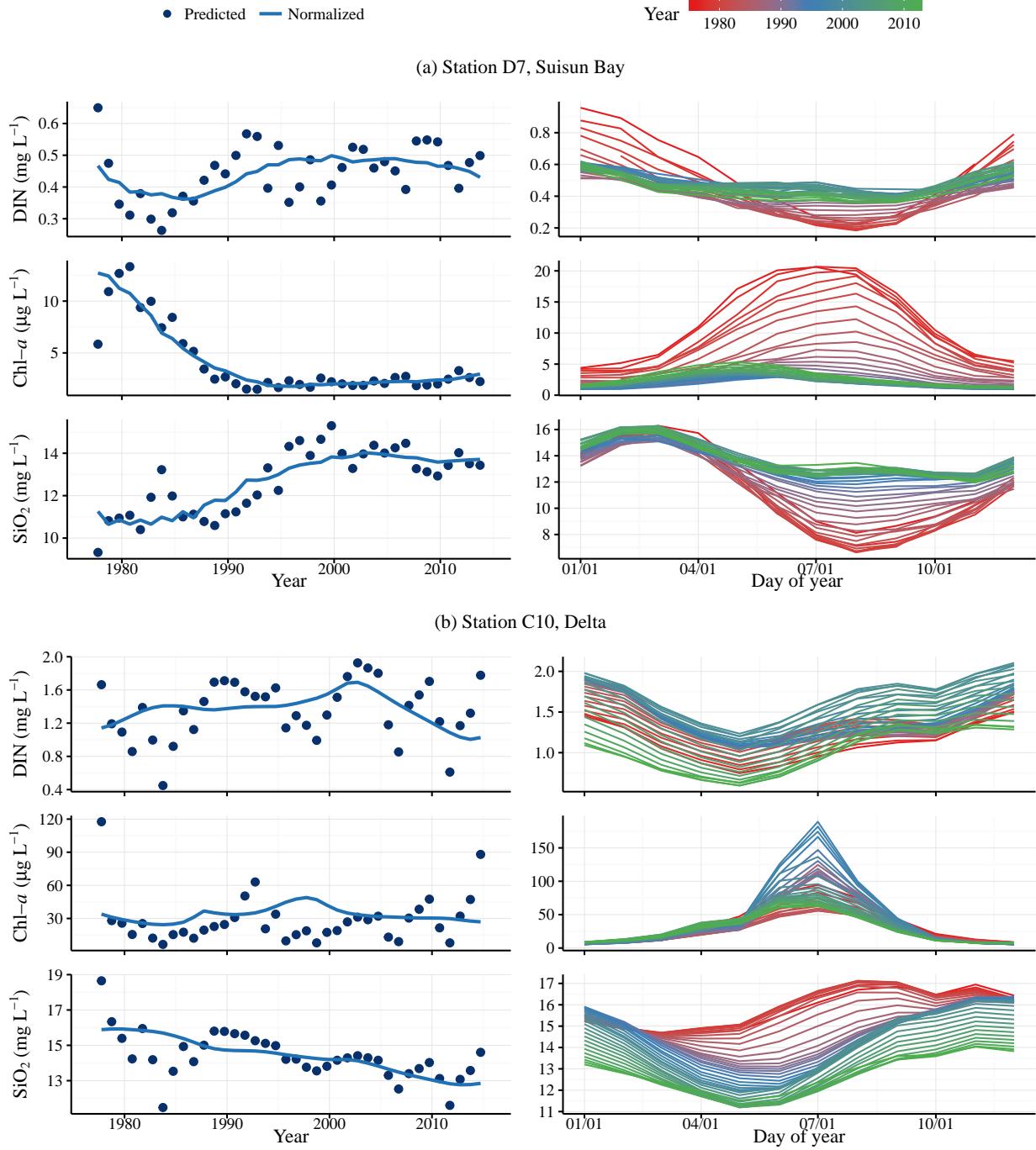


Fig. 8: Flow-normalized trends of annual (left) and seasonal (right) variation in DIN, chl- $a$ , and  $\text{SiO}_2$  at station D7 (top) and C10 (bottom). Covariation between nutrients, chl- $a$ , and  $\text{SiO}_2$  is observed at D7 but not C10, although an overall decrease in  $\text{SiO}_2$  at C10 is shown. Seasonal changes at D7 are most pronounced during the summer.

Table 1: Summaries of flow-normalized trends in nitrogen analytes for all stations and different time periods. Summaries are averages ( $\text{mg L}^{-1}$ ) and percent changes in parentheses (increasing in bold-italic). Changes are based on the difference between the ending and starting estimates within each period. See Fig. 2 for a summary of spatial trends. Months for each season are Spring: MAM, Summer: JJA, Fall: SON, Winter: DJF.

Analyte/Station	Annual		Seasonal			
	1976-1995	1996-2014	Spring	Summer	Fall	Winter
<b>DIN</b>						
C10	1.3 ( <b>35</b> )	1.4 (-28.6)	1.1 (-25.8)	1.2 (-6.3)	1.5 ( <b>5.5</b> )	1.7 (-20.7)
C3	0.4 ( <b>51.1</b> )	0.5 ( <b>3</b> )	0.4 ( <b>62.2</b> )	0.3 ( <b>71.9</b> )	0.5 ( <b>54.4</b> )	0.5 ( <b>18.3</b> )
D19	0.5 (-5.5)	0.4 (-30.7)	0.5 (-33.9)	0.3 (-25.4)	0.3 (-21.7)	0.7 (-33.5)
D26	0.4 ( <b>0.3</b> )	0.5 (-19.6)	0.5 (-19.2)	0.3 (-10.2)	0.4 (-3.5)	0.6 (-21.7)
D28	0.5 (-3.1)	0.4 (-45.6)	0.5 (-32.9)	0.2 (-56.5)	0.3 (-57.4)	0.8 (-40.2)
D4	0.4 (-8.1)	0.4 (-7.5)	0.4 (-13.6)	0.3 ( <b>4.3</b> )	0.4 (-1.2)	0.5 (-15)
D6	0.4 ( <b>11.6</b> )	0.5 (-6.1)	0.5 (-5)	0.4 ( <b>64.1</b> )	0.4 ( <b>21</b> )	0.5 (-14.6)
D7	0.4 (-1.7)	0.5 (-11.8)	0.5 (-23.8)	0.4 ( <b>49.9</b> )	0.4 ( <b>10.4</b> )	0.6 (-34.6)
P8	1.4 ( <b>81.1</b> )	1.8 (-15.8)	1.5 ( <b>35.5</b> )	1 ( <b>42</b> )	1.6 ( <b>55</b> )	2.3 ( <b>38.7</b> )
<b>NH<sub>4</sub><sup>+</sup></b>						
C10	0.1 (-37.7)	0 (-55.5)	0.1 (-68.6)	0 (-85)	0.1 (-90.8)	0.2 (-78.8)
C3	0.2 ( <b>127</b> )	0.3 ( <b>14.1</b> )	0.2 ( <b>165.1</b> )	0.2 ( <b>133.3</b> )	0.3 ( <b>107.7</b> )	0.2 ( <b>81.2</b> )
D19	0.1 ( <b>35.6</b> )	0.1 (-32.6)	0.1 (-32.9)	0 (-21)	0 (-6.4)	0.1 (-12)
D26	0.1 ( <b>58.4</b> )	0.1 (-18.7)	0.1 ( <b>3.3</b> )	0.1 ( <b>38.1</b> )	0.1 ( <b>21.1</b> )	0.1 ( <b>0.8</b> )
D28	0.1 (-10)	0 (-31.8)	0.1 (-42.8)	0 (-36.9)	0 (-42.2)	0.1 (-35.7)
D4	0.1 ( <b>74.6</b> )	0.1 ( <b>0.3</b> )	0.1 ( <b>54.2</b> )	0 ( <b>30.8</b> )	0.1 ( <b>23.8</b> )	0.1 ( <b>56.9</b> )
D6	0.1 ( <b>100.2</b> )	0.1 (-3.5)	0.1 ( <b>42.2</b> )	0.1 ( <b>74.1</b> )	0.1 ( <b>49.2</b> )	0.1 ( <b>39.8</b> )
D7	0.1 ( <b>88.2</b> )	0.1 (-13.3)	0.1 ( <b>26.8</b> )	0 ( <b>25.1</b> )	0.1 ( <b>4.3</b> )	0.1 ( <b>16.8</b> )
P8	0.3 ( <b>267.4</b> )	0.3 (-85.1)	0.2 (-51.8)	0.1 (-12)	0.3 (-44.5)	0.6 (-61.2)
<b>NO<sub>2</sub><sup>-</sup>/NO<sub>3</sub><sup>2-</sup></b>						
C10	1.2 ( <b>42.8</b> )	1.3 (-26.9)	1.1 (-21)	1.2 (-2.3)	1.4 ( <b>23.3</b> )	1.5 (-5.6)
C3	0.2 ( <b>0.7</b> )	0.2 (-6.6)	0.2 ( <b>0.9</b> )	0.1 ( <b>18</b> )	0.1 ( <b>4.3</b> )	0.2 (-17.4)
D19	0.4 (-11.7)	0.4 (-31.1)	0.4 (-32.3)	0.2 (-36.7)	0.3 (-31.6)	0.6 (-38.4)
D26	0.3 (-9.8)	0.4 (-20.1)	0.4 (-23.5)	0.2 (-18.7)	0.3 (-10.5)	0.5 (-26.4)
D28	0.4 (-10.5)	0.4 (-47.2)	0.5 (-34.6)	0.2 (-66.3)	0.3 (-64.4)	0.7 (-45.7)
D4	0.3 (-14.6)	0.3 (-9.8)	0.3 (-19.2)	0.3 ( <b>1.1</b> )	0.3 (-8)	0.4 (-25.9)
D6	0.3 (-5.6)	0.4 (-8)	0.4 (-14.5)	0.3 ( <b>38.8</b> )	0.3 ( <b>4</b> )	0.4 (-23.2)
D7	0.4 (-13.4)	0.4 (-13.6)	0.4 (-27.3)	0.3 ( <b>28.7</b> )	0.4 (-23.7)	0.5 (-46.8)
P8	1.1 ( <b>59.8</b> )	1.5 ( <b>3.3</b> )	1.2 ( <b>53.9</b> )	1 ( <b>38.8</b> )	1.4 ( <b>58.3</b> )	1.8 ( <b>62.3</b> )

Table 2: Summaries of flow-normalized trends in nitrite/nitrate and ammonium ( $\text{mg L}^{-1}$ ) concentrations before and after WWTP upgrades upstream of station P8. Upgrades were completed in May 2007 at the City of Tracy WWTP (San Joaquin County, Fig. 5). Summaries are means and percent changes based on annual means within the pre- and post-upgrade time periods (1976-2007, 2008-2013). Increasing values are in bold-italics. Months for each season are Spring: MAM, Summer: JJA, Fall: SON, Winter: DJF.

Period	$\text{NO}_2^-/\text{NO}_3^{2-}$		$\text{NH}_4^+$	
	Mean	% change	Mean	% change
<b>Annual</b>				
1976-2007	1.3	<b>74.3</b>	0.34	<b>93.1</b>
2008-2013	1.5	-7.3	0.11	-62
<b>Seasonal, pre</b>				
Spring	1.24	<b>79.5</b>	0.25	<b>57.1</b>
Summer	0.99	<b>95</b>	0.09	<b>143.5</b>
Fall	1.32	<b>77</b>	0.29	<b>137.7</b>
Winter	1.67	<b>69.2</b>	0.69	<b>72.5</b>
<b>Seasonal, post</b>				
Spring	1.27	<b>0.9</b>	0.09	-49.2
Summer	0.92	-18.7	0.06	-49.2
Fall	1.58	-8.7	0.1	-58.2
Winter	2.17	-5.1	0.18	-62.1

Table 3: Summaries of flow-normalized trends in dissolved inorganic nitrogen ( $\text{mg L}^{-1}$ ), chlorophyll ( $\mu\text{g L}^{-1}$ ), and silicon dioxide ( $\text{mg L}^{-1}$ ) concentrations for different time periods at station D7. Summaries are means and percent changes based on annual means within the time periods. Increasing values are in bold-italics. Months for each season are Spring: MAM, Summer: JJA, Fall: SON, Winter: DJF.

Period	DIN		Chl- <i>a</i>		SiO <sub>2</sub>	
	Mean	% change	Mean	% change	Mean	% change
<b>All</b>						
1976-2013	0.4	-7.8	4.1	-76.7	12.7	<b>21.8</b>
<b>Annual</b>						
1976-1985	0.4	-22.5	9.3	-57.1	10.9	-0.1
1986-1994	0.4	<b>29.4</b>	3	-61.7	12.2	<b>18.6</b>
1995-2003	0.5	-0.1	2	<b>21.1</b>	13.7	<b>5.2</b>
2004-2013	0.5	-11.9	2.4	<b>34.2</b>	13.7	-1.7
<b>Seasonal</b>						
Spring	0.5	-23.8	4.2	-60.3	14.5	<b>0.6</b>
Summer	0.4	<b>49.9</b>	6.4	-82.3	11.2	<b>51.3</b>
Fall	0.4	<b>10.4</b>	3.7	-84.9	11.1	<b>43.3</b>
Winter	0.6	-34.6	2	-63.8	14.2	<b>4.2</b>

Table 4: Summaries of flow-normalized trends in dissolved inorganic nitrogen ( $\text{mg L}^{-1}$ ), chlorophyll ( $\mu\text{g L}^{-1}$ ), and silicon dioxide ( $\text{mg L}^{-1}$ ) concentrations for different time periods at station C10. Summaries are means and percent changes based on annual means within the time periods. Increasing values are in bold-italics. Months for each season are Spring: MAM, Summer: JJA, Fall: SON, Winter: DJF.

Period	DIN		Chl- <i>a</i>		SiO <sub>2</sub>	
	Mean	% change	Mean	% change	Mean	% change
<b>All</b>						
1976-2013	1.4	-10.1	33.2	-20.6	14.4	-19.1
<b>Annual</b>						
1976-1985	1.3	<b>22.8</b>	27.5	-21.6	15.8	-3.2
1986-1994	1.4	<b>1.2</b>	35.3	<b>31.5</b>	14.8	-4.1
1995-2003	1.6	<b>16.4</b>	41	-27.5	14.2	-3.3
2004-2013	1.3	-36.3	30.2	-12.8	13.2	-7.6
<b>Seasonal</b>						
Spring	1.1	-25.8	26.2	<b>3.1</b>	13.2	-20
Summer	1.2	-6.3	79.6	-23.2	13.9	-25.4
Fall	1.5	<b>5.5</b>	19	-39.8	15.6	-18
Winter	1.7	-20.7	7.7	<b>7.3</b>	15.1	-14.1