An Analysis of Taste-and-Odor Patterns and Environmental Relationships at Selected Locations in the State Water Project

Report prepared under contract with the State Water Contractors by:

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EXECUTIVE SUMMARY

Motivation for this Study. Naturally occurring cyanobacteria in the State Water Project (SWP) produce the taste-and-odor (T&O) compounds geosmin and MIB that can impart noticeable off flavors and odors in finished drinking water and require affected water utilities to adjust their treatment operations accordingly. While these T&O issues are purely aesthetic, they are an understandable source of customer concern and complaints.

Study Objective. This study used historical data on SWP T&O concentrations, hydrology, and water quality to document patterns and sources of T&O production and their relationship to environmental conditions to help utilities anticipate when concerning levels of T&O are most likely to occur in their source waters.

Data Sources. Taste-and-odor data were obtained from the California Department of Water Resources for calendar years 2009-2023 for three sampling sites: Clifton Court Forebay Inlet (CCI), Banks Pumping Plant (BPP), and the outlet of O'Neill Forebay at Check 13 (ONF). The agency also provided hydrologic records, including annual Delta watershed runoff volumes (Water Year Index or WYI), the annual SWP water allocation (SWPA), and monthly SWP pumping records, as well as monthly water quality data at these sampling sites.

Data Analyses. Geosmin and MIB data for each site were summarized as annual, T&O-season (the period May-November based on initial analyses), and monthly mean concentrations. Two other T&O-season statistics were calculated for each compound: (1) the maximum seasonal concentration to indicate the intensity of T&O production; (2) the frequency of elevated T&O concentrations (defined as values >7 ng/L) that might affect utility operations. Various graphical analyses were used to identify temporal and spatial patterns for these statistics. Correlation and regression analysis were used to determine the strength of relationships between T&O statistics and relevant hydrologic and water quality parameters.

Taste-and-Odor Patterns. A wide range of T&O concentrations was measured between 2009-2023 at all sites with the highest values recorded at ONF. Overall, relatively few values (≤22% of geosmin values and ≤13% of MIB values depending on the site) were classified as being elevated. Highest monthly mean and maximum geosmin and MIB concentrations and nearly all elevated concentrations occurred between May and November, which was thus defined as the "T&O season." Geosmin concentrations peaked in July and August while MIB concentrations usually peaked in August and September. Taste-and-odor levels differed considerably across years at all sites, and these interannual differences were to some degree site-specific.

Taste and Odor Sources. Likely locations of T&O production were identified by comparing geosmin and MIB concentrations at paired upstream and downstream sites. Results indicate that Clifton Court Forebay (CCF) is a common source of elevated geosmin at BPP while elevated MIB at BPP usually originates in the Delta. Similarly, a comparison of paired BPP and ONF

T&O data indicated that locations downstream of BPP (likely including O'Neill Forebay) are sources of elevated geosmin and MIB at ONF.

The Influence of Hydrology. Hydrologic conditions such as watershed runoff and SWP flow volumes and timing affect T&O production both directly and indirectly through their effects on other influential environmental factors such as nutrient availability, water temperature, turbidity (an indicator of light availability), and TDS (measured here as specific conductance). The period 2009-2023 encompassed a wide range of Delta WYI values, from critically dry to wet watershed conditions, and the historical range of SWP hydrologic conditions based on the SWPA and SWP pumping. Hydrology explained some of the interannual variation in SWP T&O concentrations as geosmin and MIB levels at CCI and ONF were higher in dry vs wet years. However, geosmin and MIB levels at BPP were *not* related to hydrology, likely due to water quality influences from CCF.

The Influence of Nutrients. Nutrient supply, particularly nitrogen (N) and phosphorus (P), can limit the growth of cyanobacteria, including T&O-producing species. However, N and P concentrations in this part of the SWP are generally high (although N may be limiting during the summer) and were not strong predictors of T&O concentrations. Interannual variation in MIB was not related to nutrients at any site. At BPP and ONF, there were some positive relationships between geosmin levels and nutrients, both of which tended to be higher in drier years. Due to these intercorrelations between geosmin, nutrients, and hydrology, it was not possible to determine the relative influence of nutrients vs hydrology on geosmin production.

Other Water Quality Influences. Cyanobacteria generally prefer warmer water with low turbidity, which increases light availability for photosynthesis. Some cyanobacteria are also more tolerant of or even prefer water with higher specific conductance. These parameters were related to hydrology, with drier years having higher temperatures and specific conductance and lower turbidity levels more conducive to cyanobacteria growth. These more favorable conditions might explain the higher geosmin and MIB levels at CCI in drier years (noted above), although it is not possible in this study to separate these water quality influences from the direct effects of hydrology on T&O production. Taste-and-odor levels at Banks were not related to any of these water quality parameters, and relationships at ONF were weak.

Conclusions. Elevated geosmin and MIB concentrations in this part of the SWP are largely limited to a seasonal window between May and November with the highest concentrations occurring between July and September. This predictable seasonal pattern is likely driven by warm water temperatures during the summer and fall. There was evidence that T&O production was greatest in drier years when hydrologic and water quality conditions are most conducive to cyanobacteria growth. However, the Clifton Court and O'Neill forebays appear to be important sources of T&O production that are influenced by local environmental conditions not fully captured in the data sets available for this analysis.

Recommendations for Further Investigation: Recommendations are provided in the full report.

INTRODUCTION

Cyanobacteria (also known as “blue-green algae”) are photosynthetic microorganisms that occur naturally in aquatic environments. Most of these organisms are innocuous parts of the aquatic food web, but a small number of these species can also produce malodorous (e.g., taste-and-odor (T&O) substances such as geosmin and 2-methylisoborneol (MIB)) and toxic (e.g., microcystins) compounds that impair water quality conditions for beneficial human uses. Drinking water utilities that rely on surface-water sources of raw water for their operations are often affected by these compounds, which can impact the quality of finished drinking water and can be difficult and costly to remove using conventional treatment processes. Considerable scientific research has focused on understanding the physiology of the organisms that produce these undesirable compounds and the environmental conditions that promote “blooms” or “events” where the production of these compounds reach undesirable levels. While this work has provided considerable insight into the general suite of environmental factors that regulate cyanobacterial growth, the current state of the science is not at a stage where the occurrence of these events can be predicted with much accuracy, particularly at the scale of individual waterbodies.

Cyanobacteria have been documented to cause water quality issues throughout the State Water Project (SWP). Drinking water utilities that rely on the SWP have had to respond to both T&O and toxin events, but by far most operational issues have been caused by T&O compounds. Although T&O issues are often attributed to cyanobacteria “blooms”, implying high densities of organisms, T&O-producing cyanobacteria do not need to be the dominant organisms in the cyanobacteria-algal assemblage or even be visually obvious to cause issues. Even extremely low concentrations of the compounds geosmin and MIB in finished drinking water (e.g., ≤ 5 ng/L for sensitive palates) can impart noticeable off flavors and odors, and concentrations ≥ 10 ng/L can result in widespread customer complaints (Taylor et al. 2006). While T&O is an aesthetic issue rather than a direct public health concern, the consensus among utilities as noted by Taylor et al. (2006) is that a common customer reaction is *“if the water tastes and smells bad, then it is not safe to drink.”* Beyond the additional operational costs to remove these compounds, water utilities must also commit resources to issue customer notifications and respond to customer complaints.

In response to concerns by the State Water Contractors (SWC), the California Department of Water Resources (DWR) began monitoring geosmin and MIB at fixed sampling sites in the SWP to inform these utilities of potential T&O issues that could affect their water treatment operations. This monitoring has been conducted regularly over many years and produced a long-term record of T&O concentrations that can be analyzed to identify T&O patterns and trends. At these same sites, DWR performs monthly water quality sampling for parameters such as temperature, nutrients, specific conductance, and turbidity that can potentially influence cyanobacterial growth and T&O production. Hydrologic conditions are an important driver of cyanobacterial growth and abundance and can be evaluated for these sites using SWP pumping records as well as broader indicators of Delta and SWP hydrology. Collectively, these data sets provide the information needed to document historical T&O patterns and their relationship to these environmental factors.

The current analysis used the above information from one portion of the SWP to address the following types of questions:

1) Does geosmin and MIB production follow repeatable patterns within and among years?
2) Do these two compounds exhibit similar patterns of production?
3) Are T&O patterns similar among sampling locations?
4) Are the above patterns related to variations in hydrology and/or water quality?
5) What are the source areas for T&O production at different locations?

The goal of this analysis was *not* to develop a model or other method *to predict* when and where a T&O issue will occur; the confluence of conditions that trigger individual T&O events remain poorly understood but likely include physiological and environmental triggers beyond changes in one or more of a handful of environmental parameters that are routinely monitored. Instead, the analysis pursued a more attainable goal of using T&O concentration patterns and related environmental factors (based on answers to questions 1 through 4 above) to identify conditions associated with lower or higher frequencies of elevated T&O in source water so that water utilities can better *anticipate* the *risk* of water treatment issues and prepare as needed. A secondary goal was to identify source locations for T&O production (answer to question 5) to inform future decisions concerning the feasibility of source water T&O management.

METHODS

Study Locations

The DWR conducts routine T&O monitoring at several fixed sites across the SWP. At the request of the SWC, this analysis was limited to three sites: 1) Clifton Court Forebay Inlet (CCI), representing water coming from the Delta, 2) Banks Pumping Plant (BPP), representing water leaving Clifton Court Forebay (CCF); 3) the outlet of O'Neill Forebay at Check 13 (ONF) where water is released back into the California Aqueduct (CAA). O'Neill Forebay is located 67 aqueduct miles downstream of BPP and receives a varying mixture of inflows from the CAA, San Luis Reservoir, and the Delta Mendota Canal. Google Earth images of these sites are shown in Figure 1. The flow path of water overlaid on these images shows that water travels through the Old River Channel to reach CCI and then follows a northward arc as it moves through CCF towards the channel leading to BPP (per communication with D. Wisheropp, DWR). This flow path leaves the northern part of CCF partially isolated and with a somewhat independent circulation pattern as documented previously (MacWilliams and Gross, 2013). However, there is certainly some mixing between water in the northern forebay and the Delta inflows, allowing for forebay water quality to influence conditions at BPP. Water discharged into the CAA through Banks flows a long distance to reach ONF and passes through Bethany Reservoir, a much smaller basin that serves as the forebay for the South Bay Pumping Plant. As already noted, flow patterns in the O'Neill Forebay are complex and vary depending on the balance of water supplies and demands. Therefore, water quality conditions at sampling station ONF can be influenced both by processes internal to the forebay as well as by the water quality entering from various sources.

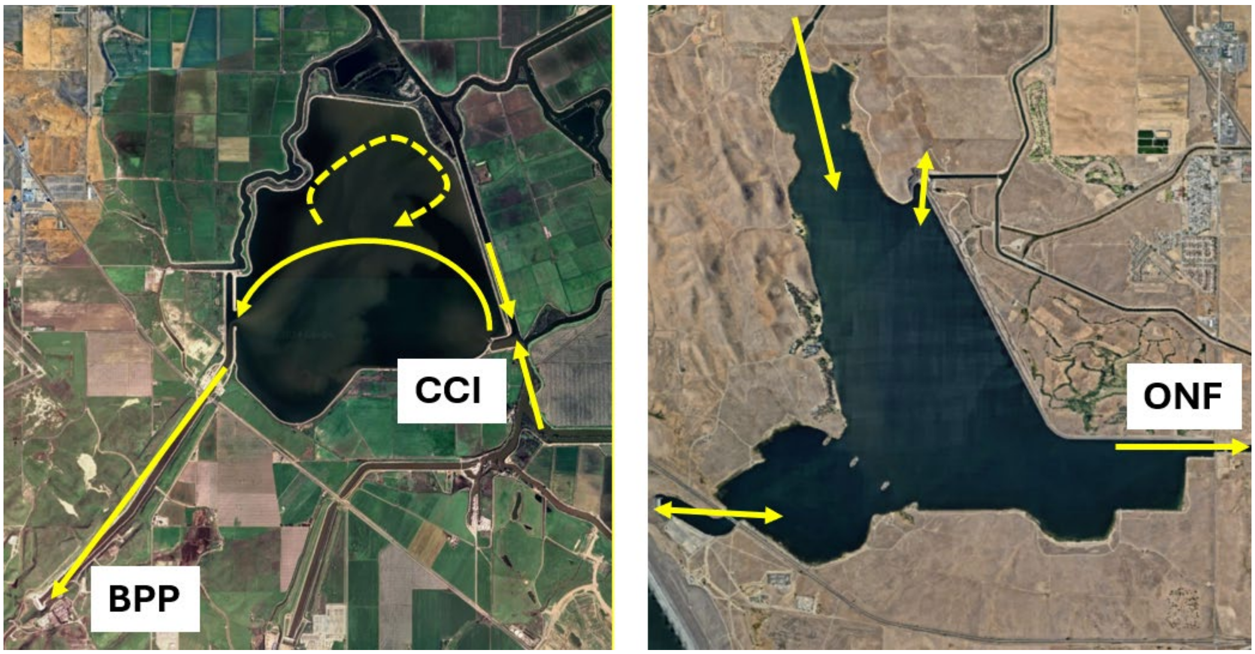

Figure 1 - Monitoring site locations in the SWP overlaid on Google Earth images. Directions of flow paths affecting these sites are shown as yellow arrows. The dashed line within Clifton Court Forebay depicts a possible circulation pattern whereby forebay water mixes with flows from the Delta.

Taste & Odor Data Set

DWR has conducted routine (usually weekly) monitoring of geosmin and MIB concentrations at CCI, BPP, and ONF since January 2009. The 15-year period of record (POR) spanning 2009-2023 was used for this analysis. These data were screened to identify unusable data entries and unreasonably high outlier data points. Based on this review, the following changes were made before analysis: (1) data entries reported as “>” the reporting limit (above the laboratory calibration curve) were deleted as no defensible value could be inserted as a replacement; (2) data entries reported as “<” the reporting limit (below the laboratory calibration curve) were also removed for the same reason unless they were below the detection limit for the analysis, in which case they were changed to one-half the reported detection limit (e.g., a <2 ng/L entry was reported as 1 ng/L); (3) data entries of “ND” were changed to 0.5 ng/L, which is one-half the value of the lowest analytical detection limit possible for this analysis (1 ng/L); (4) a couple of entries were “1-2 ng/L” and these were changed to 1 ng/L. These changes were required to make the data suitable for graphical and statistical analysis and were not so extensive as to change any results or conclusions presented in this report.

Screened T&O data for each site were summarized as annual, "T&O-season" (defined in Results section), and monthly mean concentrations for geosmin and MIB. Two other statistics were also calculated for each compound during the T&O season: (1) the maximum concentration to indicate T&O production intensity; (2) the frequency of "elevated" T&O concentrations (defined as values >7 ng/L) during the T&O season. The value of >7 ng/L was used as a representative threshold above which T&O can affect utility operations while recognizing that individual SWC utilities have different thresholds of concern ranging from 5-10 ng/L (L. Palencia, personal communication). These summary statistics rather than individual data points were used for most data analyses.

Environmental Data Sets

The SWC has noted that T&O concentrations in the SWP appear to be higher in dry vs wet years, suggesting an important influence of hydrology on T&O production. This observation is consistent with many studies both within and outside the Delta showing that hydrologic conditions can influence cyanobacterial growth (e.g., examples provided in Berg and Sutula, 2015). Planktonic cyanobacteria, which includes several common SWP T&O producers (Taylor et al., 2006), generally prefer quiescent water conditions with low flows and minimal turbulence. Accordingly, these species may be more abundant during dry, low-flow years as compared to wetter years with high Delta flows and SWP pumping. Note that hydrologic preferences may be different for benthic cyanobacteria, which are also T&O producers in the SWP (Taylor et al., 2006). Three hydrologic indicators – the Water Year Index (WYI), the annual State Water Project Allocation (SWPA), and monthly pump station flow volumes – were used to examine the strength of hydrology-T&O relationships. The WYI is a measure of the wetness of the Delta watershed (Sacramento and San Joaquin Rivers) and is calculated by DWR after the end of each water year. The WYI is calculated separately for the Sacramento and San Joaquin watersheds, and the indices for the two rivers are strongly correlated (Pearson $r = 0.968$, $p < 0.001$) during the POR. Therefore, the mean values of the WYI for the two watersheds were used for this analysis. The SWPA is calculated and usually finalized by April of the preceding WY based on watershed hydrologic conditions during the previous winter and other operational considerations. The SWPA is reported as a percentage of the maximum allocation available to the SWP under contract with DWR, ranging from 0-100%. Monthly pump station flow data for the POR were obtained from Table 1 of the SWP Annual Operation reports to provide the actual volumes of water moving through the SWP each year. The relationship between pumping and T&O concentrations at each site was analyzed using Banks Pumping Plant flow volumes for stations CCI and BPP and Dos Amigos Pumping Plant (DAPP) flow volumes for station ONF. Note that DAPP volumes only capture water moving southward from ONF through the CAA and do not account for water exchanges between O'Neill Forebay and San Luis Reservoir and the Delta Mendota Canal.

An environmental monitoring data set generated by DWR was accessed online to obtain monthly water quality data for the three sites. Water quality parameters used for analysis were those that are known to influence cyanobacteria activity (Berg and Sutula 2015): water temperature, specific conductance, turbidity, and the nutrients nitrogen (N) and phosphorus (P). Cyanobacteria as a group prefer warmer water conditions than most algae, with maximum growth rates occurring at temperatures above 20ºC. These requirements favor their dominance during the warmer months of the year in the Delta and other temperate water bodies. Specific conductance measures the total dissolved solids (TDS) or salinity in the water, and fluctuations in conductance were used to indicate changes in the sources of water entering the SWP (e.g., contributions of low conductance snowmelt vs the influence of high conductance seawater) and the overall chemistry of this water. Studies have found freshwater cyanobacteria to tolerate higher TDS than competing algal species, although levels in the SWP portion of the Delta have not been shown to offer competitive advantages to either group of organisms. Turbidity was used as an indicator of light availability for cyanobacterial growth as turbidity levels directly affect light penetration through the water column. Increasing light availability (lower turbidity) generally promotes faster cyanobacterial growth (assuming other factors are not growth limiting), although some species are adapted to grow under low-light conditions. Elevated turbidity levels in the Delta have been identified as a factor limiting growth of certain species, such as the toxin (not T&O) producer *Microcystis*. Nitrogen and phosphorus are the nutrients most commonly limiting to cyanobacterial growth. Although nutrient levels in the Delta are generally high, experimental studies suggest that nutrient availability can limit cyanobacterial growth under certain conditions. For this analysis, nutrient availability was represented by concentrations of dissolved inorganic forms of N (ammonium (NH_4) and nitrate (NO_3)) and P (orthophosphate (PO_4)). These nutrient forms are readily available for biological uptake and, therefore, are commonly referred to as "bioavailable" nutrients. The analytical parameter nitrate+nitrite in the DWR data set was used as the NO_3 measurement since NO_3 levels in the Delta are generally quite high and nitrite is rarely present at detectable concentrations. All bioavailable nutrient concentrations analyzed here are reported as mg/L N and P. The relative concentrations of total N and total P as indicated by the N:P ratio is widely used to indicate which nutrient is most likely to be limiting. A mass ratio of 7.23:1 N:P -- rounded up here to 8:1 for simplicity -- has traditionally been used to delineate conditions more likely to favor P limitation (N:P > 8:1) and those more likely to favor N limitation (N:P < 8:1) (Redfield, 1958). Subsequent studies have shown this critical ratio to vary depending on other environmental circumstances, and the 8:1 ratio is used here simply to illustrate how nutrient limitation may change seasonally.

A factor complicating the relationships between these water quality parameters and T&O concentration patterns is that all these parameters can be influenced by hydrologic conditions, which may also be related to T&O production. As one example, higher water flows can directly limit cyanobacteria abundance as described above but can also entrain sediment that increases turbidity, which can further reduce cyanobacteria abundance by limiting light availability. Using this example, if both hydrology and turbidity are significantly related to T&O concentrations but are themselves significantly related then it is not possible to untangle the relative influence of the two environmental factors using the data sets available for this analysis.

Statistical Analyses

A conceptual diagram (Figure 2) shows potential relationships (based on scientific literature) between environmental parameters and T&O statistics considered in this analysis. The configuration of the diagram assigns a central role for hydrology as a potential driver of both T&O production and other environmental parameters (nutrients, water temperature, specific conductance, turbidity) that can affect this production. Therefore, when assessing the relationship between these other environmental parameters and T&O, the possibility of confounding relationships with hydrology must also be considered. The statistical significance of the relationships shown in Figure 2 was measured using Pearson product-moment correlation coefficients and least-squares regression analysis. These statistical procedures were applied to both untransformed and natural-log-transformed data to account for the curvilinear nature of some relationships, and the strongest of these relationships was reported.

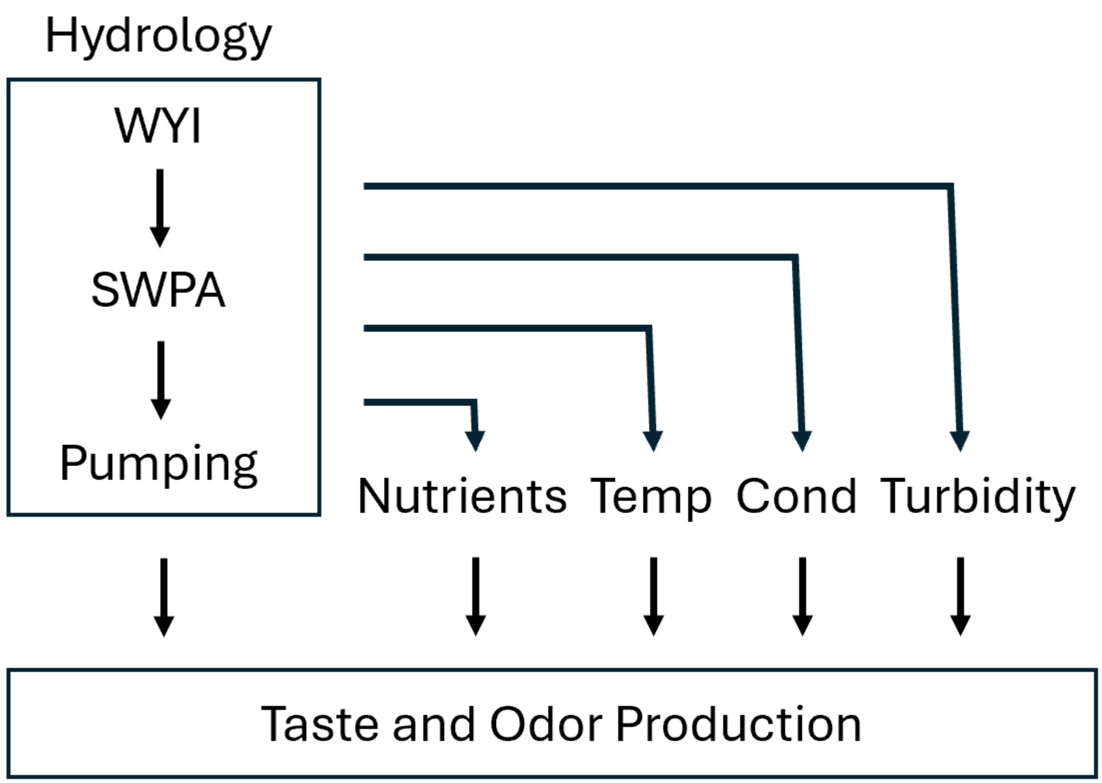

Figure 2 – Conceptual diagram of possible relationships between environmental parameters and T&O production. Statistical analyses were performed to assess the strength of each relationship shown as arrows in the diagram.

RESULTS

Taste and Odor Patterns

Summary of the Entire Dataset

During the 15-year POR (2009-2023), T&O samples were collected nearly every week at CCI and BPP, yielding between 734 and 735 values each for geosmin and MIB (after screening) for data analysis. Sampling was less frequent in some years at ONF but still yielded 647 screened values for each T&O compound for analysis.

Overall patterns in the data sets, summarized using box plots (Figure 3), were similar across sites, with relatively few elevated (>7 ng/L) T&O values. Based on separate calculations, between 15% (CCI) and 22% (BPP) of geosmin samples had elevated concentrations, while 8% (BPP and ONF) to 13% (CCI) of MIB samples were elevated. The highest geosmin and MIB concentrations were measured at ONF, including extreme high levels in 2015 (MIB) and 2020 and 2021 (geosmin). Across all other years, the range of T&O concentrations was similar among the three sites.

T&O Seasonal Patterns

The production of T&O compounds is highly seasonal in waterbodies across the region, with little detectable production during the cooler months (winter-early spring) and higher production during the warmer months (late spring-fall) when environmental conditions are more favorable for cyanobacterial growth. All three T&O statistics exhibited strong seasonal patterns that were similar at all sites. Monthly geosmin concentrations never exceeded 10 ng/L during the period January-April but began increasing in May and June and peaked in July and August before subsiding by December (Figure 4). This peak subsided more quickly at CCI than at BPP, indicating that water leaving CCF tended to have higher geosmin than inflow water during late summer into the fall. An exception to the consistent seasonal pattern for geosmin was an event at ONF in the fall of 2020 that peaked in November at 149 ng/L – the highest geosmin concentrations measured at ONF during the POR – and continued into December. Monthly MIB concentrations followed a similar predictable seasonal pattern with the potential for peak concentrations later in the season than for geosmin, usually in August and September (Figure 4). Again, ONF showed the potential for elevated MIB into December due to an MIB event in the fall of 2015 that peaked in November at 292 ng/L – the highest MIB concentration measured at ONF during the POR – and continued into December. Based on these patterns, the May-November period was identified as the “T&O season” for this part of the SWP and statistical analyses below were limited to data for these months.

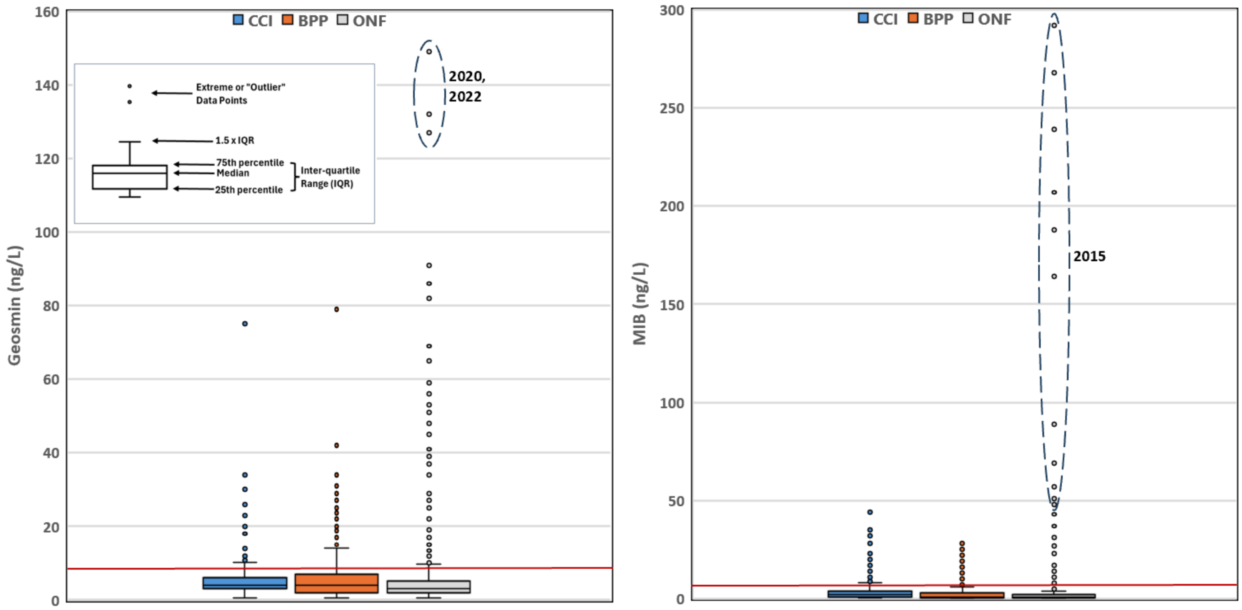

Figure 3 - Box plots showing distribution of all data collected at each site during the period 2009-2023. See inset in geosmin graph for description of boxplot elements. Red horizontal line denotes >7 ng/L for these T&O compounds, a level that is potentially concerning for the SWC. For ONF, several extreme high data points are circled to highlight that these T&O levels only occurred in a few years.

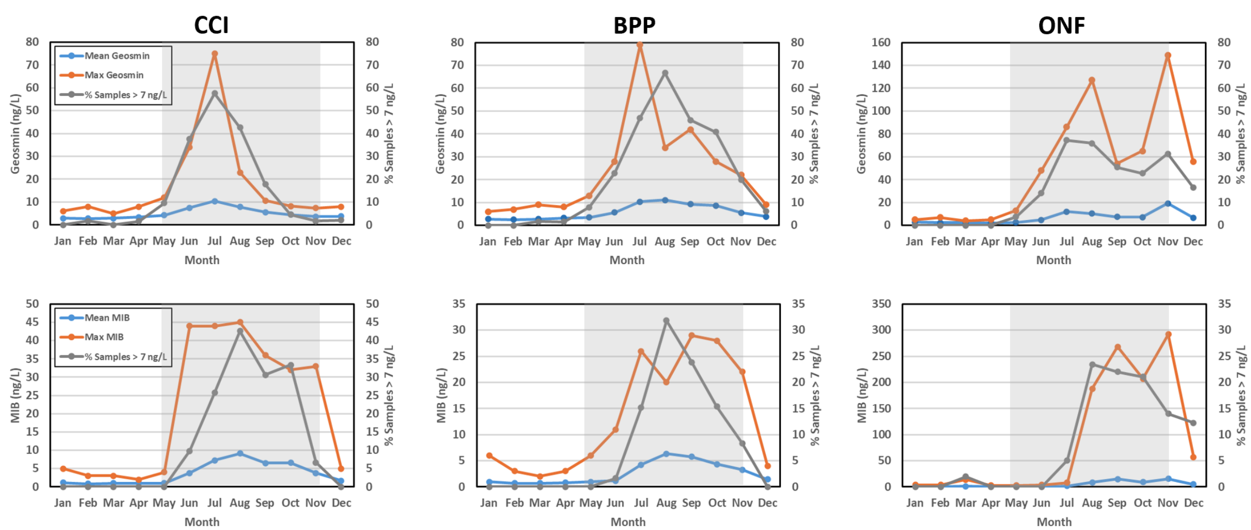

Figure 4 – Monthly variation in three T&O statistics at each site averaged across the period 2009-2023. The gray shaded area encompasses the months when T&O issues occur, defined as the "T&O season" in this report.

T&O Interannual Patterns

Taste-and-odor production varied considerably among T&O seasons across years (Figure 5). All sites experienced lower concentration years interspersed with one or more higher concentration years, but there were notable differences in this interannual pattern among sites. Seasonal mean and maximum geosmin concentrations were relatively low at all sites early in the POR (2009-2013) and then trended higher during the period 2014-2016. The years 2017-2019 encompassed a period of lower means and maxima at CCI and ONF, whereas these concentrations at BPP increased during these years. And, when means and maxima rebounded at CCI and ONF during 2020-2022, they trended lower at BPP. Finally, these concentrations declined at ONF in 2023 but increased at CCI and BPP. Elevated geosmin concentrations were measured at all sites in most years and ranged between 30-79% of samples in years with the highest mean geosmin and 0-29% in years with the lowest mean geosmin.

Mean and maximum MIB concentrations also peaked at all sites during the period 2013-2015 and showed a smaller increase during 2020-2022 (Figure 5). Elevated MIB concentrations ranged between 14-67% of samples in years with the highest mean MIB and 0-7% in years with the lowest mean MIB.

Correlation analysis was used to assess whether interannual variation in T&O-season mean concentrations followed a similar pattern (i.e., positively correlated) between pairs of sites. All inter-site correlations were positive, but not all were statistically significant. Geosmin patterns were significantly correlated at CCI and ONF (Pearson $r=0.562$, $p<0.050$), but BPP patterns were not significantly related to those at other sites. MIB patterns at CCI were significantly correlated to patterns at both BPP (Pearson $r=0.600$, $p<0.050$) and ONF (Pearson $r=0.661$, $p<0.010$), but BPP and ONF patterns were not significantly related.

Thus, while there was evidence that certain years were more conducive than others to T&O production across all sites, correlation results showed that interannual production patterns were influenced by site-specific conditions as well, particularly at BPP.

Sources of T&O Production

To identify sources of production for geosmin and MIB, monthly mean T&O concentrations for upstream (x axis) and downstream (y axis) sites were paired across all T&O seasons and graphed as scatterplots (Figure 6). The site CCI (upstream) was paired with BPP (downstream) to assess the importance of contributions from the Delta vs CCF to BPP T&O concentrations, and the site BPP (upstream) was paired with ONF (downstream) to assess the contribution of locations downstream from BPP to concentrations at ONF. A “1:1 line” of equality between upstream and downstream values in each plot separates months where T&O concentrations were higher at the upstream site (indicating this site as the primary T&O source) and those where concentrations were higher downstream (indicating T&O sources between the two sites). Given the proximity of CCI and BPP at the inlet and outlet of CCF, respectively, data points were color coded (see

Figure 6 caption) to indicate when the Delta, CCF, or both were likely sources of T&O production.

Scatterplots of monthly CCI vs BPP geosmin showed 23 months when geosmin concentrations became elevated only after water moved through CCF and only 10 months where elevated concentrations at CCI declined to below that level once water reached BPP. There were 15 months when elevated concentrations occurred at both sites. This analysis shows that elevated concentrations of geosmin occurred at BPP during 36% of T&O-season months during the POR and that CCF was often a contributor to these elevated levels in addition to any contributions from the Delta.

The same analysis for CCI vs BPP MIB showed only 4 months when MIB concentrations became elevated after water moved through CCF, whereas there were 13 months when elevated concentrations at CCI declined below this level once water reached BPP. There were 9 months when concentrations were elevated at both sites. This analysis shows that elevated MIB concentrations occurred at BPP during 12% of T&O season months during the POR and identifies the Delta rather than CCF as the most frequent source of elevated MIB at BPP.

The above conclusions were further supported by a comparison of T&O-season mean concentrations for BPP and CCI for each year during the POR (Figure 7). Seasonal values for CCI were subtracted from those for BPP to assess whether CCF was a seasonal T&O source (difference between BPP and CCI was positive) or a "sink" (difference between BPP and CCI was negative) during each year. In most years, the difference for geosmin was positive, again implicating CCF as an important geosmin source for BPP. By contrast, the difference for MIB was negative in most years, implicating the Delta (CCI) as the most frequent source of MIB for BPP.

A detailed comparison of BPP vs ONF was not attempted because the long physical distance and transit times between the two sites and the complex hydrology of O'Neill Forebay creates uncertainty as to whether BPP could be considered a significant contributor to T&O issues at site ONF. A review of the scatterplot between the two sites (Figure 6) shows infrequent but substantial geosmin and MIB production downstream of BPP.

Figure 5 – Interannual variation in seasonal T&O statistics at each site during the period 2009-2023.

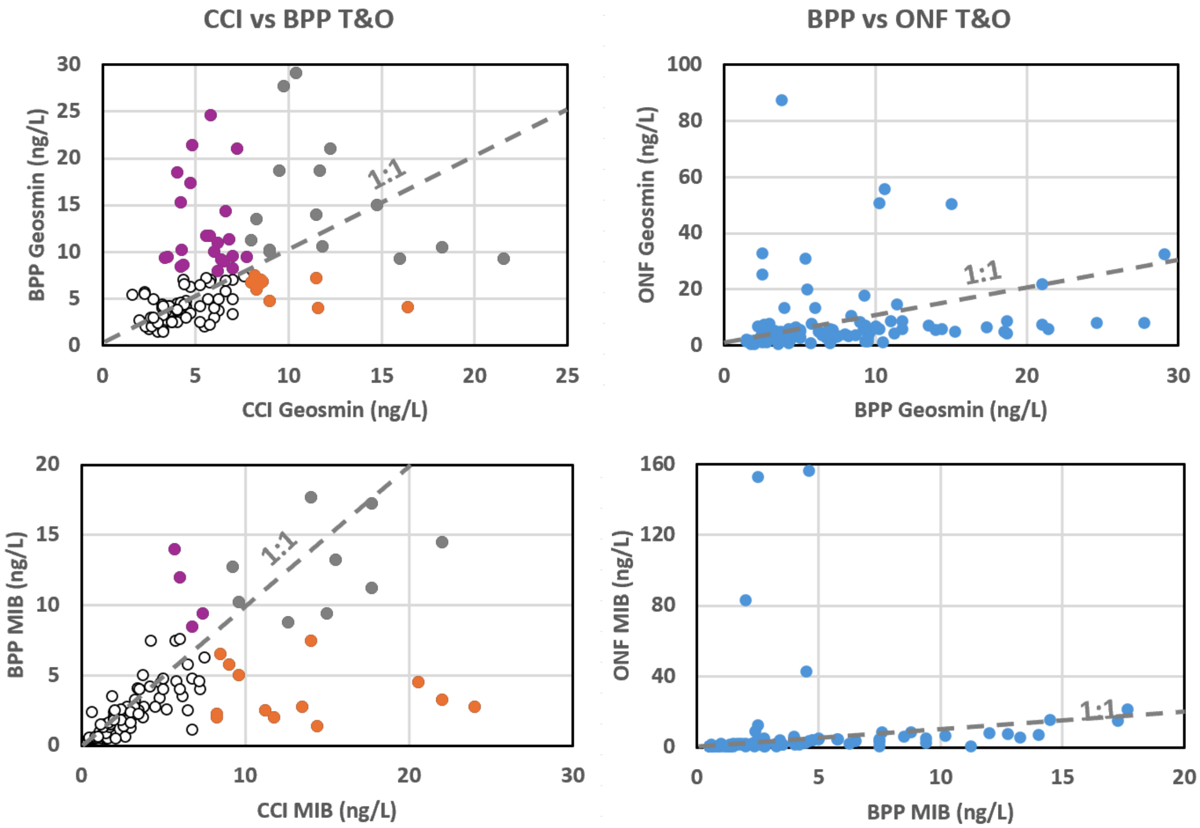

Figure 6 – Scatterplots of paired monthly mean T&O concentrations for upstream (x axis) and downstream (y axis) sites across all T&O seasons. The gray dashed "1:1 line" of equality between upstream and downstream values in each plot separates months where T&O values were higher at the upstream site (indicating this site is the primary T&O source) and those where values were higher downstream (indicating a T&O source between the two sites). Paired data points for the CCI-BPP plots were color coded as follows: (1) open black circles – neither site had elevated T&O values; (2) orange circles – only the upstream site had elevated T&O values; (3) magenta circles – only the downstream site had elevated T&O values; (4) gray circles - both sites had elevated T&O values. No color coding was applied to the BPP-ONF graphs for reasons described in the text.

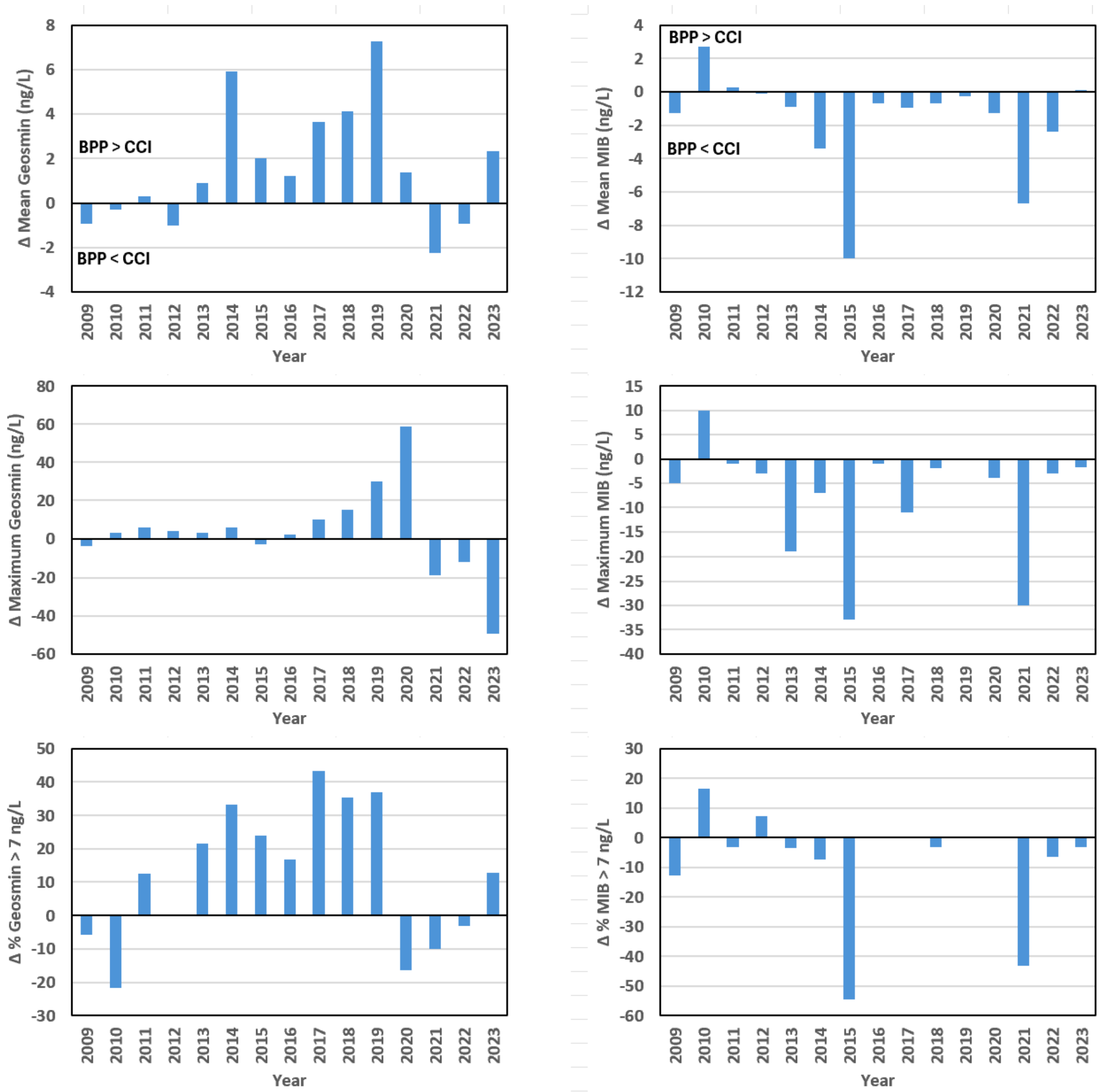

Figure 7 – Bar graphs showing differences (Δ) in seasonal T&O statistics between BPP and CCI for each year during the POR. Each bar is the seasonal value at CCI subtracted from that at BPP to assess whether CCF was a seasonal T&O source (difference between BPP and CCI was positive) or a "sink" (difference between BPP and CCI was negative) during each year.

Hydrology

Hydrologic Conditions during the Period of Record

The period 2009-2023 encompassed a wide range of hydrologic water years in the Delta watersheds. According to the WYI, there were more drier years than wetter years and there were two periods when conditions were critically dry (2014-2015 and 2021-2022 in the Sacramento watershed and 2013-2015 and 2021-2022 in the San Joaquin watershed). The "composite" WYI used in this analysis, which considered conditions in both watersheds, is shown in Figure 8.

Consistent with the variation in WYI, the SWPA and T&O-season pumping volumes also varied considerably during the POR (Figure 8). The SWPA ranged between 5% and 100% among years and monthly BPP and DAPP pumping volumes during the T&O season varied by 10-fold and 6-fold, respectively, again encompassing the wide range of annual hydrologic variation historically experienced in the Delta and the SWP.

Relationships between Hydrologic Indicators

The three hydrologic indicators used in this analysis to examine T&O-hydrology relationships were all strongly correlated (Figure 9). The relationships between WYI and both the SWPA and pumping volumes was curvilinear (logarithmic fit), with increasingly wet years not translating into a corresponding increase in allocations or pumping. This relationship could be due to: (1) limits to the SWPA (maximum allocation is 100%) and the capacity of the SWP to convey and store water; and (2) operational factors peculiar to a given wet year that might reduce SWP flows below what would be expected based on the WYI (e.g., refilling upstream reservoirs following a series of drought years, pumping constraints dictated by environmental regulations or other factors). The relationship between SWPA and pumping volumes was linear as higher water availability to the SWP resulted in correspondingly higher water flows through the SWP. These statistical results showed that all three indicators provided similar information on hydrologic differences among years, albeit with some divergence in Delta-wide and SWP conditions during the wettest years. To the extent that hydrology is a useful indicator of seasonal T&O production, the use of the SWPA has the advantage of being known prior to the WY T&O season (i.e., can be used to anticipate the potential for T&O issues) whereas the WYI is calculated several months after the WY has ended. Seasonal and monthly pumping volumes provide more of a real-time indicator of the actual hydrologic conditions being experienced at different sites and might help explain local T&O issues within a particular T&O season.

Hydrology Relationships with T&O Production

<u>Geosmin at CCI</u>. Seasonal geosmin concentrations coming from the Delta (CCI) were higher in drier years than in wetter years except for 2023, which was a wet year with unusually high geosmin levels at CCI. Including 2023 in the analysis yielded no significant relationships between CCI geosmin and hydrology. Excluding this unusual year from the CCI analysis yielded significant relationships between all three seasonal geosmin statistics and the three hydrologic

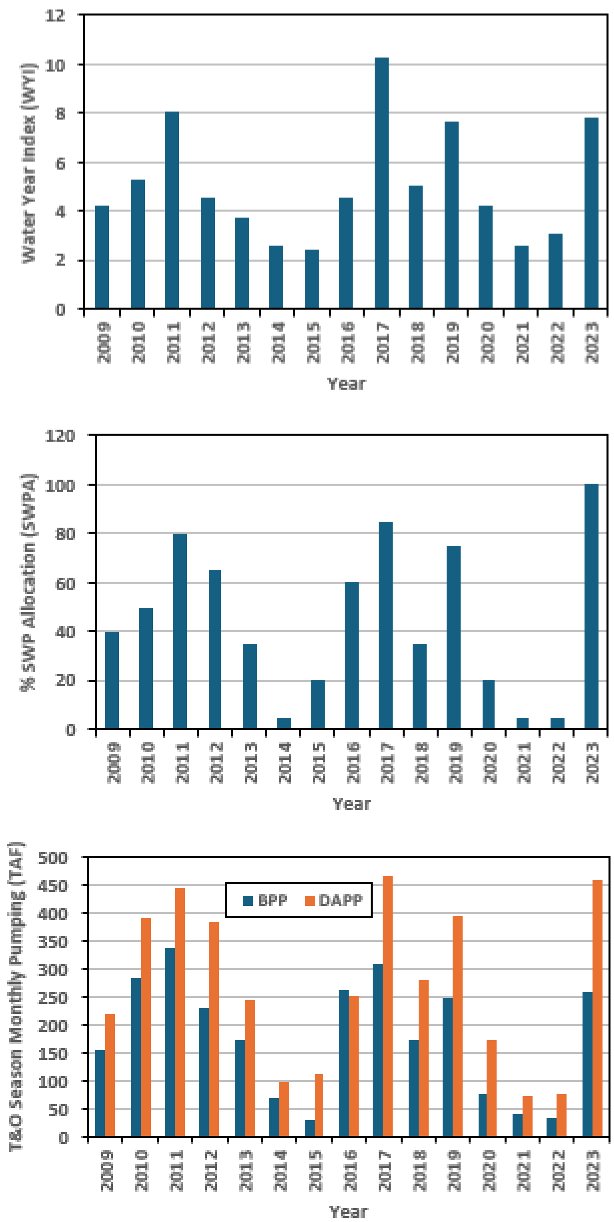

Figure 8 -Interannual variation in the hydrologic indicators used for analysis.

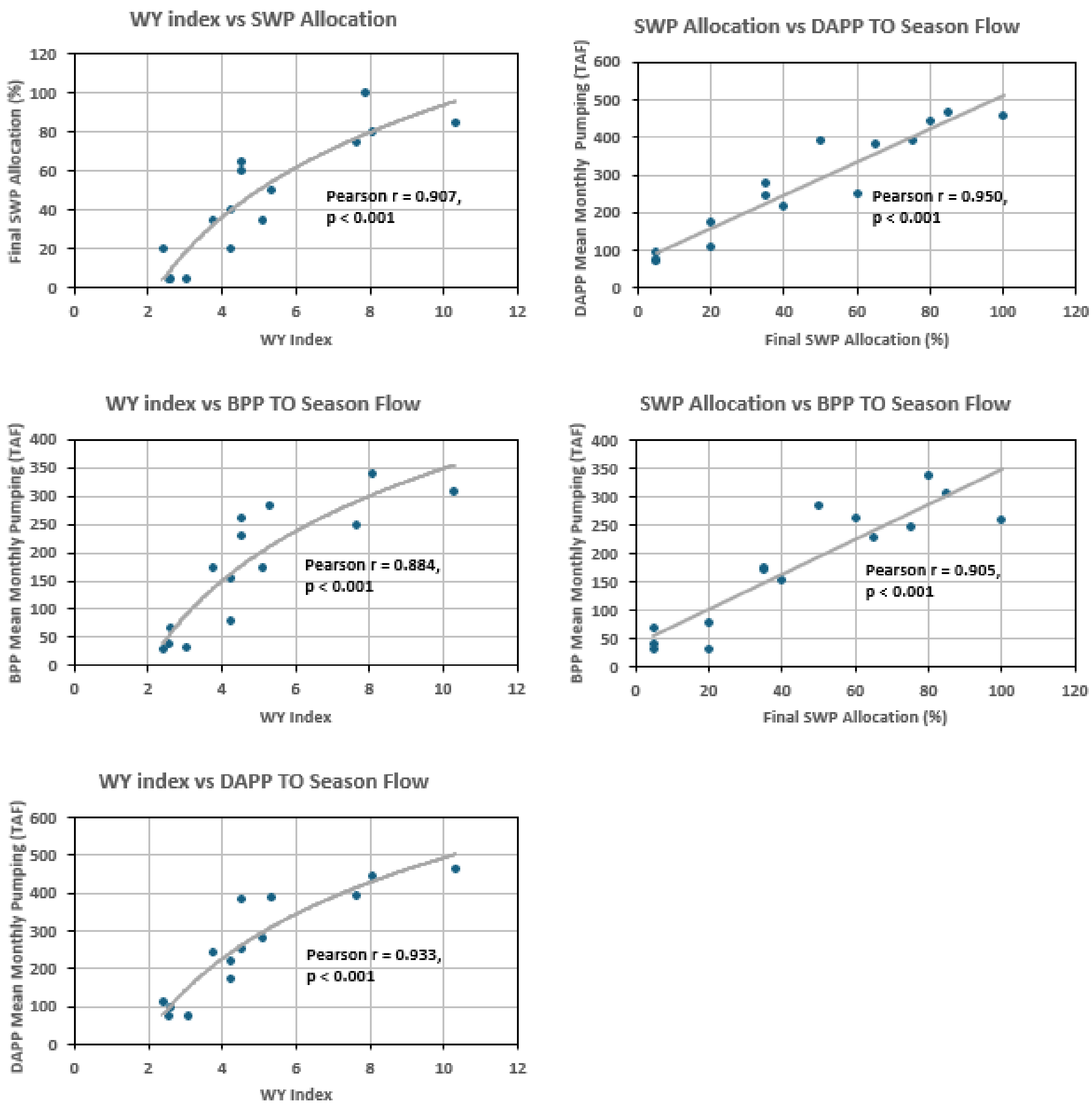

Figure 9 – Statistical relationships between hydrologic indicators. Gray lines show significant relationships, and the corresponding statistical significance and correlation coefficient is displayed on each graph.

indicators (Figures 10 and 11). Comparing the WYI extremes, maximum geosmin concentrations in the three wet-category years (2011, 2017, 2019) ranged between 7 and 12 ng/L and elevated concentrations occurred in 0 to 22% of T&O-season samples. By contrast, maximum geosmin concentrations in the four critical dry years (2014, 2015, 2021, 2022) ranged between 20 and 34 ng/L and elevated concentrations occurred in 19 to 44% of T&O-season samples. Geosmin levels during the outlier wet year 2023 were similar to those occurring in dry years, with a maximum concentration of 75 ng/l and elevated concentrations 42% of the time. Monthly correlations (Table 1) found the strongest relationship between higher geosmin and dry conditions early in the T&O season (May-July), whereas there was some evidence that wetter conditions were associated with higher geosmin late in the season (September-November). Thus, the overall pattern was for higher CCI geosmin concentrations in drier years with occasional exceptions.

Geosmin at BPP. Despite the short physical distance between CCI and BPP, seasonal geosmin concentrations at BPP were not related to any of the hydrologic indicators (Figures 10 and 11). Regardless of whether conditions were dry or wet, maximum geosmin concentrations ranged between 10 and 30 ng/L in most years – although a maximum value of 79 ng/L was measured in the dry year of 2020 – and the frequency of elevated concentrations typically varied between 10 and 60%. Monthly analyses also found little evidence of a relationship between geosmin levels and hydrology (Table 1). As already shown (Figures 6 and 7), monthly and seasonal geosmin concentrations were frequently higher at BPP than at CCI. These results indicate that CCF is a significant source of geosmin production affecting BPP that is unrelated to annual variation in watershed or SWP hydrology.

Geosmin at ONF. Similar to CCI, seasonal geosmin concentrations at ONF were higher in drier years. All three geosmin statistics were negatively related to both the SWPA and seasonal pumping volumes at DAPP (water leaving ONF), and the highest levels also occurred in years with the lowest WYI (Figures 10 and 11). Comparing the hydrologic extremes, maximum geosmin concentrations in the four years with the highest SWPA and DAPP flows (2011, 2017, 2019, 2023) ranged between 8 and 18 ng/L and elevated concentrations occurred in 4 to 32% of T&O-season samples. By contrast, maximum geosmin concentrations in the four lowest SWPA and pumping years (2014, 2015, 2021, 2022) ranged between 54 and 127 ng/L and elevated concentrations occurred in 36 to 47% of T&O-season samples. Monthly correlations were strongest in May, at the beginning of the T&O season (Table 1).

MIB at CCI. At CCI, all three MIB statistics were negatively correlated with all three hydrologic indicators (Figures 12 and 13). Comparing the hydrologic extremes, maximum MIB concentrations in the wettest four years ranged between 2 and 4 ng/L and elevated concentrations occurred in 0 to 19% of T&O-season samples. By contrast, maximum MIB concentrations in the four driest years ranged between 23 and 45 ng/L and elevated concentrations occurred in 13 to 67% of T&O-season samples. Monthly correlations showed that this negative relationship was consistent throughout the season (Table 1). These results indicate that MIB production in the Delta upstream of CCI is greater in dry years.

MIB at BPP. Similar to geosmin, MIB statistics at BPP were not significantly correlated with any of the hydrologic indicators (Figures 12 and 13). Monthly correlations also showed no significant relationship (Table 1). However, unlike geosmin patterns at this site, a tendency towards higher mean and maximum MIB concentrations in drier years similar to the significant trend at CCI was suggested by the graphs. As already shown (Figures 6 and 7), the source of MIB measured at BPP can often be attributed to production entering CCF from the Delta at CCI. A likely explanation of the differing MIB patterns at BPP and CCI is that MIB entering from the Delta undergoes varying degrees of dilution in CCF before reaching BPP, thus masking the direct influence of CCI inputs.

MIB at ONF. At ONF, MIB statistics were not correlated with any of the hydrologic indicators (Figures 12 and 13), and monthly analyses also found a lack of significant relationships (Table 1). Highest MIB levels occurred during two of the driest years, 2014 (maximum MIB = 43 ng/L, elevated concentrations = 41%) and 2015 (maximum MIB = 291 ng/L, elevated concentrations = 48%). However, the other driest years (2021, 2022) had lower MIB levels that were similar to wetter years, when maximum concentrations never exceeded 18 ng/L and elevated concentrations never occurred in more than 23% of samples. Thus, while the highest MIB concentrations did occur in dry years, there was no consistent relationship with hydrology across the POR.

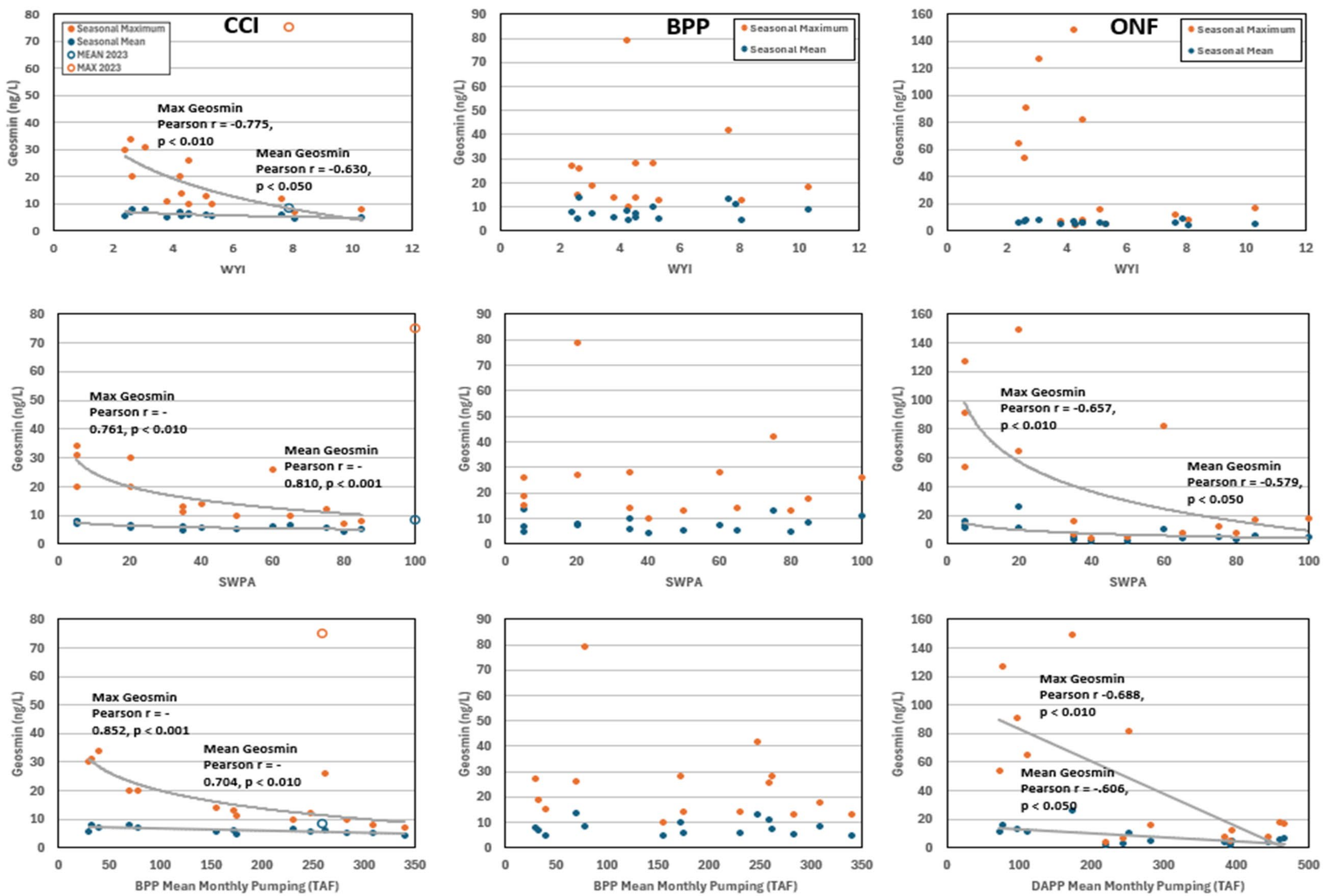

Figure 10 – Statistical relationships between seasonal mean and maximum geosmin and hydrologic indicators during the POR. Gray lines show significant regression relationships with the statistical significance and correlation coefficient displayed on each graph. Graphs without statistical information indicate no significant relationship. Note that the analysis for CCI excludes the outlier year 2023, data for which are shown as open circles.

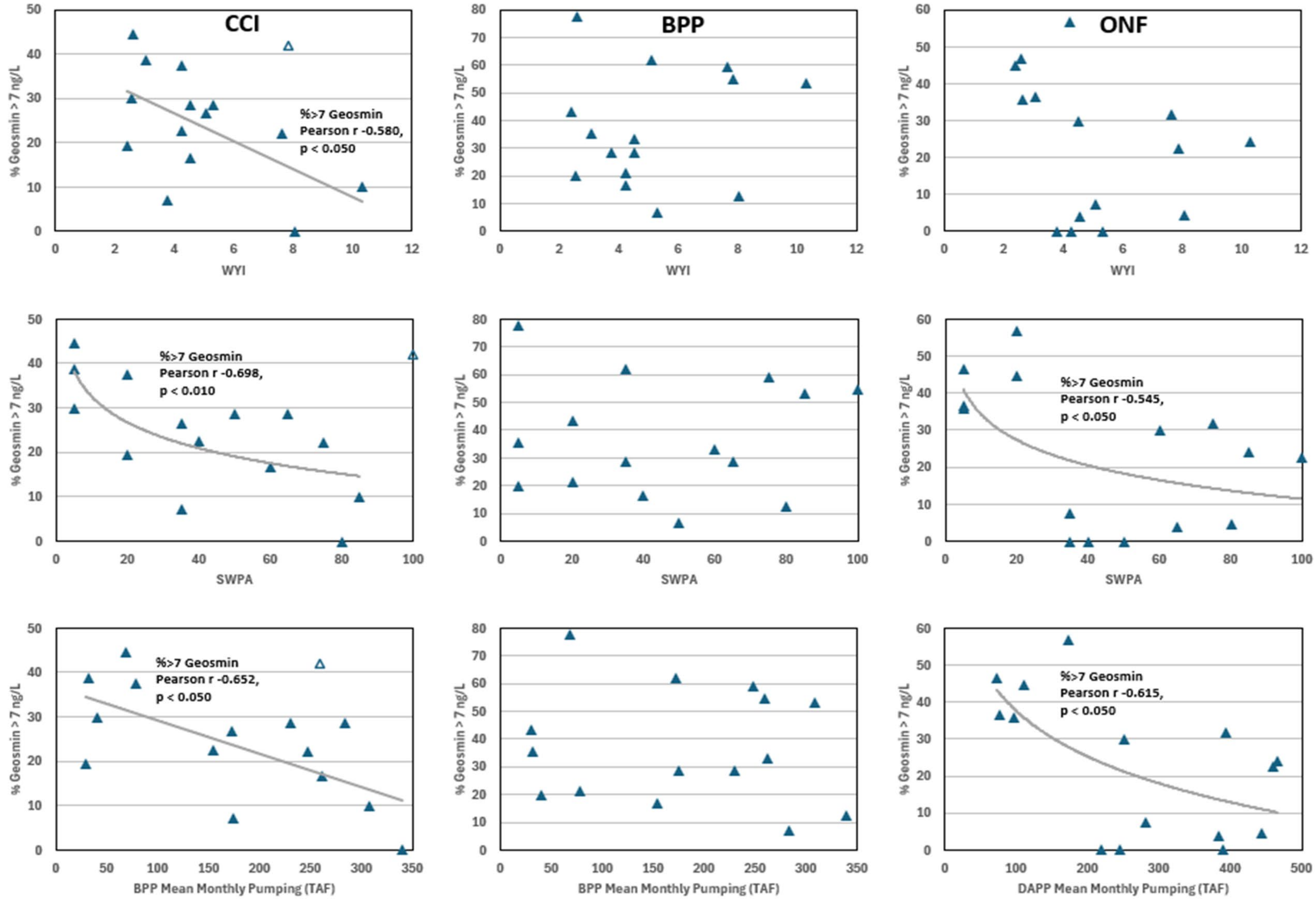

Figure 12 - Statistical relationships between the percentage of elevated (>7 ng/L) seasonal geosmin values and hydrologic indicators during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on each graph. Graphs without statistical information indicate no significant relationship. Note that the analysis for CCI excludes the outlier year 2023, data for which are shown as open triangles.

GEOSMIN							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.630L	-----	-----	-----	-----	-----	0.539L
SPWA	-0.816L	-0.687L	-----	-----	-----	-----	-----
Pumping	-0.621L	-0.582L	-----	-----	0.571L	0.595L	-----
CCIex'23	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.645L	-0.576L	-0.718L	-----	-----	-----	-----
SPWA	-0.838L	-0.771L	-0.612	-----	-----	-----	-----
Pumping	-0.678L	-0.645L	-0.549L	-----	0.560L	0.598L	-----
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-----	0.545L	-----	-----
SPWA	-----	-----	-----	-----	0.590	-----	-----
Pumping	-----	-----	-----	-----	-----	-----	-----
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-----	-----	-----	-----
SPWA	-0.564L	-----	-----	-0.533L	-----	-----	-----
Pumping	-0.593L	-----	-----	-----	-----	-----	-----
MIB							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.656L	-0.680L	-0.678L	-0.681L	-0.691L	-0.695L	-0.526L
SPWA	-0.754L	-0.613L	-0.581L	-0.698L	-0.641L	-0.615L	-0.519L
Pumping	-0.657L	-0.532L	-0.646L	-0.847L	-----	-0.527L	-----
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-----	-----	-----	-----
SPWA	-----	-----	-----	-----	-----	-----	-----
Pumping	-----	-----	-----	-----	-----	-----	-----
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-0.523L	-----	-----	-----
SPWA	-----	-----	-----	-----	-----	-----	-----
Pumping	-----	-----	-----	-----	-----	-----	-----

Table 1 – Correlations between monthly mean T&O concentrations during T&O season and hydrologic indicators. Only significant ($p<0.050$) relationships are shown. An L next to the correlation coefficient indicates that a logarithmic model provided a better fit than a linear model.

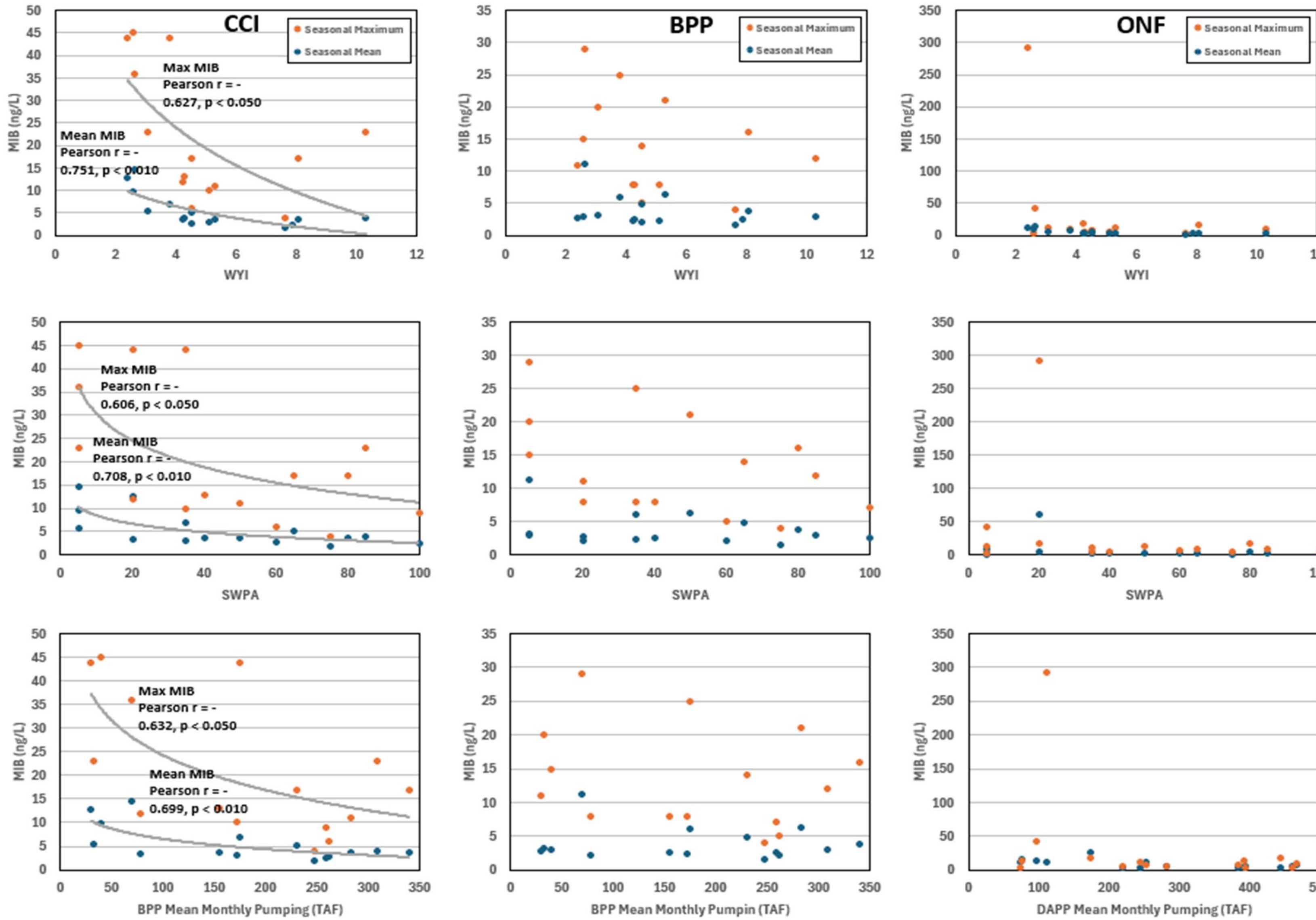

Figure 12 - Statistical relationships between seasonal mean and maximum MIB and hydrologic indicators during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

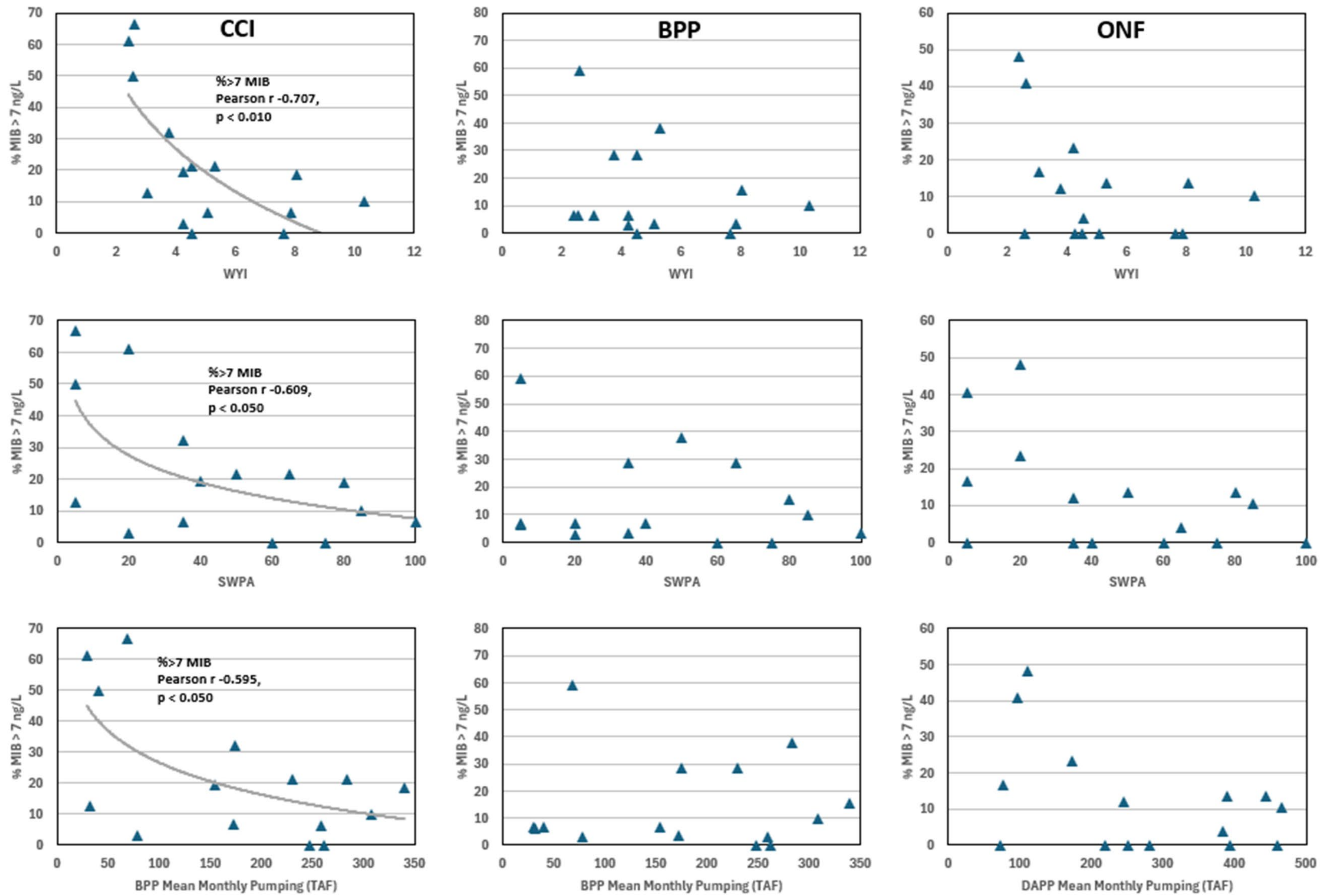

Figure 13- Statistical relationships between the percentage of elevated (>7 ng/L) seasonal MIB values and hydrologic indicators during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

Nutrients

Seasonal and Interannual Variation

Bioavailable nutrient concentrations were generally high and similar at all three sites during the POR (Figure 14). Nitrate was the largest component of bioavailable N and varied predictably during each year, with highest mean concentrations (~1 mg/L) during the winter followed by a decline during the spring and summer with minimum concentrations (~0.10-0.15 mg/L) occurring during August and September. Ammonium availability was considerably lower and followed a similar annual pattern to NO_3, with highest mean concentrations (~0.06-0.08 mg/L) during the winter and minimum mean concentrations (~0.02-0.03 mg/L) during T&O season. Box plots for both N forms showed modest interannual variation in concentrations during T&O season, indicating that the potential for N limitation differed among years. In contrast to bioavailable N, PO_4 levels were consistently high throughout the POR with comparatively little monthly variation in mean concentrations (~0.06-0.09 mg/L) (Figure 15). As for N, boxplots indicated modest interannual variation in PO_4 during T&O season, but levels in all years were higher than those that would be expected to limit cyanobacterial growth. Total N:P mass ratios were consistently above 8:1 during the winter when concentrations of both nutrients were high (and likely not limiting) and decreased below 8:1 during the summer as N concentrations declined, making N limitation more likely (Figure 15).

Nutrient Relationships with Hydrology

Nutrients were most strongly related to pumping volumes (shown in Figure 16), although relationships with other hydrologic indicators were often significant as well. Monthly correlations (Table 2) showed that the strength of these relationships varied during the T&O season depending on the site and nutrient form.

<u>CCI</u>. Delta water entering the SWP at CCI had higher PO_4 concentrations in low-pumping years. Nitrate concentrations at CCI were not significantly correlated with pumping operations but were lower in drier (low WYI) years (Pearson $r = 0.542$, $p < 0.050$). Monthly correlations showed that PO_4 relationships were significant early in the T&O season while NO_3 relationships were significant later in the season.

<u>BPP</u>. Relationships were stronger at BPP, with higher PO_4 and NH_4 concentrations and lower NO_3 concentrations in low-pumping years, and these relationships tended to be strongest during the peak T&O months (July-September). Stronger relationships at BPP (CCF outlet) as compared to CCI (CCF inlet) appeared to be due to increasing contributions of NH_4 and PO4 from CCF during lower pumping years as illustrated by the change in nutrient concentrations between these two sites in years with different pumping volumes (Figure 17). In contrast, NO_3 was lost within CCF (increasingly lower concentrations at BPP vs CCI) in all years, but monthly correlations found this loss to be significantly higher in drier years during the period May through July (Pearson $r \geq 0.516$, $p < 0.050$).

ONF. Similar to BPP, NH_4 concentrations at ONF were higher and NO_3 concentrations were lower in low pumping years, but with the strongest relationship later in the season. However, PO_4 concentrations were not significantly related to hydrology. Due to the complicated hydrology of ONF (multiple inflows and outflows unlike CCF) and its distance downstream of the nearest monitoring site (BPP), it was not possible to assess the effects of O'Neill Forebay on nutrient levels as was described above for CCF.

Overall, these relationships indicate that sediment fluxes of nutrients (NH_4 and PO_4 release, NO_3 loss by denitrification)) affect nutrient availability at all three sites and that hydrologic conditions influence these fluxes.

Nutrient Relationships with T&O Production

Geosmin. Seasonal geosmin concentrations were not consistently related to nutrients, but where significant, these relationships showed a pattern of higher geosmin levels in years with higher NH_4 and PO_4 concentrations and lower NO_3 concentrations (Figures 18-19). Monthly correlations between mean geosmin concentrations and nutrients did not reveal any consistent relationship within the T&O season (Table 3). The following site-specific relationships were identified.

CCI. Seasonal mean geosmin concentrations were unrelated to NH_4 and PO_4 but negatively related to seasonal NO_3.

BBP. Seasonal mean and elevated geosmin concentrations were positively related to PO_4 but unrelated to NH_4 or NO_3.

ONF. All three seasonal geosmin statistics were positively related to PO_4 and negatively related to NO_3, and the frequency of elevated geosmin concentrations was positively related to NH_4.

Interpreting significant relationships between geosmin concentrations and nutrients is complicated by the fact that years with higher NH_4 and PO_4 and lower NO_3 are associated with drier hydrologic conditions, which are also significantly related to geosmin concentrations at some sites. This intercorrelation makes it difficult to discern the relative importance of hydrology vs nutrients in determining geosmin patterns using the data available for this analysis.

MIB. Seasonal MIB concentrations were not related to nutrients at any of the sites with the exception that elevated MIB concentrations were more frequent at ONF during years with higher NH_4 (Figures 20-21).

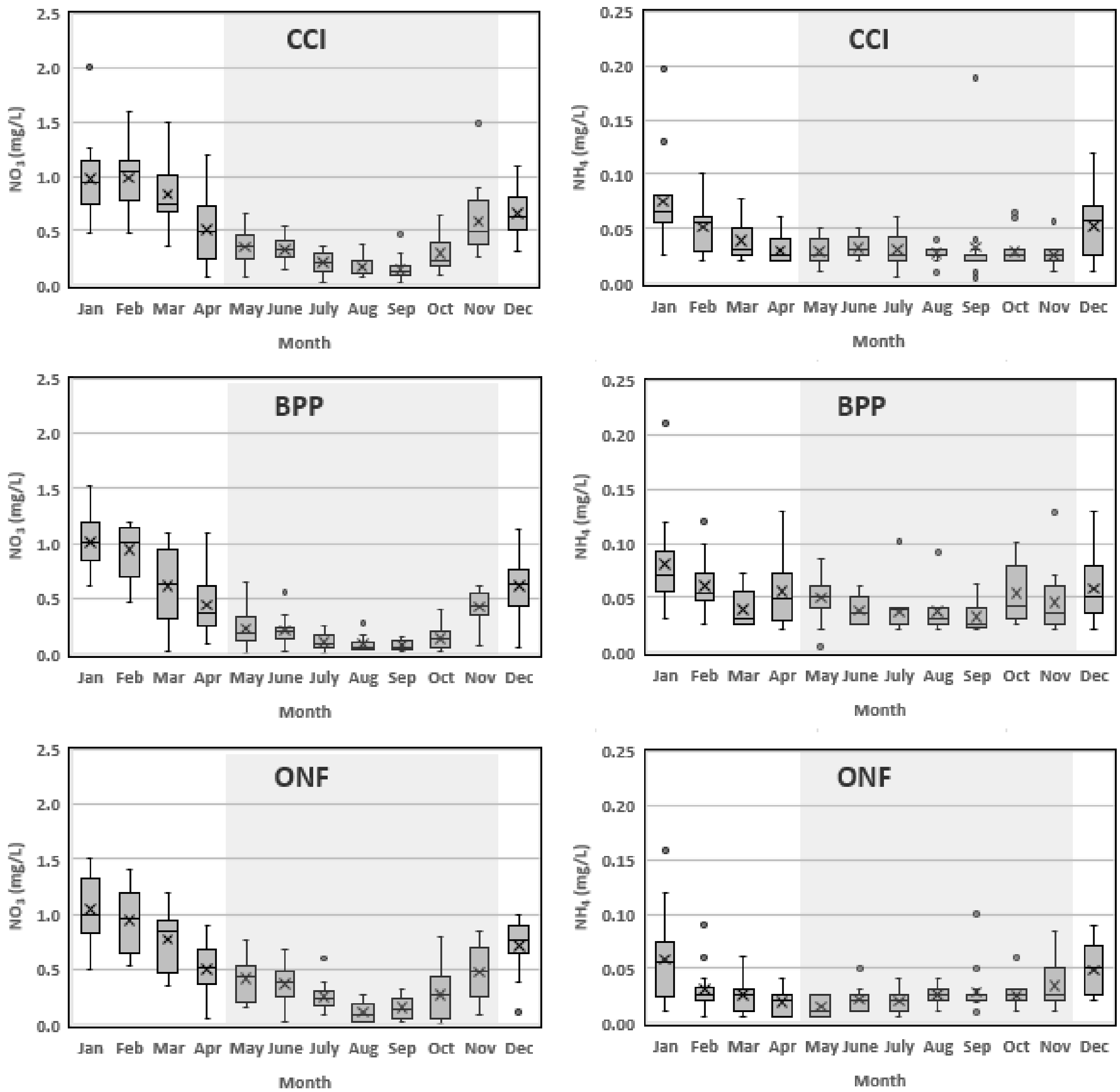

Figure 13 – Boxplots showing variation in monthly NO_3 and NH_4 concentrations at each site during the POR. A description of boxplot elements is provided in Fig. 3. Monthly mean values are included in these boxplots and are shown as an "X" in each box. Gray shaded area denotes the T&O season.

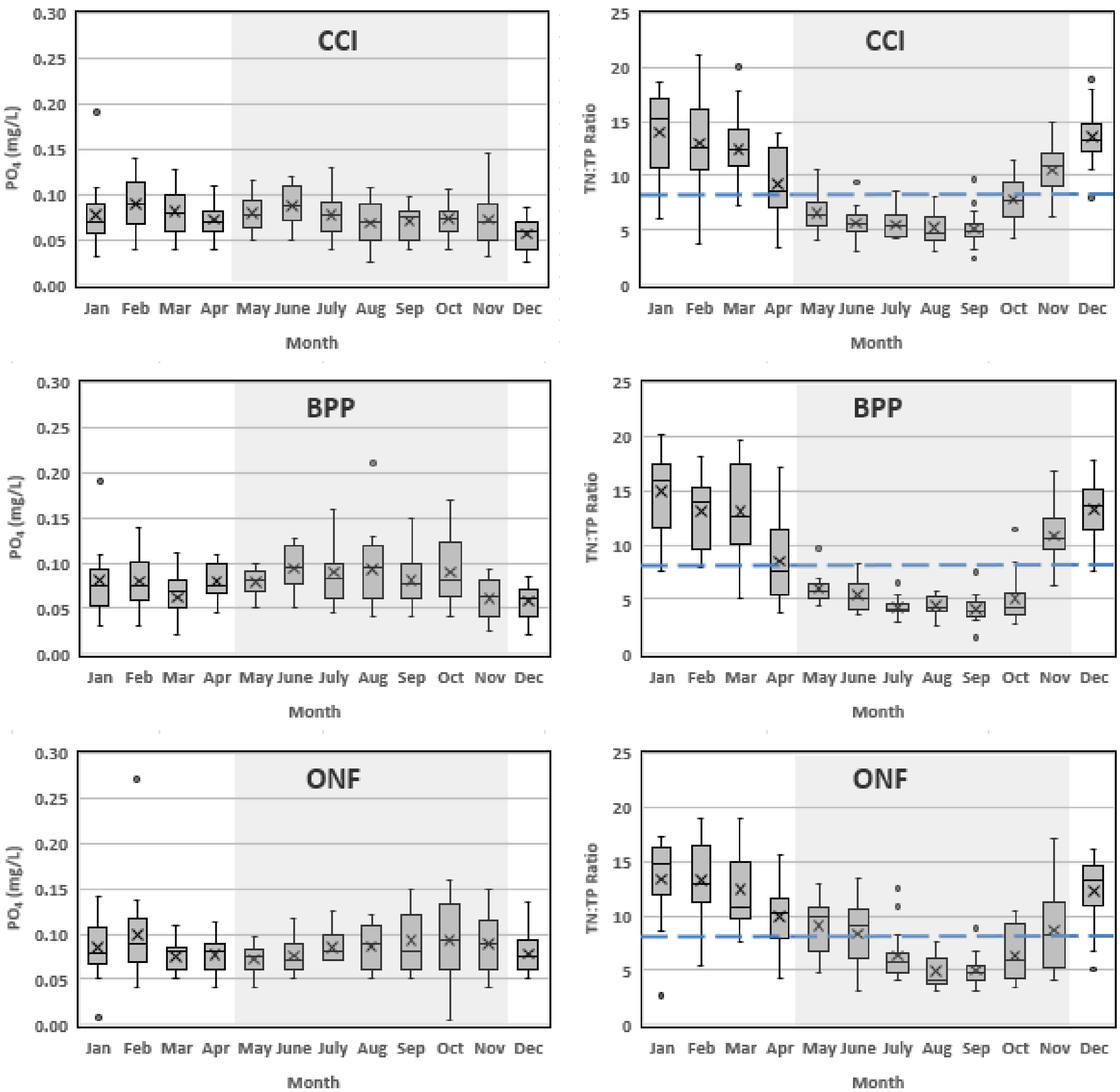

Figure 15 - Boxplots showing variation in monthly PO_4 concentrations and TN:TP ratios at each site during the POR. A description of boxplot elements is provided in Fig. 3. Monthly mean values are included in these boxplots and are shown as an "X" in each box. Blue dashed line shows the 8:1 N:P mass ratio defined in the Gray shaded area denotes the T&O season.

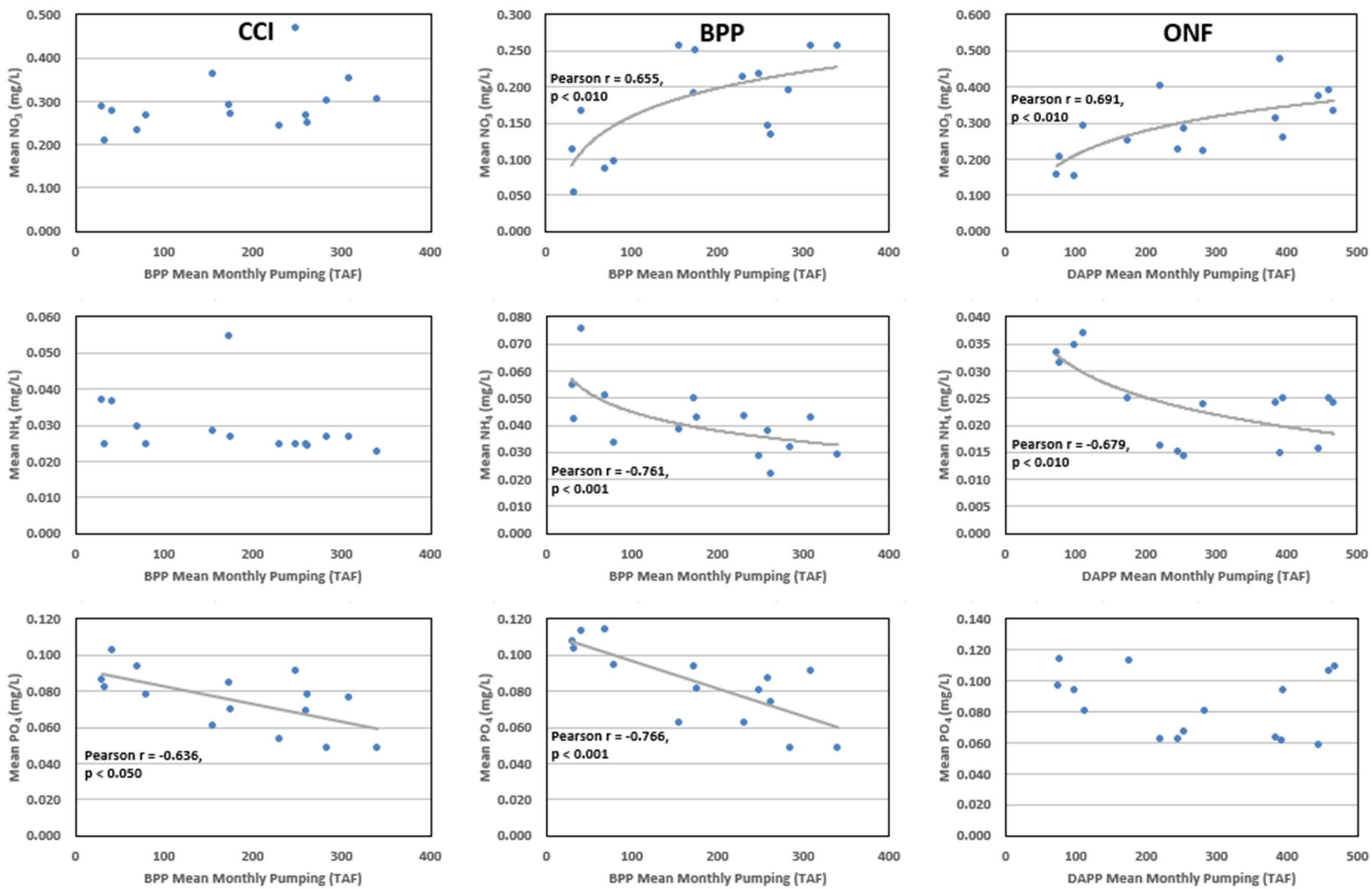

Figure 14 – Statistical relationships between seasonal mean bioavailable nutrients and seasonal pumping volumes during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

NOX							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-----	0.690	0.6363L	-----
SPWA	-----	-----	-----	0.516	-----	0.661	-----
Pumping	-----	-----	-----	-----	-----	-----	-----
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	0.760	0.874	0.841	-----	-----
SPWA	-----	-----	0.696	0.656	0.596	-----	-----
Pumping	-----	-----	0.761	0.519	0.615	-----	-----
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	0.833	0.852	0.778L	-----
SPWA	-----	-----	-----	0.763	0.744	0.744	-----
Pumping	-----	-----	-----	0.818	0.832	0.759	-----
NH4							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-----	-----	-----	-----
SPWA	-----	-----	-----	-----	-----	-----	-----
Pumping	-----	-----	-----	-----	-----	-----	-----
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.565	-0.595	-----	-----	-0.659L	-----	-----
SPWA	-0.550	-----	-0.579L	-0.717L	-0.644L	-----	-----
Pumping	-0.533	-0.656	-0.719L	-0.830L	-0.865L	-----	-----
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-----	-0.558L	-----	-----
SPWA	-----	-----	-----	-----	-----	0.548L	-0.730L
Pumping	-----	-----	-----	-----	-0.539L	-----	-0.707L
PO4							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.576L	-0.758L	-----	-----	-----	-----	-----
SPWA	-0.636	-0.680L	-0.669L	-0.612L	-----	-----	-----
Pumping	-0.643L	0.648	-0.875L	-0.601	-----	-0.720	-----
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-0.600L	-----	-----	-----	-----	-----
SPWA	-0.536	-0.626	-0.725L	-0.710L	-0.605L	-----	-----
Pumping	-----	-0.668	-0.782L	-0.767	-0.636L	-0.690L	-----
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	-----	-----	-----	-----	-----
SPWA	-----	-----	-----	-----	-0.705	-----	-----
Pumping	-----	-----	-----	-----	-0.618L	-----	-----

Table 2 - Correlations between monthly mean bioavailable nutrient concentrations and hydrologic indicators during T&O season. Only significant ($p<0.050$) are shown. An L next to the correlation coefficient indicates that a logarithmic instead of a linear regression model was used.

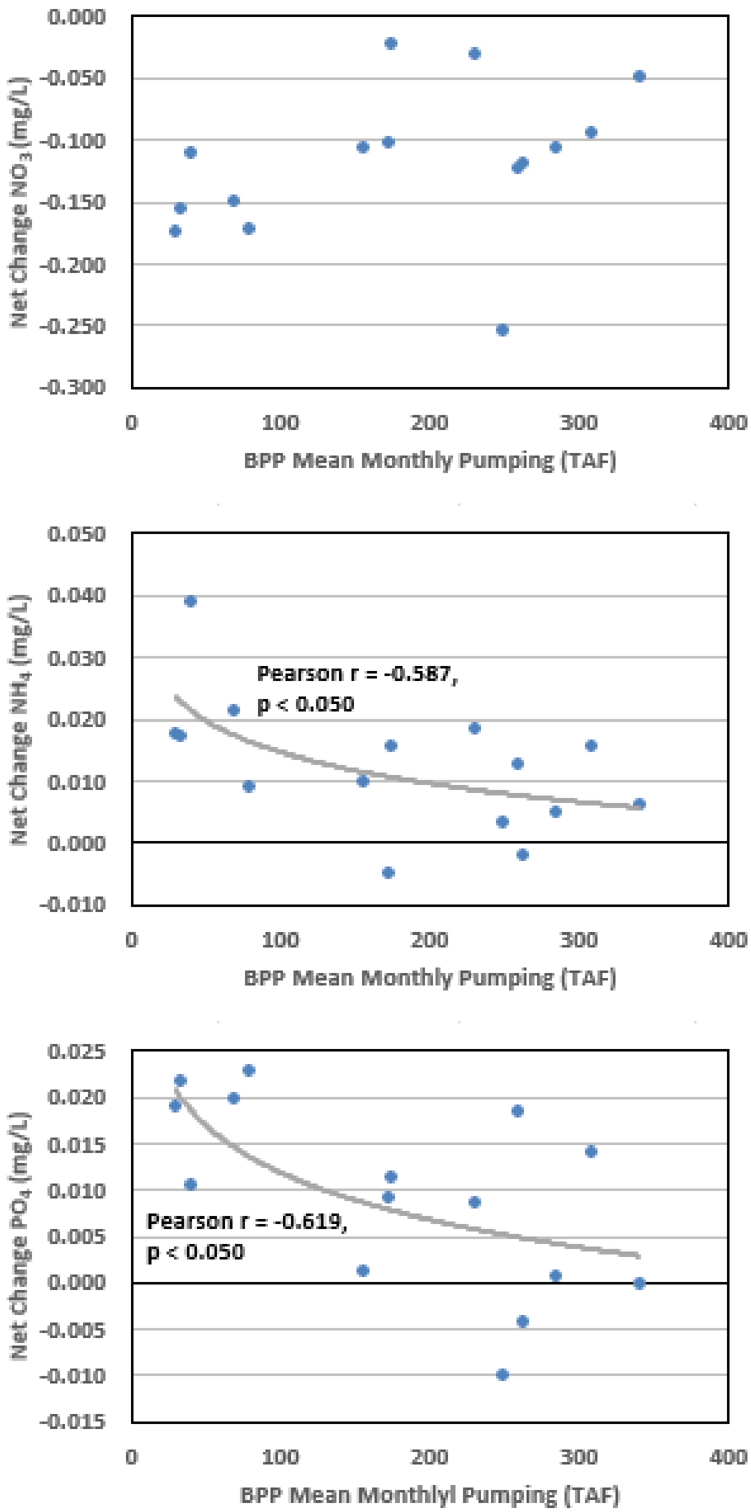

Figure 17 – Statistical relationships between the net change in bioavailable nutrient concentrations between CCI (upstream) and BPP (downstream) and T&O-season pumping volumes at BPP. Gray lines show statistically significant relationship with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

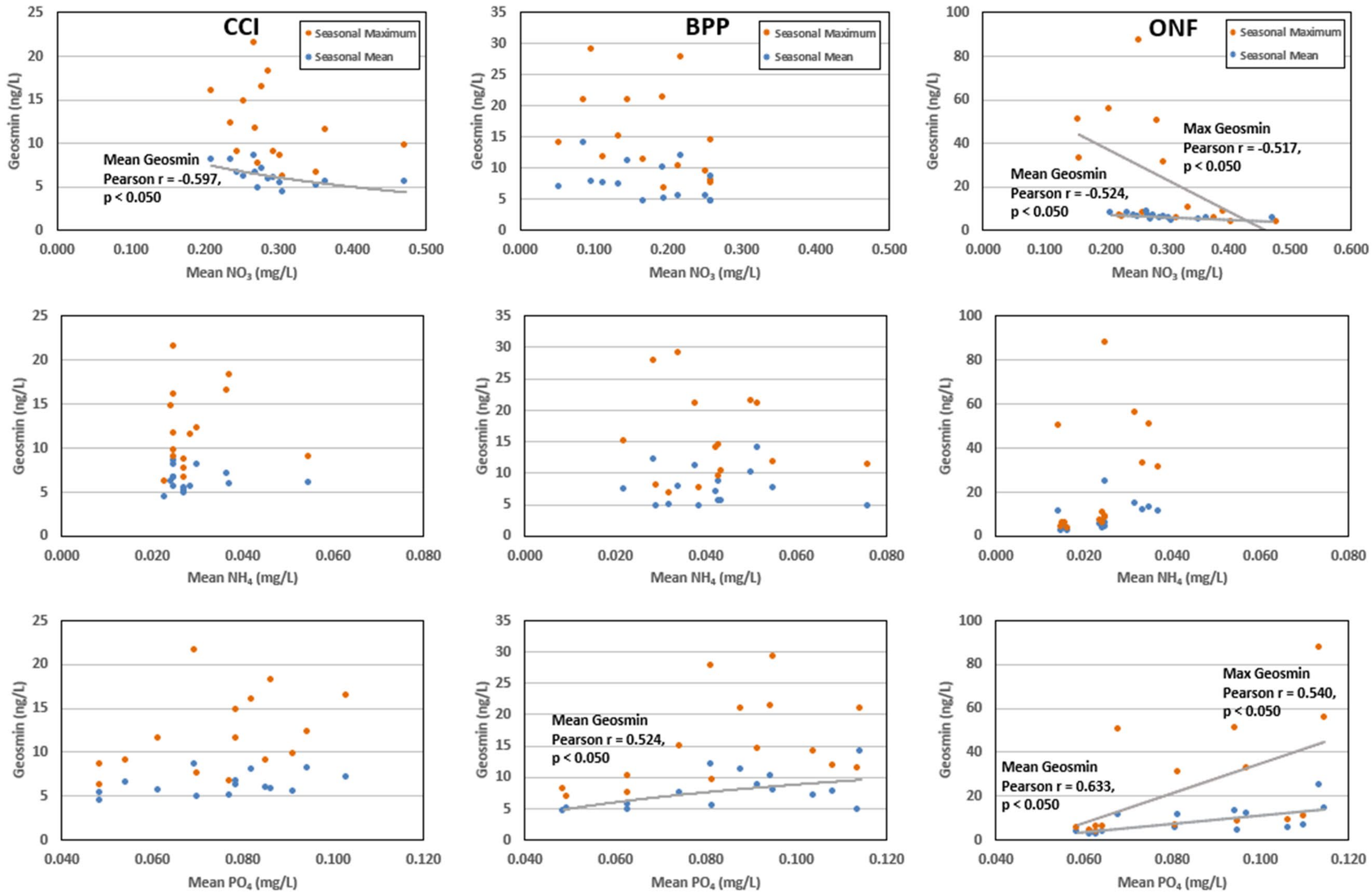

Figure 18 - Relationships between seasonal mean and maximum geosmin and bioavailable nutrients during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

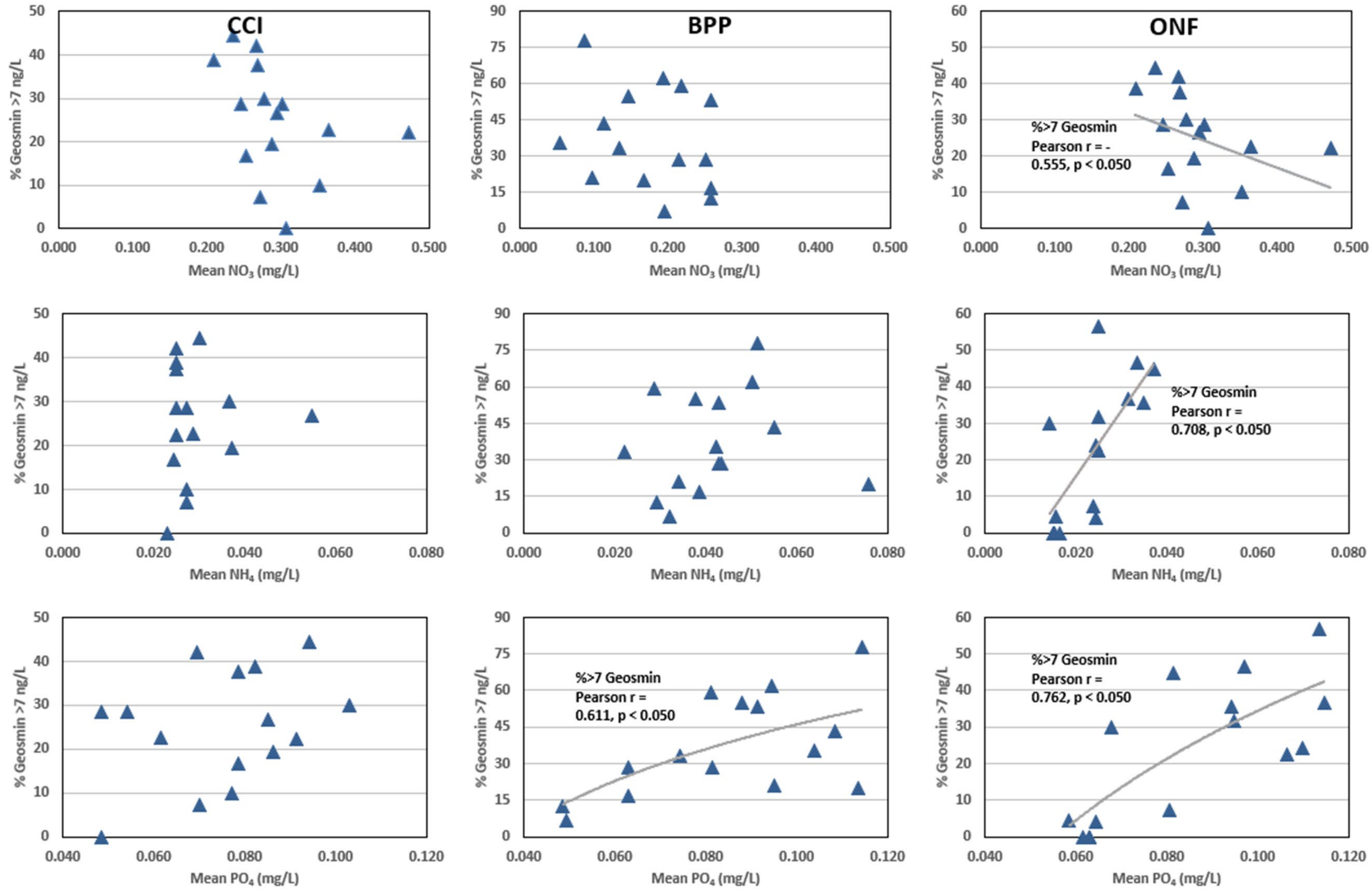

Figure 19 - Relationships between the frequency of elevated (>7 ng/L) seasonal geosmin values and bioavailable nutrients during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

GEOSMIN							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
NOX	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
NH4	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
PO4	- - - - -	0.705	- - - - -	- - - - -	- - - - -	-0.518L	- - - - -
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
NOX	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
NH4	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	0.768
PO4	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
NOX	-0.599L	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	-0.617L
NH4	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
PO4	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	0.525	- - - - -
MIB							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
NOX	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
NH4	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	0.683	- - - - -
PO4	- - - - -	0.589	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
SPWA	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Pumping	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
NOX	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
NH4	- - - - -	- - - - -	- - - - -	- - - - -	0.930	- - - - -	- - - - -
PO4	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -

Table 3 - Correlations between monthly mean T&O concentrations and monthly mean bioavailable nutrients during T&O season. Only significant ($p<0.050$) are shown. An L next to the correlation coefficient indicates that a logarithmic instead of a linear regression model was used.

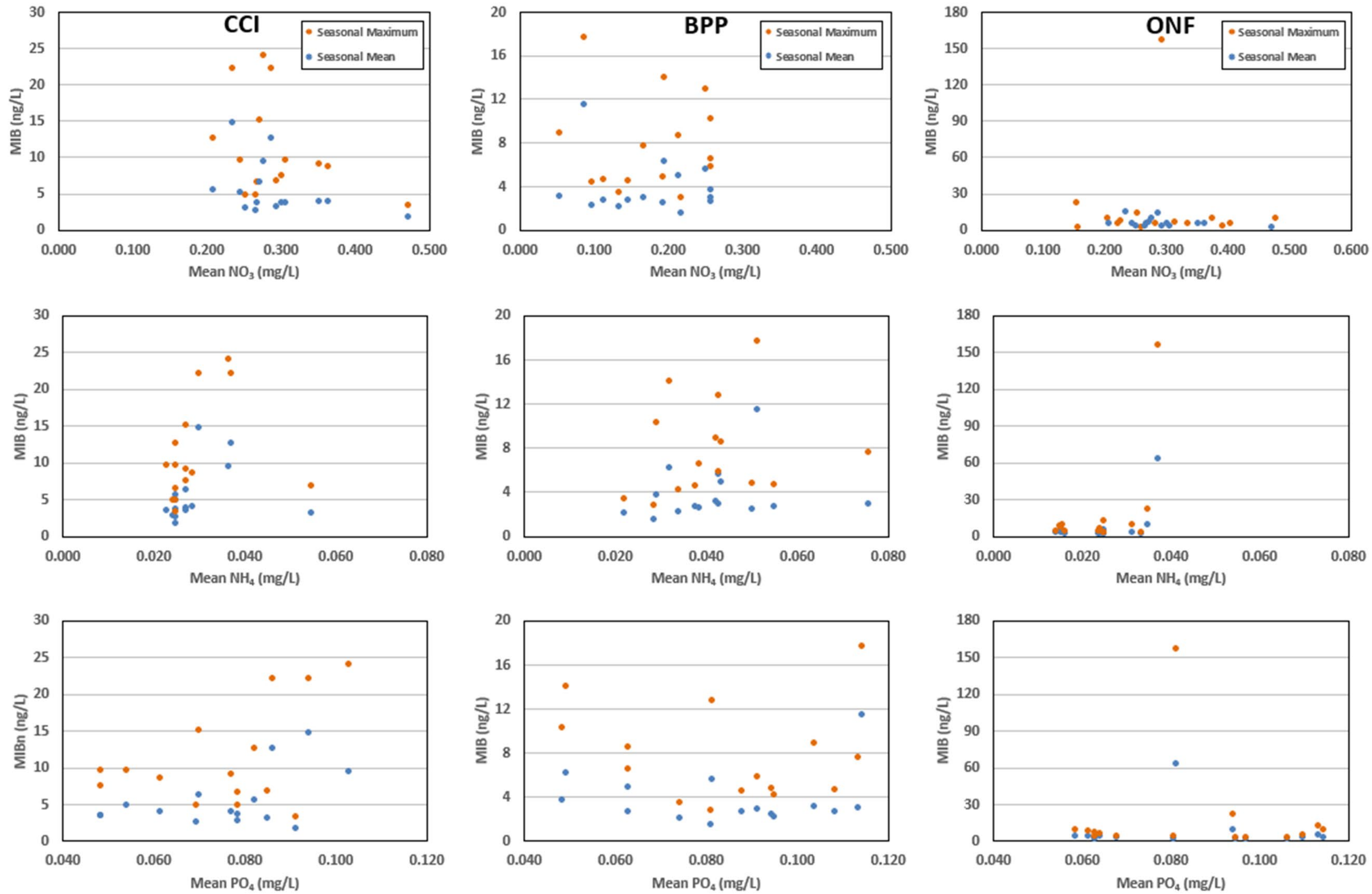

Figure 20 – Relationships between seasonal mean and maximum MIB and bioavailable nutrients during the POR. As described in the text, there were no statistically significant relationships between MIB and nutrients.

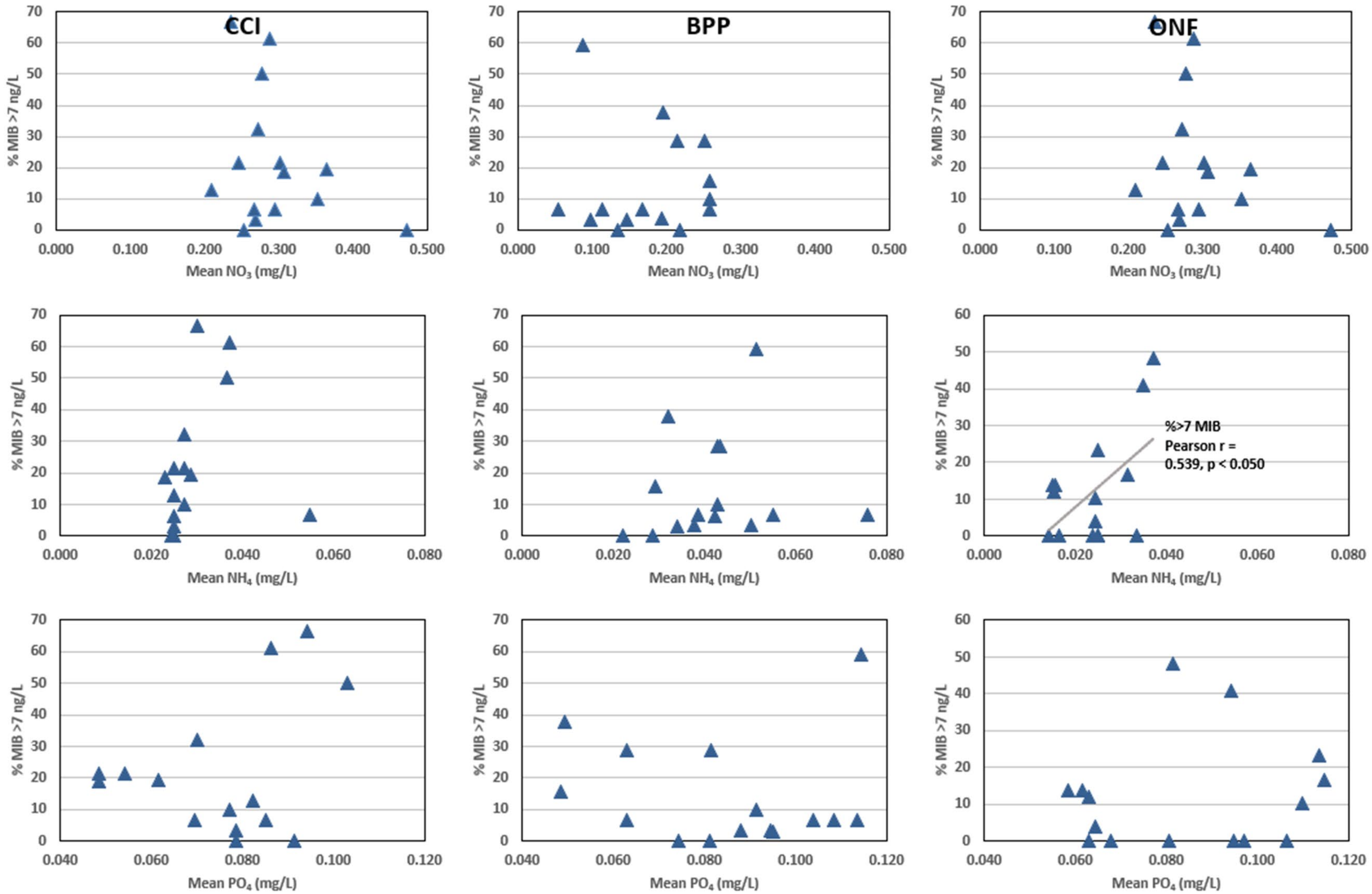

Figure 21 - Relationships between the frequency of elevated (>7 ng/L) seasonal MIB values and bioavailable nutrients during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

Other Environmental Parameters

Seasonal and Interannual Variation

Water temperatures followed a similar pattern in each T&O season with peak temperatures occurring in July and August (Figure 22). Early in the season, water temperatures declined as water flowed through the SWP (CCI > BPP > ONF) while temperatures later in the season were similar at all sites. Box plots showed the greatest interannual temperature variation early and late in the season. The highest temperatures during the T&O season were likely most favorable for cyanobacterial growth and possibly contributed to higher T&O production from mid-summer to early fall.

Specific conductance during the T&O season varied considerably among years, a reflection of the relative contribution of water sources with differing TDS to SWP flows (Figure 23). Average conductance was generally higher late in the season (September-November), possibly due to some combination of lower overall Delta flows, a decline in low-TDS snowmelt runoff, and an increased contribution of higher TDS water sources (seawater intrusion, pumped agricultural runoff) to water intakes later in the season. The connection between specific conductance and cyanobacterial growth is not clear, although freshwater cyanobacteria as a group are tolerant of higher TDS levels than many competing algal species.

Turbidity levels (Figure 24) were highest and most variable among years early in the T&O season, likely due to greater particulate resuspension from higher Delta flows in wetter years and possibly residual turbid winter runoff. During this period, turbidity levels tended to decline as water flowed through the SWP (CCI > BPP > ONF). By August, levels had declined to near or below 5 NTU at all sites and remained there for the remainder of the season. Therefore, light availability to planktonic and especially benthic cyanobacteria was higher and more predictable later in the T&O season. Greater light penetration favors increased aquatic primary production. However, cyanobacteria species vary widely in terms of their light requirements and, therefore, may exhibit different tolerances to turbidity-induced changes in light availability.

These three parameters tend to be intercorrelated. At CCI, seasonal specific conductance was positively related to water temperature (Pearson $r = 0.714$, $p < 0.010$) and inversely related to turbidity (Pearson $r = -0.762$, $p < 0.001$), and seasonal specific conductance and turbidity were also inversely correlated at BPP (Pearson $r = -0.551$, $p < 0.050$) and ONF (Pearson $r = -0.567$, $p < 0.050$).

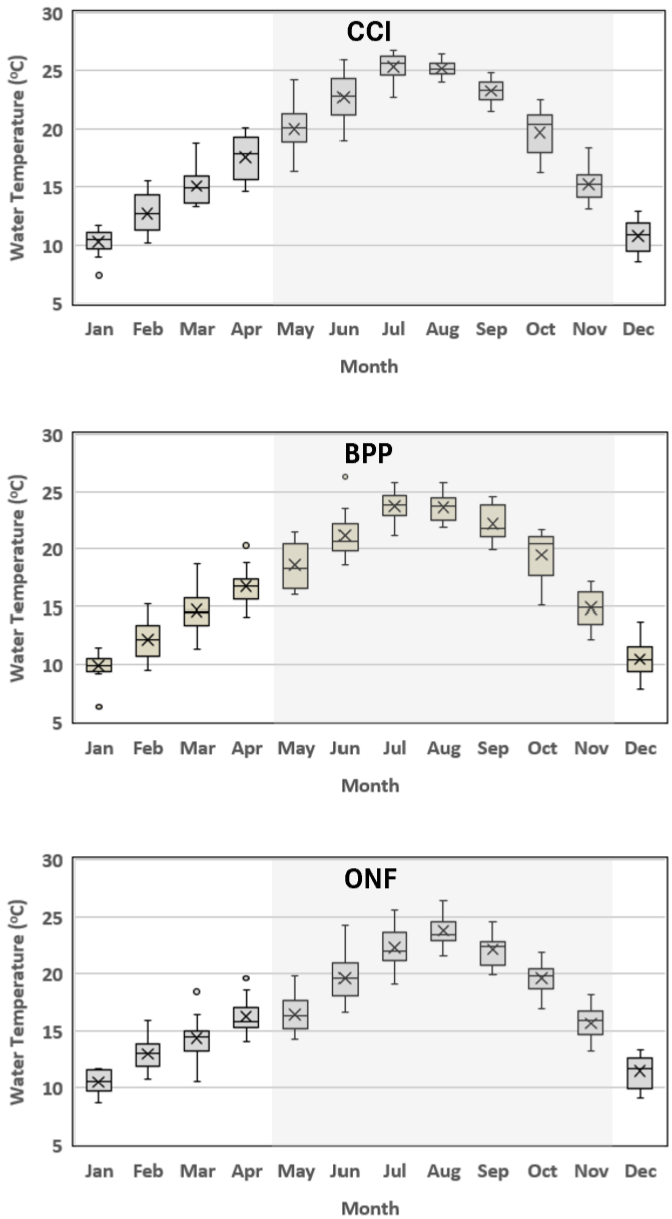

Figure 22 - Boxplots showing variation in monthly water temperature at each site during the POR. A description of boxplot elements is provided in Fig. 3. Monthly mean values are included in these boxplots and are shown as an "X" in each box. Gray shaded area denotes the T&O season.

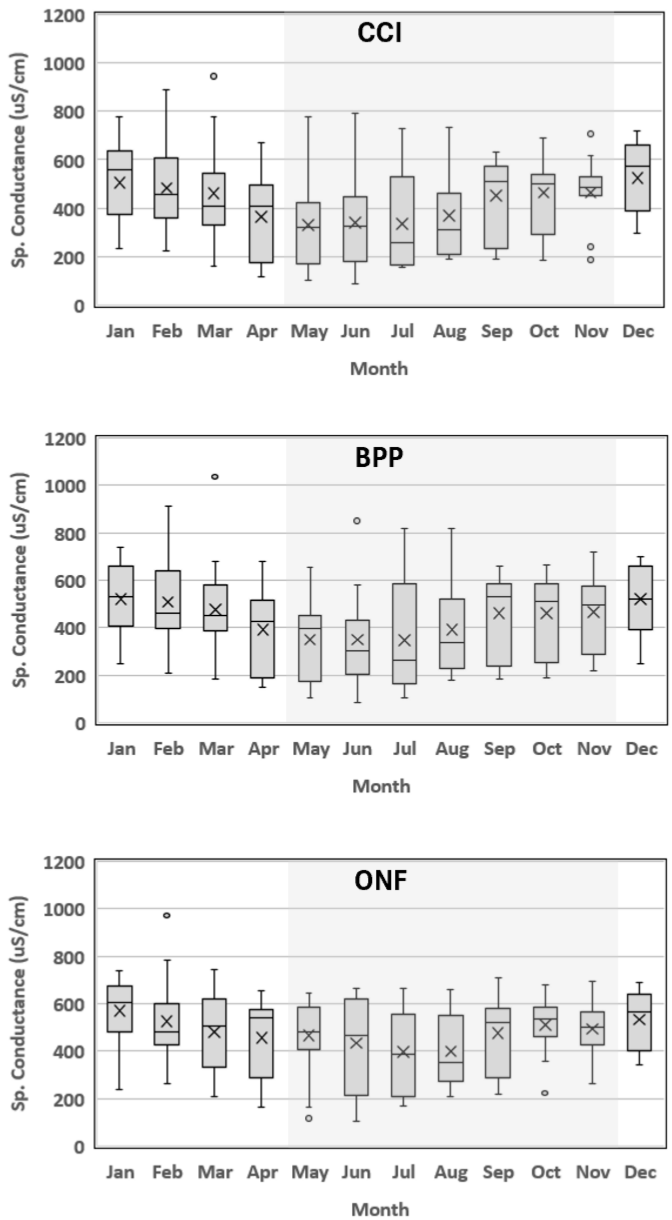

Figure 23 - Boxplots showing variation in monthly specific conductance at each site during the POR. A description of boxplot elements is provided in Fig. 3. Monthly mean values are included in these boxplots and are shown as an "X" in each box. Gray shaded area denotes the T&O season.

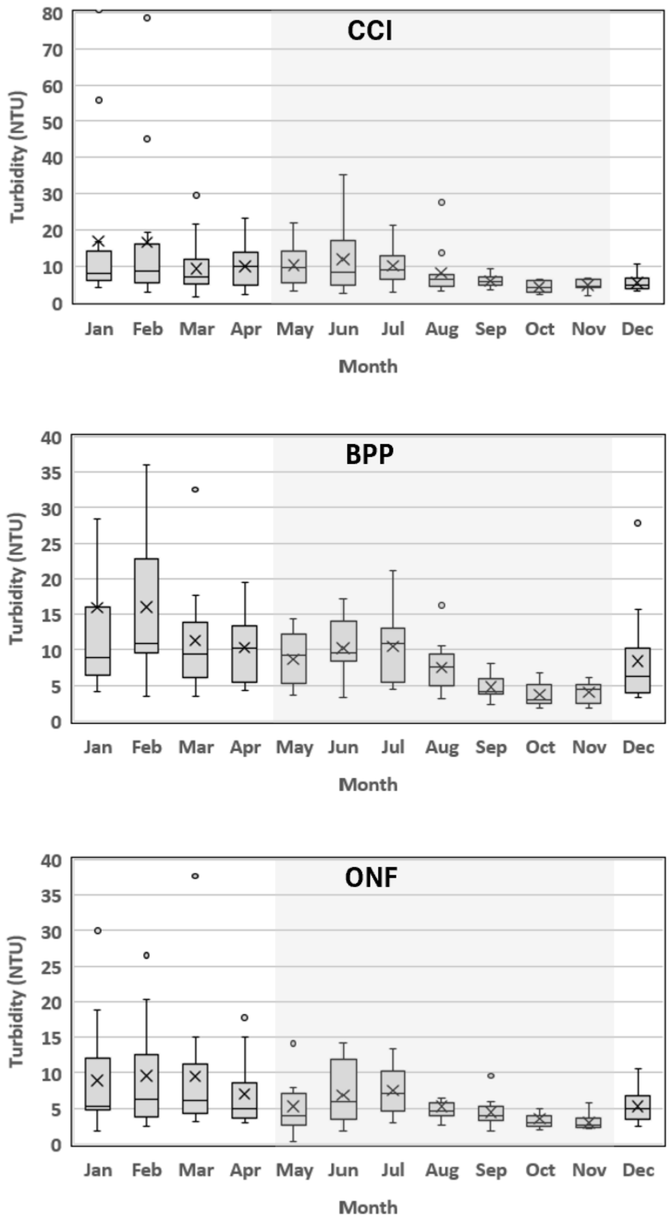

Figure 24 - Boxplots showing variation in monthly turbidity at each site during the POR. A description of boxplot elements is provided in Fig. 3. Monthly mean values are included in these boxplots and are shown as an "X" in each box. Gray shaded area denotes the T&O season.

Relationships between other Environmental Parameters and Hydrology

Levels of all three environmental parameters during the T&O season were significantly related to annual hydrology, particularly the WYI (Figure 25). Monthly correlations are shown in Table 4.

Temperature. Seasonal mean water temperatures at CCI (water entering from the Delta) were higher in drier years, although monthly means did not consistently follow this trend. The interannual range for mean temperature was approximately 1.5ºC. Temperatures at BPP and ONF were not related to any of the hydrologic indicators, indicating an influence of local conditions within the SWP. The interannual mean temperature ranges were also greater in the SWP, ranging from 2 to 2.5ºC.

Specific Conductance. Specific conductance was higher in drier years at all sites and was 3-fold higher in the driest vs the wettest years. This relationship was consistent throughout the T&O season. This variation reflects differences in the sources of Delta flows, possibly including greater marine (high TDS) influence and lower snowmelt (low TDS) influence in drier years.

Turbidity. Turbidity levels were higher in wetter years. Seasonal turbidity was 3-fold higher in Delta inflows (CCI) in wet vs dry years. This trend was also evident but less consistent at BPP and ONF, with lower peak turbidity levels and less variation between wet and dry years. Monthly correlations found this pattern to be fairly consistent throughout the T&O season at CCI, but the relationship was only significant during the first part of the season at BPP and ONF. Higher turbidity at CCI was likely due to increased runoff and sediment resuspension in the Delta, while resuspension of sediments within the aqueduct and forebays may also contribute to turbidity levels within the SWP.

Relationships between other Environmental Parameters and T&O Production

Geosmin at CCI. Seasonal geosmin concentrations at CCI were not significantly related to any of these three environmental parameters when the full POR was analyzed. As explained earlier, this lack of significance was due to data from 2023, an extremely wet year that also exhibited unusually high geosmin levels at CCI for such wet conditions. When this year was excluded from the analysis (reducing the dataset to a 14-yr POR), all three geosmin statistics at CCI were positively related to specific conductance and negatively related to turbidity and mean and maximum concentrations were positively related to temperature (Figures 26 and 27). Geosmin relationships to turbidity were strongest early in the T&O season (Table 5) when interannual variation in turbidity levels were generally greatest. Monthly relationships were not significant for temperature or specific conductance.

Geosmin at BPP. In contrast to CCI (the inlet to CCF), seasonal geosmin concentrations at BPP (the outlet of CCF) were not significantly related to any of these environmental parameters (Figures 26 and 27), suggesting that water quality conditions within CCF were influencing conditions at BPP. Monthly relationships (Table 5) were rarely significant, and a significant negative relationship between BPP geosmin and turbidity in May was likely a downstream consequence of the same relationship at CCI.

Geosmin at ONF. While there were no significant relationships between geosmin concentrations and these environmental parameters at ONF, the highest mean and maximum concentrations occurred in years with the highest specific conductance and lowest turbidity (Figure 26).

MIB at CCI. All three seasonal MIB statistics were positively correlated with specific conductance and negatively correlated with turbidity, and mean MIB concentrations were positively correlated with temperature (Figures 28 and 29). Monthly correlations showed the relationships with specific conductance and turbidity to be consistent during the T&O season while the relationship with temperature was only statistically significant in August (Table 5).

MIB at BPP. Seasonal MIB concentrations at BPP were not significantly related to any of these environmental parameters, again suggesting an influence of CCF on BPP water quality. As mentioned earlier, this influence was likely in the form of dilution of higher MIB water from CCI with lower MIB water in CCF during transit to BPP.

MIB at ONF. Seasonal mean and maximum MIB concentrations at ONF were not significantly related to any of these environmental parameters (Figure 28), but the frequency of elevated concentrations was negatively related to temperature and positively related to specific conductance (Figure 29). Monthly correlations showed that this relationship was strongest at the end of the T&O season (Table 5). Monthly MIB concentrations were significantly correlated with higher turbidity towards the end of the T&O season. The negative correlation with temperature and positive correlation with turbidity is counterintuitive to the known environmental preferences of cyanobacteria but may reflect the complex hydrology of O’Neill Forebay and the temperature and turbidity differences among its multiple water sources (CA Aqueduct, Delta-Mendota Canal, and San Luis Reservoir) that vary in their water contributions to ONF depending on water operations.

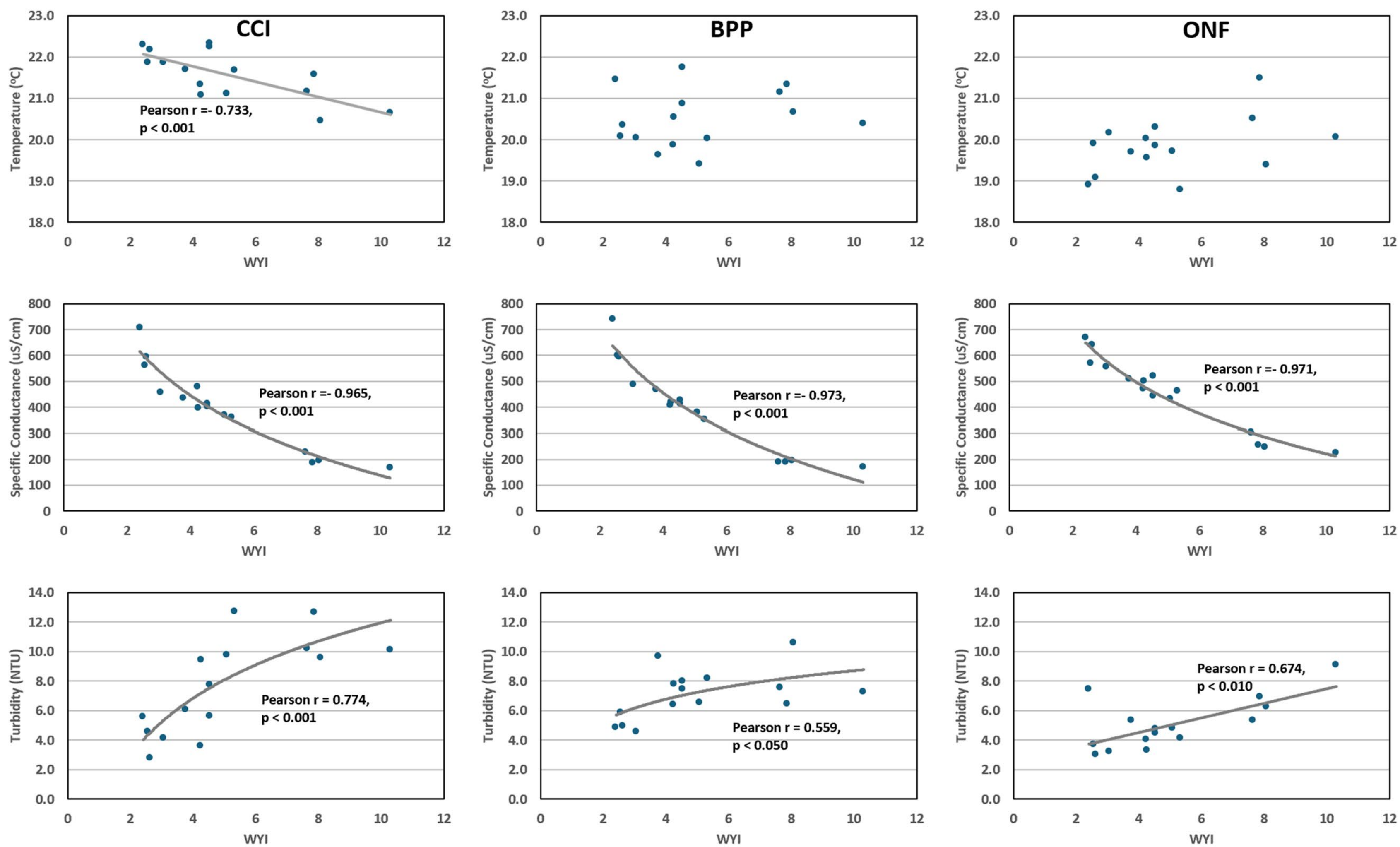

Figure 25 - Statistical relationships between seasonal water temperature, specific conductance, and turbidity and WYI at each site during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

Temperature							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.687	-----	-----	-0.678L	-----	-----	-----
SPWA	-----	-----	-----	-0.601	-----	-----	-----
Pumping	-----	-----	-----	-0.744	-----	-----	-0.609L
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	0.538L	-----	-----	-----	-----
SPWA	-----	-----	-----	-----	-----	-----	0.580
Pumping	-----	-----	-----	-----	-----	-----	0.853L
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	0.643	-----	-----	-----	-----	-----
SPWA	-----	-----	-----	-----	-----	-----	-----
Pumping	-----	-----	-----	-----	-----	-----	-----
Specific Conductance							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.884L	-0.927L	-0.898L	-0.914L	-0.844	-0.953	-0.823
SPWA	-0.716	-0.828	-0.852L	-0.808	-0.666	-0.850	-0.810
Pumping	-0.719L	-0.809L	-0.889L	-0.809	-----	-----	-----
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.937L	-0.896L	-0.870L	-0.918L	-0.899	-0.925	-0.915L
SPWA	-0.795	-0.796	-0.806L	-0.809	-0.772	-0.781	-0.831
Pumping	-0.798L	-0.809	-0.879L	-0.837	-0.547	-----	-0.592L
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-0.866	-0.911	-0.876L	-0.936L	-0.924	-0.872	-0.916L
SPWA	-0.744	-0.811	-0.818	-0.857	-0.835	-0.755	-0.782
Pumping	-0.750	-0.738	-0.772L	-0.894L	-0.858	-0.769	-0.809
Turbidity							
CCI	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	0.610L	0.798L	0.586	0.788	-----	0.542L
SPWA	0.548L	0.581L	0.777	0.619	0.766	-----	0.604L
Pumping	-----	0.623L	0.632	-----	-----	-----	-----
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	-----	0.530L	0.530L	-----	-----	-----
SPWA	-----	0.638L	0.578L	-----	-----	-----	-----
Pumping	-----	0.623L	0.700	-----	-----	0.597	-----
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WYI	-----	0.871	0.631L	0.564	-----	-----	-----
SPWA	-----	0.746	0.739	-----	-----	-----	-----
Pumping	-----	0.684	0.630	-----	-----	-----	-----

Table 4 - Correlations between monthly mean water temperature, specific conductance, and turbidity during the T&O season and hydrologic indicators. Only significant (p<0.050) are shown. An L next to the correlation coefficient indicates that a logarithmic instead of a linear regression model was used.

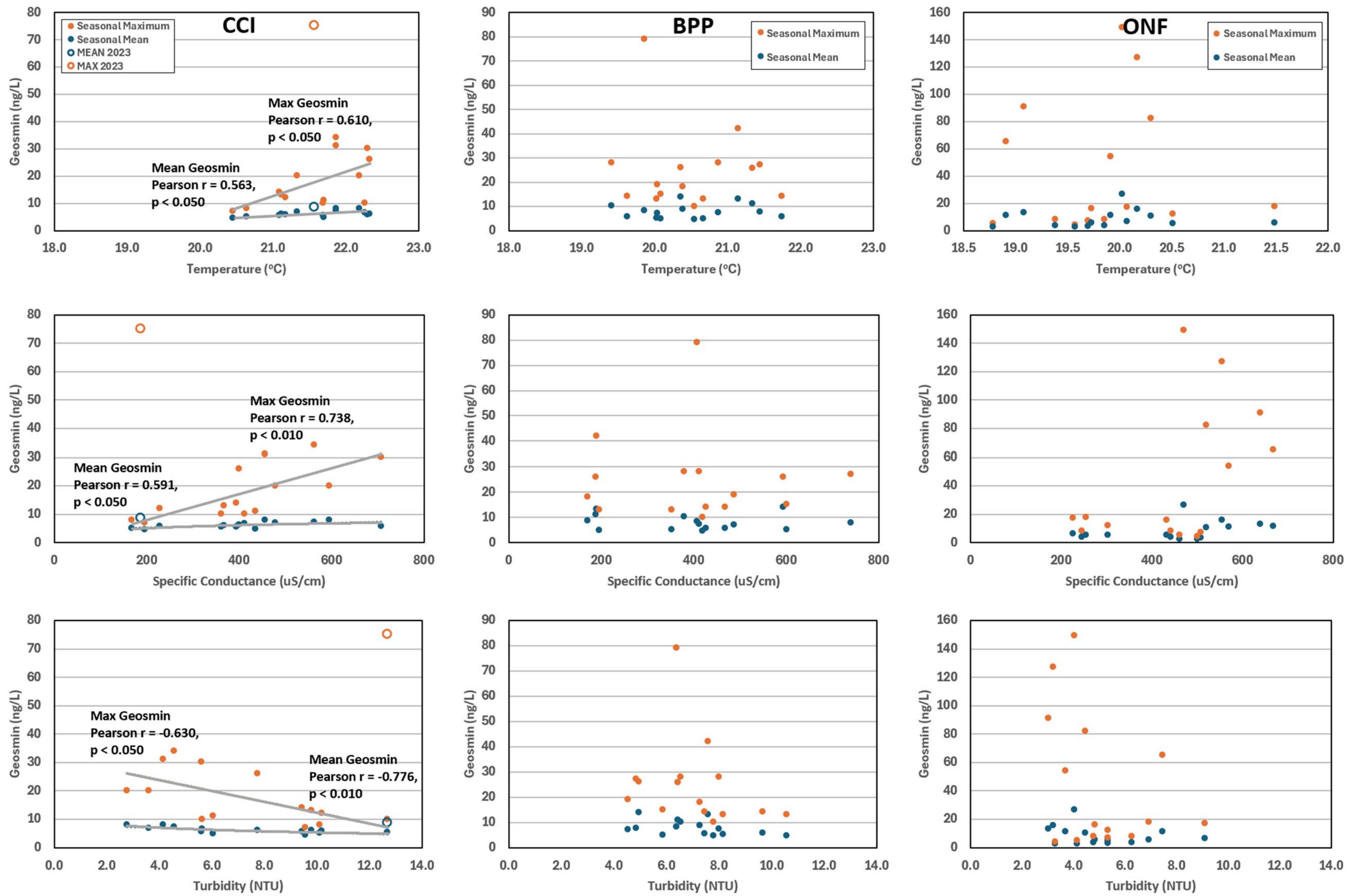

Figure 26 - Statistical relationships between seasonal mean and maximum geosmin and water temperature, specific conductance, and turbidity during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

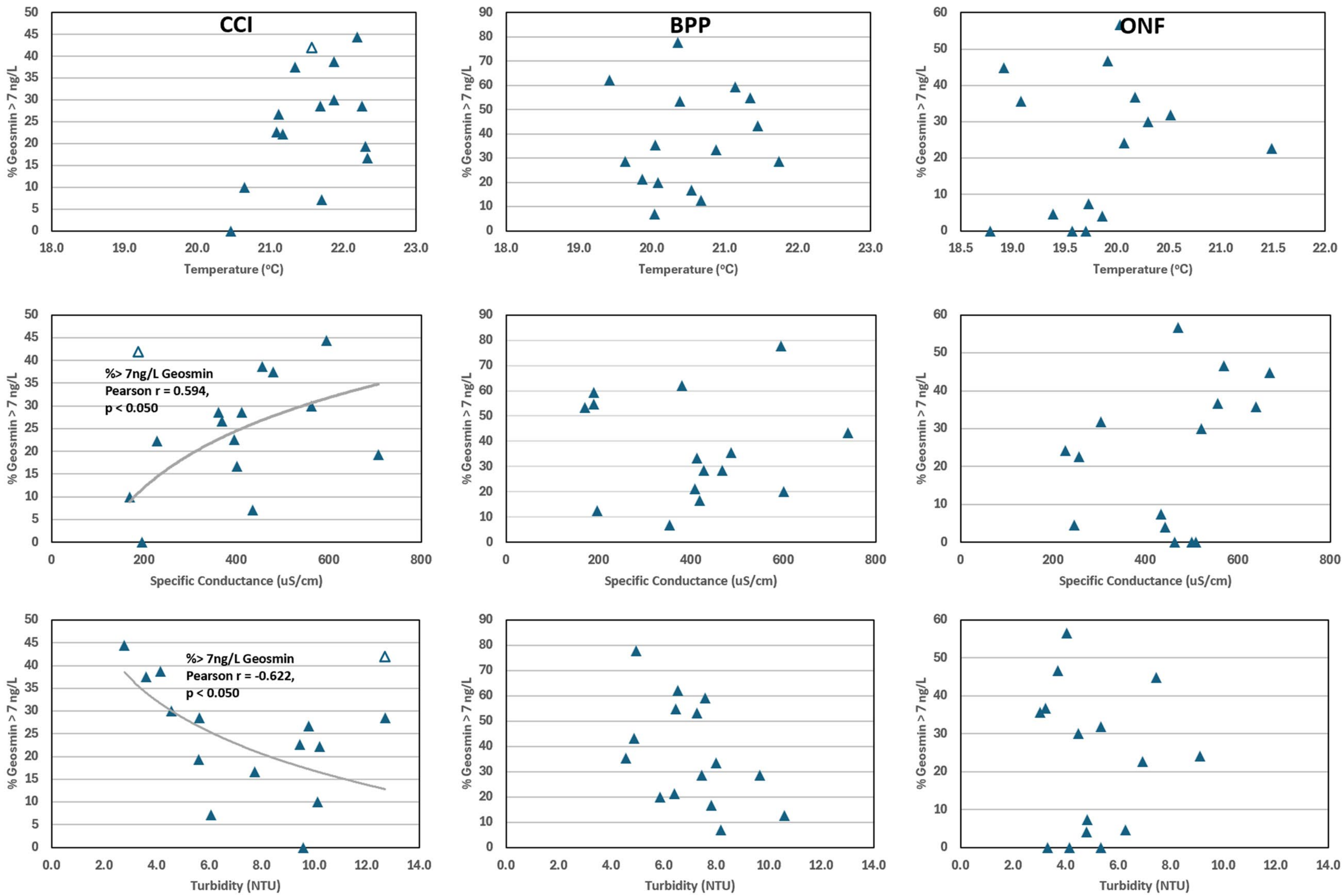

Figure 27 – Statistical relationships between the frequency of elevated (>7 ng/L) seasonal geosmin values and water temperature, specific conductance, and turbidity during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

GEOSMIN							
CCl	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
SpCond	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Turbidity	-0.913L	-0.714L	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
CClex'23	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
SpCond	- - - - -	- - - - -	0.708L	- - - - -	- - - - -	- - - - -	- - - - -
Turbidity	-0.913L	-0.777L	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
SpCond	- - - - -	- - - - -	- - - - -	- - - - -	-0.614L	- - - - -	- - - - -
Turbidity	-0.622	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
SpCond	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Turbidity	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
MIB							
CCl	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp	- - - - -	- - - - -	- - - - -	0.562	- - - - -	- - - - -	- - - - -
SpCond	0.549L	0.865	0.854	0.761	- - - - -	0.662	0.588
Turbidity	-0.802L	-0.657L	-0.695L	- - - - -	-0.584L	- - - - -	-0.666L
BPP	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
SpCond	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	0.574
Turbidity	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
ONF	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	-0.534L
SpCond	- - - - -	- - - - -	- - - - -	0.662	- - - - -	- - - - -	0.533
Turbidity	- - - - -	- - - - -	- - - - -	- - - - -	0.751	0.836	0.779

Table 5 - Correlations between monthly mean T&O concentrations and monthly mean water temperature, specific conductance, and turbidity during the T&O season. Only significant (p<0.050) are shown. An L next to the correlation coefficient indicates that a logarithmic instead of a linear regression model was used.

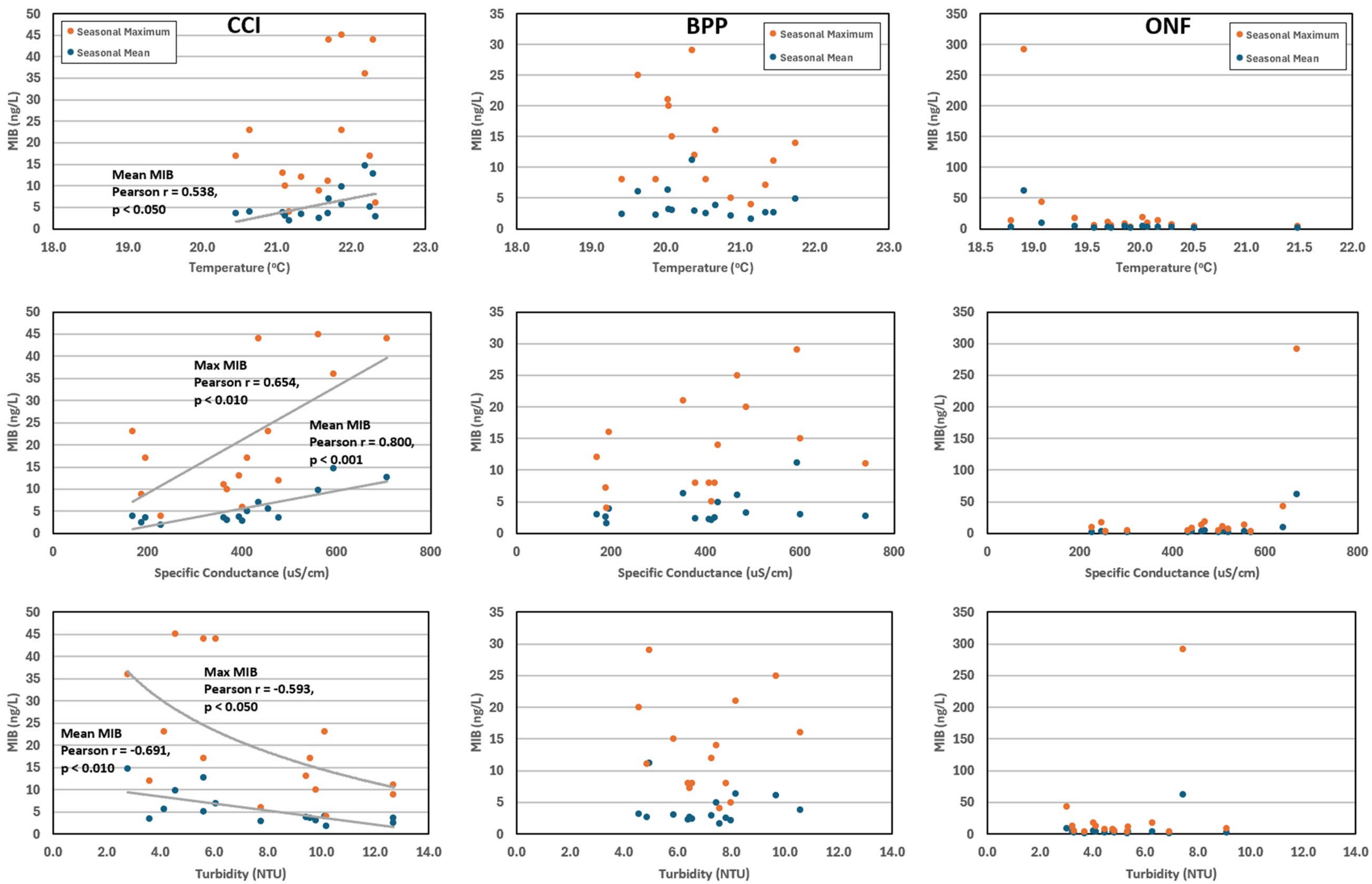

Figure 28 - Statistical relationships between seasonal mean and maximum MIB and water temperature, specific conductance, and turbidity during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

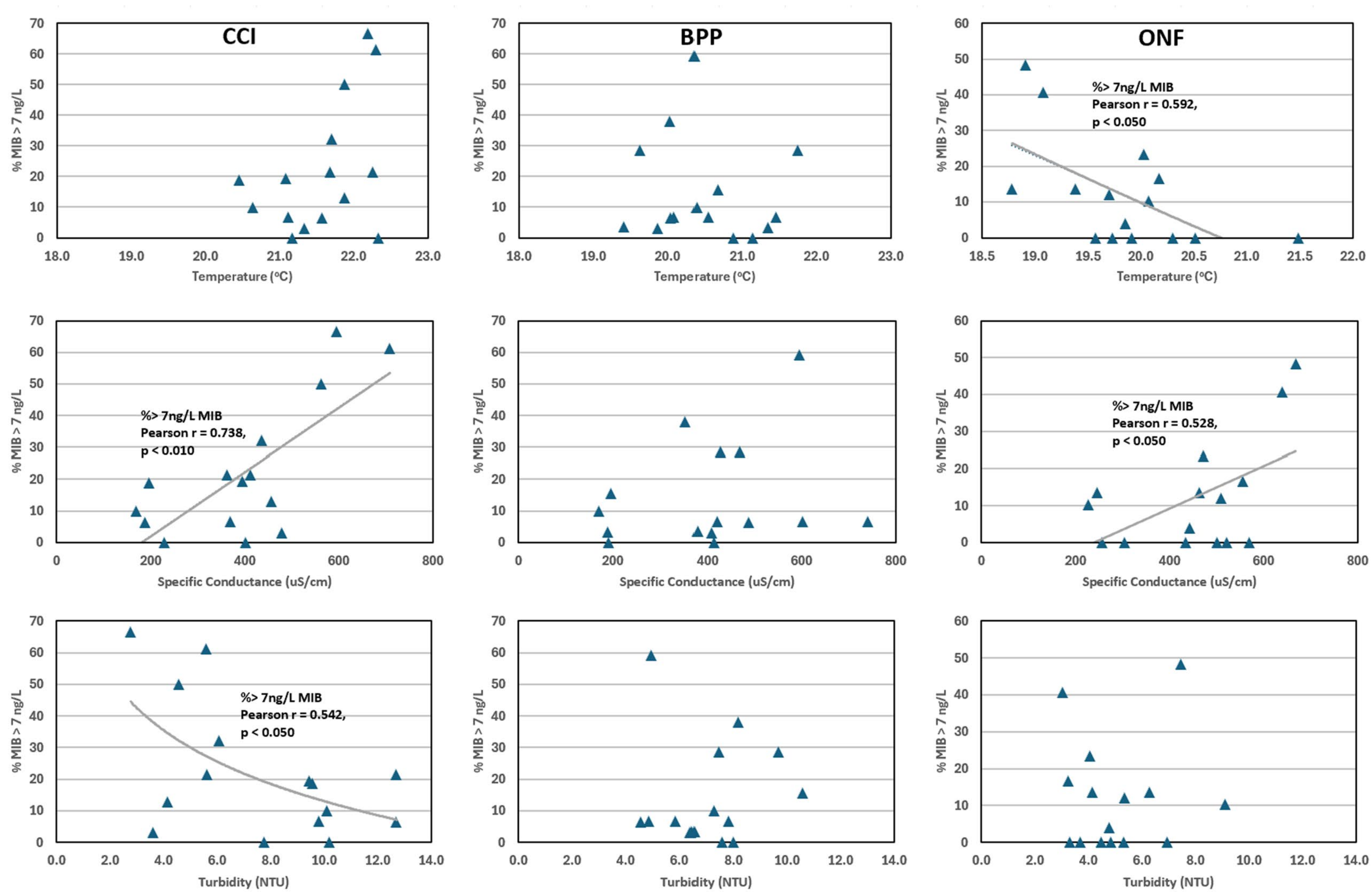

Figure 29 - Statistical relationships between the frequency of elevated (>7 ng/L) seasonal MIB values and water temperature, specific conductance, and turbidity during the POR. Gray lines show statistically significant relationships with the statistical significance and correlation coefficient displayed on the graph. Graphs without statistical information indicate no significant relationship.

Summarizing Environmental-T&O Relationships

The conceptual diagram presented in Figure 2 is modified in Figure 30 to graphically depict the relative strength of interannual T&O-environmental relationships on a site-specific basis. It is important to recognize that these diagrams are based on correlative associations and do not establish cause-effect pathways. It is likely that some of the associations are "spurious" in the sense that a particular parameter may be simply associated with T&O production because it also happens to be associated with another variable that does affect T&O production.

With the above caveat in mind, the site-specific graphics show that T&O-environmental relationships vary among the three sites as follows.

CCI. Seasonal geosmin and MIB concentrations at CCI are most closely associated with interannual variation in Delta-SWP hydrologic indicators and other environmental parameters (temperature, specific conductance, and turbidity) that are also related to hydrology. Nutrient levels are not closely tied to T&O at this site. Thus, the risk of elevated T&O concentrations at CCI is best anticipated using a hydrologic indicator such as the SWPA, which is known prior to the start of T&O season. For example, a lower SWPA could be used to indicate greater risk of T&O issues in the following T&O season.

BPP. Seasonal geosmin and MIB concentrations at BPP were not associated with hydrology. Geosmin concentrations were positively associated with PO_4 concentrations, but this relationship is subject to the alternate interpretations that it either directly influences T&O or that it is simply an indicator of other conditions that affect BPP geosmin (see Discussion). It is difficult to anticipate annual T&O risk at BPP with currently available data, probably because BPP T&O concentrations are strongly influenced by conditions in CCF, which is not currently monitored for water quality.

ONF. Relationships between T&O concentrations and environmental conditions at ONF are the most complicated, likely due to the complex hydrology involving multiple water sources at this site. Seasonal concentrations of geosmin and, to a lesser extent, MIB have some association with hydrologic indicators and weak associations with related environmental parameters (specific conductance and turbidity), indicating that the risk of T&O issues is greater in drier years. However, as already noted, elevated T&O concentrations at ONF are sporadic even in dry years, making the association with hydrology weaker. There may be other triggers, perhaps related to San Luis Field Division operations, that determine whether a particular dry year will have T&O issues. Associations between nutrients and T&O levels at ONF are more pronounced than at BPP and subject to the same issues of interpretation since nutrients levels could simply be an indicator of other T&O influences. It is likely that some of these nutrient associations are not causal in nature (e.g., lower NO_3 concentrations in dry years may be due to microbial NO_3 reduction in anoxic forebay sediments rather than having any direct connection to elevated geosmin concentrations that can occur in these years).

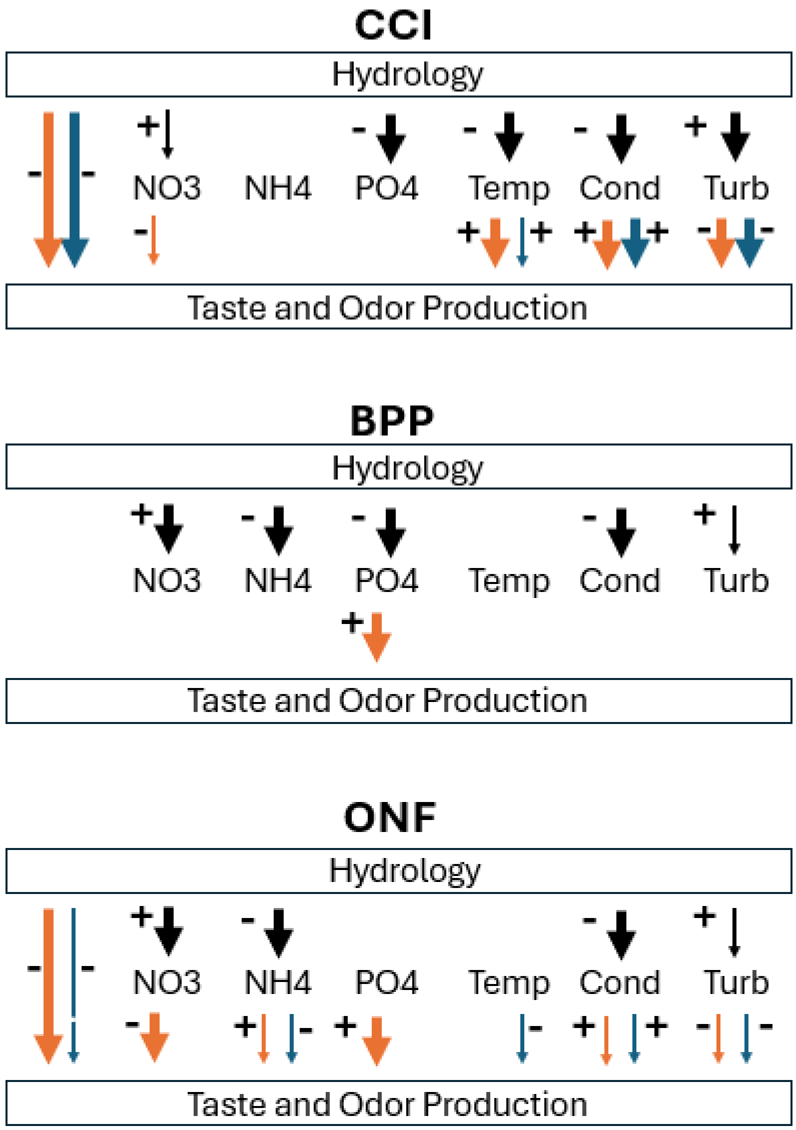

Figure 15 -Conceptual diagram of environmental-T&O relationships for each site based on analyses presented in this report. The strength of each relationship (based on graphical and statistical analysis) is shown as follows: thick arrows = stronger relationship; thin arrows = weaker relationship, no arrow = no relationship. Color coding of arrows: black = a relationship between two environmental parameters; orange = a relationship between geosmin levels and an environmental parameter; blue = a relationship between MIB levels and an environmental parameter. The + and – signs indicate whether a particular relationship is positive or negative.

DISCUSSION

Elevated levels of geosmin and MIB are frequent enough at sites CCI, BPP, and ONF (e.g., geosmin and MIB concentrations >7 ng/L were detected in as many as 22% and 13% of all samples, respectively, during the POR) to pose periodic issues for downstream drinking water treatment operations. Affected utilities have developed a sense that these issues may be more likely at certain times, e.g., during the warmer months of the year and during drier years. The goal of this analysis was to establish the strength of these and other patterns so that utilities can better anticipate when the risk of T&O issues is greatest. Taste-and-odor patterns at these three sites were found to be similar to those in other parts of the SWP in the following respects: (1) both geosmin and MIB production exhibit a repeatable seasonal pattern where T&O concentrations are elevated during the summer and fall and low during the winter and spring; (2) the prevalence and intensity of T&O production vary substantially among years; (3) each site has unique seasonal T&O patterns, indicating differences in the factors affecting T&O concentrations among the hydrologic units represented by each site (the Delta (CCI), Clifton Court Forebay (BPP), and O'Neill Forebay (ONF)).

Seasonality was the most reliable indicator of T&O risk to utility operations because elevated T&O concentrations at all sites during the 15-year POR were essentially restricted to the months May-November. This well-defined T&O season as well as variation in T&O levels during this season were most closely aligned with the predictable seasonality in water temperature, which is known to be a key factor regulating cyanobacteria activity. Specifically, this is the seasonal window when water temperatures are warm enough to favor dominance by cyanobacteria over other competing algal species. For example, based on their review of Delta-relevant literature, Berg and Sutula (2015) proposed a threshold of 19ºC above which the relative growth rates of cyanobacteria are increasingly likely to exceed those of common Delta algae. As shown in temperature boxplots for the sites in this study (see Figure 22), monthly water temperatures begin exceeding this threshold in the April-May timeframe and decline below the threshold in November. Taste-and-odor production during November and, rarely, December (ONF) when monthly water temperatures have cooled below this threshold may reflect the final phase of fall T&O events. Seasonality in cyanobacteria activity in temperate zone waterbodies (which includes the Sacramento-San Joaquin Delta) has been attributed to both higher water temperatures and to other factors such as higher solar radiation during the summer and fall as well as lower flows during this period, which is often the driest part of the year in this climate zone. While solar irradiance follows a repeatable annual cycle, many other factors such as water clarity and shading affect underwater light availability, and light requirements vary greatly among the types of cyanobacteria (e.g., planktonic vs benthic) responsible for T&O production. Therefore, the influence of seasonal light availability on cyanobacteria is more complicated than the predictable seasonal variation in water temperature. And, while the summer and fall are the driest seasons in the Delta watershed, the hydrology of the Delta-SWP system is regulated for water supply based on annual hydrologic conditions such that flows during the "dry season" vary considerably among years. Thus, water temperature is likely the main determinant of the predictable T&O season identified here.

Predicting the level of T&O production during a particular T&O season is challenging for various reasons: (1) the environmental triggers contributing to T&O events are poorly understood; (2) environmental data typically collected by routine monitoring programs may not be good indicators for these environmental triggers; (3) the spatial scale of monitoring may be too coarse to characterize local conditions where T&O production occurs. The current analysis is further limited by the lack of taxonomic data to identify potential cyanobacteria species responsible for T&O production (discussed further below). Despite these limitations, some insight was gained from the present analysis to identify years when T&O risk is greatest in this part of the SWP. First, while temperature was likely the major factor determining seasonality in T&O production (i.e., when production *might* occur), this parameter was not especially useful for anticipating whether elevated production *will* occur during a particular T&O season. Among the environmental parameters considered here, hydrologic conditions provided the best indicator of seasonal T&O levels at sites CCI and ONF with higher concentrations in dry years vs wet years. Hydrology can influence cyanobacteria both directly (e.g., water velocity and turbulence) as well as indirectly through its effect on other environmental factors such as nutrients (potentially limiting resources) and turbidity (light availability). In the Delta, watershed hydrologic conditions also affect the importance of different water sources to the SWP; this variation in sources influences water TDS (measured here as specific conductance), which may have some influence on cyanobacteria. Data available for this analysis do not allow for these potential effects of hydrology on T&O production to be separated. Regardless, it can be concluded that hydrologic indicators such as the final SWPA (usually provided by DWR in April) can provide a useful tool for forecasting potential T&O risks during the upcoming T&O season.

Nutrient availability is recognized as a key regulator of cyanobacterial growth, but the strength of this relationship depends on the frequency with which N and/or P becomes growth limiting in a particular waterbody. Taste-and-odor concentrations were related to nutrient levels at the two sites located within the SWP (BPP and ONF), but the interpretation of these relationships must consider: (1) the high (non-limiting?) ambient N and P levels in all years; and (2) the potentially confounding relationship between bioavailable nutrient levels and hydrology at these sites. Using the trophic classification system proposed by Dodds et al. (1998) as an example, the nutrient status of Delta-SWP waters has been classified as eutrophic (highly enriched) based on TP concentrations and mesotrophic (moderately enriched) based on TN concentrations (Palencia Consulting Engineers and Starr Consulting, 2022). This previous assessment is consistent with the high bioavailable nutrient levels at the sites examined here. Bioavailable P levels were always high and unlikely to be an important limiting factor. Bioavailable N levels were also high in the winter but showed a predictable decline during the T&O season, suggesting the possibility of seasonal N limitation. Cyanobacteria have evolved various adaptations to grow under N-limiting conditions such as might occur during the summer in the Delta; for example, one of the most common planktonic T&O producing genera identified in the SWP, *Dolichospermum*, has the capacity to fix atmospheric N if this nutrient becomes limiting to growth. Benthic cyanobacteria are likely responsible for some of the T&O production at the sites investigated here, and these organisms have access to sediment nutrient pools and, therefore, are less dependent on nutrients in the overlying water. Higher levels of bioavailable N (NH_4) and P (PO_4) fractions during dry years may be due to internal nutrient loading from Delta and forebay sediments that are more likely to become anoxic (releasing these soluble nutrients) during low flow conditions associated with droughts. This hypothesis is also consistent with lower NO_3 concentrations during dry years, a possible consequence of NO_3 loss (denitrification) processes in anoxic sediments. To the extent that T&O production is favored by dry conditions, any association between nutrients and T&O may simply be due to their common relationships with hydrology. Regardless, high nutrient levels certainly predispose the Delta-SWP system to cyanobacteria issues such as T&O production, with the actual occurrence of these issues being regulated by other factors related to hydrology (e.g., Lehman et al. 2022) and light availability (e.g., Jassby et al. 2002).

While all sites exhibited a similar seasonal pattern of T&O production -- indicating the importance of a common regulator such as water temperature – interannual relationships between environmental conditions and T&O production differed among sites. Most striking was the disconnect between annual T&O patterns at CCI, which were associated with hydrologic conditions and related factors (temperature, specific conductance, and turbidity), and T&O patterns at BPP, which were unrelated to hydrologic factors. Differences in T&O relationships between these two monitoring sites result from the mixing of Delta inflows at CCI with the large volume of water (capacity of ~31,000 AF) stored within CCF. The CCF is a biologically active basin that supports both significant SAV production requiring active management and, based on historical satellite imagery (My Water Quality: California Harmful Algal Blooms (HABs)), seasonal cyanobacteria blooms that may include T&O producers. A previous study of circulation patterns in CCF (MacWilliams and Gross, 2013) supports a contrary view that water quality conditions at BPP result from the mixing of water entering from the Delta through CCI and water already detained within CCF, which has a water quality influenced by biological activity within the basin. Based on T&O differentials between the two sites (Figures 6 and 7), it is apparent that CCF is a primary source of elevated geosmin at BPP. By contrast, the Delta is likely the major source of MIB at BPP, and the lower levels typically measured at BPP vs CCI can be attributed to the dilution of Delta-produced MIB with water from CCF. Given that elevated T&O levels at BPP are of particular concern to the SWC, an understanding of T&O-season water quality in CCF is needed to better anticipate T&O risk to downstream utilities. Specific recommendations are provided in the Conclusions section below.

The outlet site ONF also exhibits unique T&O patterns, likely due to the influence of O'Neill Forebay, which has a larger surface area than many SWP reservoirs and is influenced by multiple water sources and complex operations. As for CCI, ONF tended to have the highest T&O levels during dry years; however, T&O issues were less frequent at ONF and, when they did occur, had the potential to be more intense. Hydrologic operations of the San Luis Field Division were not accounted for in this analysis and, as for CCF, there is no information on internal T&O production within this large basin. As for BPP, a better understanding of environmental conditions within the forebay itself is needed to better understand T&O patterns at the monitoring site ONF. Thus, similar recommendations to those for CCF are made for this forebay in the Conclusions section below.

As already noted, a major limitation to understanding T&O patterns at these monitoring sites is the lack of information on the organisms responsible for producing geosmin and MIB at different times and locations. Both planktonic and benthic cyanobacteria have been identified as T&O producers within the SWP, and it is likely that both growth forms contribute to T&O production at the sites analyzed here. For example, satellite imagery of CCF and ONF (My Water Quality: California Harmful Algal Blooms (HABs)) document T&O-season growth of planktonic cyanobacteria, which may include T&O producers. Unfortunately, benthic cyanobacteria cannot be detected by remote sensing and require "on-the ground" sampling methods for detection. These two growth forms respond differently to environmental conditions as they are exposed and adapted to different light regimes, have preferential access to different nutrient sources (sediment vs water), and respond differently to hydrologic conditions such as water flow. A clearer picture of T&O-environmental relationships would be gained if planktonic and benthic T&O production could be considered separately in a future analysis.

CONCLUSIONS AND RECOMMENDATIONS

The following patterns were identified in this analysis:

(1) Elevated T&O levels in this portion of the Delta-SWP occur during the period May-November and are most closely aligned with water temperature. The frequency and intensity of T&O production and, therefore, the level of risk to utility operations vary within this seasonal window, and these risks could be further parsed with additional analysis of the existing data set.

(2) There was no consistent relationship between interannual variation in T&O production and environmental conditions across all sites, but there was evidence that elevated T&O levels are more likely in dry vs wet years based on statistical associations of T&O with hydrology and other environmental parameters correlated with hydrology. Among the environmental parameters considered here, the SWPA provides the best annual forecasting tool to anticipate the risk of T&O issues in the upcoming T&O season at CCI and ONF. Continued monitoring through another wet-dry cycle would help further establish the relationships between T&O and hydrology and test the ability to forecast seasonal T&O production.

(3) Interannual T&O patterns are site specific to varying degrees. Most notably, T&O levels at CCI (CCF inlet) were associated with interannual variation in hydrology, while levels at BPP (CCF outlet) were unrelated to hydrologic conditions. Environmental relationships with T&O were most complicated at ONF where all environmental parameters were to some degree associated with geosmin and/or MIB production. This inter-site variation might be explained with information on hydrologic and water quality conditions within the major forebays upstream of BPP and ONF that are likely sources of T&O production. For example, better forecasting of T&O issues at BPP would benefit from a new monitoring station to collect T&O and other water quality data within CCF in the same manner as is currently being done at CCI and BPP. Near-term forecasting of potential T&O issues could also be performed using remote sensing such as satellite imagery (My Water Quality: California Harmful Algal Blooms (HABs)) in conjunction with (not as a substitute for) routine T&O sampling. Similar data collection efforts are recommended for the ONF forebay to the extent that T&O issues at ONF -- which can occasionally be severe – pose a risk to SWC utility operations. A more detailed analysis of T&O patterns at ONF should also include hydrologic data from all potential inflow and outflow points.

(4) Following from (3), there are clearly multiple sources of T&O production in this portion of the SWP, including (but perhaps not limited to) the Delta, CCF, and the ONF forebay. Knowledge of these sources is important from both a monitoring and forecasting perspective as well as in the event where future circumstances require active T&O management, because successful T&O management must target the source of T&O production.

(5) A major limitation to the present analysis was a lack of information on the cyanobacteria responsible for T&O production in this part of the Delta-SWP because individual cyanobacteria species respond differently to environmental conditions. Efforts should be made to identify the organisms responsible for T&O production at different locations and times within the T&O season. An understanding of the contribution of planktonic vs benthic cyanobacteria to T&O issues is especially important from a T&O forecasting and management perspective.

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