INTERNATIONAL STORMWATER BMP DATABASE
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International Stormwater Best Management Practices (BMP) Database Advanced Analysis:

Influence of Design Parameters on Achievable Effluent Concentrations

Prepared by
Geosyntec Consultants, Inc.
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1 INTRODUCTION

One of the fundamental long-term goals of the International Stormwater BMP Database (BMPDB) is to provide a source of information to practitioners on the relationship between performance and various BMP design parameters. Statistical analysis of the BMPDB to date has been primarily focused on performance of BMP types (e.g. wet ponds, buffer strips) by summarizing influent and effluent concentration statistics along with some limited analysis of volume reduction.

Given significant growth of the BMPDB, the Project Team has reviewed the available design information stored in the BMPDB for various BMP types to assess the potential for more detailed analysis to relate performance to specific BMP design variables. This report provides the results of this effort, including:

- Identifying major design factors for several BMP types that are expected to influence performance.
- Summarizing the availability of design information for studies in the BMPDB as of March 2013 for BMP types with substantial data.
- Describing the analyses used to explore relationships between various design parameters and BMP performance, within the constraints of the available data set.
- Discussing the results of the statistical analysis conducted with respect to these design factors.

This analysis should be considered exploratory, as it is intended only to identify whether or not relationships between design and performance potentially exist. The analysis and development of specific functional relationships (e.g., regression equations) between design variables and water quality performance is outside the scope of this current effort. The statistical procedures used in this document are similar to those used in previous BMPDB analysis efforts, including the use of the regression-on-order statistics (ROS) method for handling non-detects (Helsel and Cohn, 1988) and the bias corrected and accelerated method (BCa) bootstrap method for computing confidence intervals (Efron and Tibishirani, 1993). See the Technical Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals Report (Geosyntec Consultants and Wright Water Engineers, 2012a) for additional description of these procedures and how they are implemented.

A summary of the analyses that were conducted to evaluate the relationship between performance and design variables for various BMP types is provided below followed by the presentation and discussion of results. Conclusions of the analysis and recommended future research are provided at the end of the report.

2 ANALYSES BY BMP TYPE

The number of BMP studies by type varies in the BMPDB, as does the amount of water quality data and design information reported with each study. As an initial step in developing the analysis approach, the BMP types were qualitatively screened to select those with potentially adequate numbers of studies and design data to enable potentially meaningful analysis. As a result of this initial screening, the BMP types included in this analysis are bioretention, detention basins, grass strips, grass swales, media filters, and retention ponds. Although manufactured devices have a large number of studies as an overall category, they were excluded from this analysis due to completion of the relatively recent Manufactured Devices Performance Summary Report (Geosyntec and Wright Water Engineers 2012b) that focused on unit treatment process groups.

Potential relationships between design parameters for each BMP type and a selected subset of pollutants that are well represented in the BMPDB were analyzed, including: total suspended solids (TSS), total phosphorus (TP), dissolved phosphorus (DP), nitrate (NOx)[2], total copper (TCu), and dissolved copper (DCu). BMP performance for each of these pollutants has been explored at the BMP category level in a series of technical reports completed during 2010-2012. This analysis includes additional data sets uploaded to the BMPDB in early 2013.

The statistical methods used for this analysis include:

- Mann-Whitney rank sum tests on median influent and effluent concentrations for the analysis data set to first evaluate whether the BMP type provides statistically significant reductions in the pollutant. (Note: additional studies with water quality data are available in the BMPDB; however, this analysis only includes a subset of studies with design data selected for inclusion in this report.)

- Development of scatterplot matrices to visually inspect the relationship between design parameters and monitored median effluent concentrations. Median influent concentrations were also plotted in the matrices to help identify whether any differences in the effluent achieved are partially due to differences in influent concentrations for the evaluated studies rather than the expected design parameters alone.

- To supplement the scatterplot matrices, correlation analyses using Spearman's rho correlation coefficient and associated significance value (p-value). Generally scatterplot matrices and correlation analyses are only provided for the BMPs and pollutants with six or more data points.

- Side-by-side boxplots of median effluent concentrations for BMP design parameters that can be logically binned, such as presence/absence of a design feature or when the design information has natural breaks in the database (e.g., drawdown times < 12 hours and > 72

[2] NOx is considered a single parameter that combines nitrate+nitrite as N with nitrate as N into a single data set for each BMP type with the assumption that the nitrite fraction is negligible in stormwater. For studies that report both nitrate+nitrite and nitrate, only nitrate+nitrite are used in the analysis.

hours). If few samples are available, dot plots are shown instead of boxplots. Similar to the rationale for including influent concentrations in the scatterplot matrices, median influent concentrations were also included in these plots to help discern whether any differences observed could be due to differences in influent quality.

- To supplement the boxplots, Mann-Whitney rank sum tests were conducted on design parameter groups to evaluate whether median effluent concentrations are statistically different. Test results are flagged as unreliable when there are a small number of available data points.

While reviewing the results presented in this report it is important to note that any statistically significant correlation identified does not necessarily indicate there is a causal relationship. Similarly, a lack of statistically significant correlation does not indicate there is no causal relationship.

2.1 Bioretention

Due to the limited number of representative systems without underdrains, only bioretention systems with underdrains were evaluated. This allowed for more of an “apples-to-apples” evaluation of bioretention performance since bioretention cells without underdrains function differently than cells with underdrains. Three different design parameters were evaluated, including the BMP footprint to drainage area ratio, the media depth above the underdrain, and the presence/absence of internal water storage. Internal water storage is a relatively novel design variation that is intended to provide a “dead” storage zone below the underdrain outlet to improve volume reductions and provide anaerobic conditions for nitrate removal (Brown and Hunt, 2011a and 2011b). One potentially very important aspect of bioretention performance is the media composition, including the compost fraction. Unfortunately, the information regarding media mix in the BMP database is inconsistent and incomplete, so no analysis was conducted on the potential effects of media composition on effluent concentrations.

Table 1 summarizes the design parameters evaluated and the analyses performed on those parameters.

Table 1. Bioretention design parameters analyzed.

Design Parameter	Analysis Performed
Footprint/drainage area ratio	Non-parametric correlation of median effluent concentration vs. drainage area ratio
Media depth	Non-parametric correlation of median effluent concentration vs. media depth
Internal Water Storage/No Internal Water Storage	Side-by-side boxplots; hypothesis tests on difference between median effluent concentrations

Table 2 presents the number of available studies for analysis of each parameter. In general, statistical tests were not performed when there were fewer than six BMPs available for analysis. For example, no analysis was conducted on total or dissolved copper or dissolved phosphorus due to the small number of data points available. While only 5 studies are available for analyzing the effects of the area ratio on TSS effluent concentration and internal storage, results have been provided with caveats due to the importance this constituent.

Table 2. Number of bioretention studies available for indicated pollutant and parameter.

Constituent	Area Ratio	Has Internal Storage	No Internal Storage	Media Depth (m)	Influent Median
Total Phosphorus as P	9	6	6	13	17
Dissolved Phosphorus as P	-	-	-	1	2
NOx as N	9	6	7	14	17
Total suspended solids	5	3	4	8	12
Copper, Total	-	-	-	2	4
Copper, Dissolved	-	-	-	1	3

Table 3 presents the results of Mann-Whitney analysis of the median influent and effluent concentrations for the studies with available design information. The median effluent concentrations are statistically significantly lower than the median influent concentrations ($p=0.001$) for total suspended solids only (bolded). The influent and effluent concentrations are not significantly different at the $p=0.1$ level for the other two constituents for which sufficient data were available. The side-by-side boxplots of the median influent and effluent concentrations shown in Figure 1 agree with the hypothesis test results.

Table 3. p-values from Mann-Whitney analysis of influent and effluent concentrations for bioretention.

Constituent	MW p-value
Phosphorus as P, Total	0.43
NOx as N	0.12
Total suspended solids	**0.001**

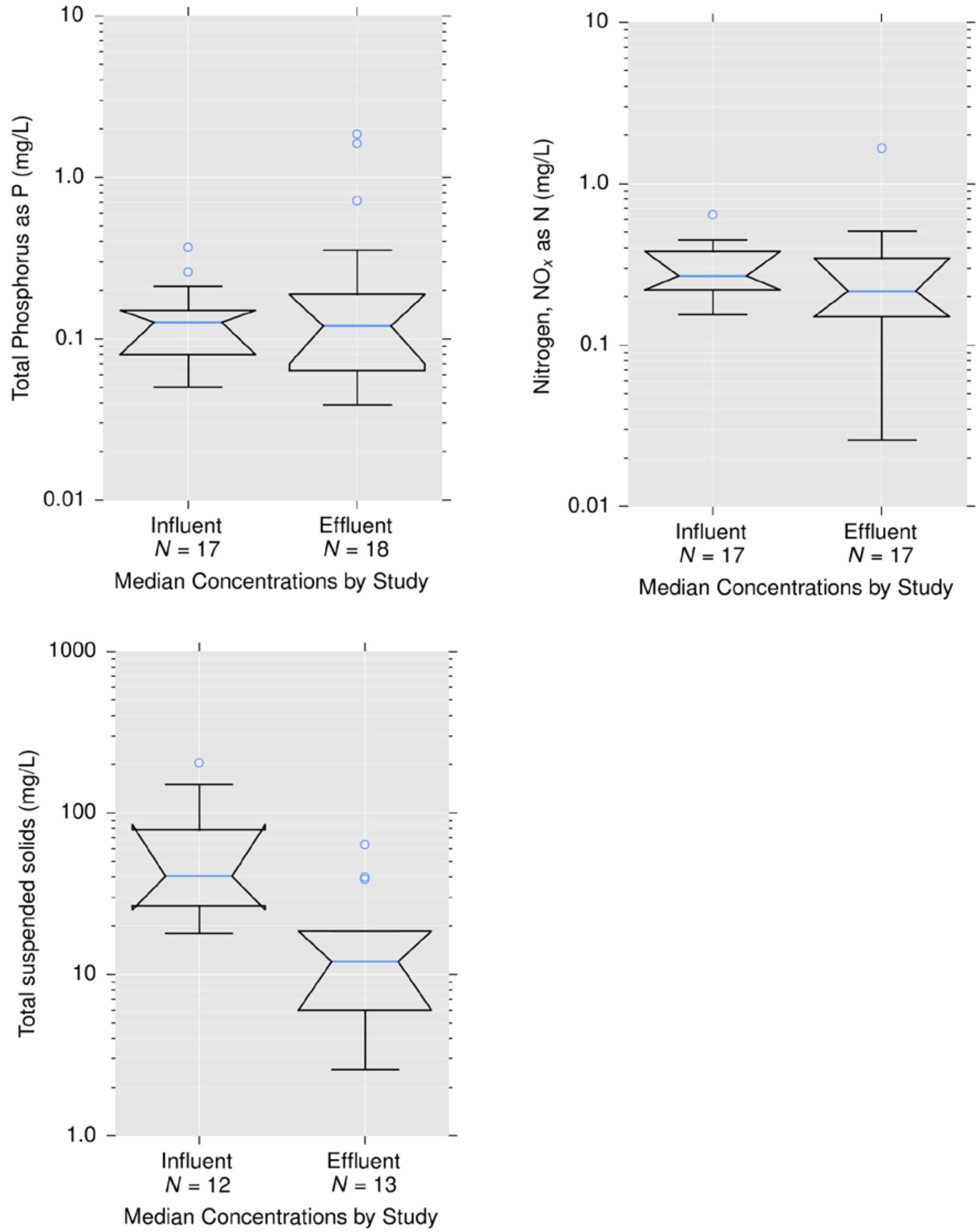

Figure 1. Side-by-side boxplots of median influent and effluent concentrations of TP, NOx, and TSS for bioretention.

Table 4 indicates there is a strong correlation, defined as $p<0.1$, between median influent concentration and median effluent concentration for total phosphorus and NOx (as measured by the p-value from Spearman's rho tests (significant values shown in bold), but no statistically significant correlation between any of the design parameters evaluated and effluent concentration.

Table 4. Spearman's rho correlation coefficients (p-values) between median effluent concentration and the listed parameters.

Constituent	Area Ratio	Media Depth (m)	Influent Median
Phosphorus as P, Total	0.24 (0.55)	0.18 (0.57)	**0.52 (0.03)**
NOx as N	-0.30 (0.43)	-0.36 (0.21)	**0.48 (0.05)**
Total suspended solids	0.21 (0.74)*	0.04 (0.93)	0.29 (0.37)

* Less than 6 data points, so results unreliable.

The following section presents scatter matrices between median effluent concentration, median influent concentration and the two design parameters listed in Table 4.

2.1.1 Total Phosphorus

In agreement with the hypothesis test results (Table 4), Figure 2 does not indicate a relationship between effluent total phosphorus concentration and either of the design parameters. Net export of total phosphorus is indicated for several of the BMP studies analyzed, but as indicated by the Mann-Whitney test results in Table 3, the influent and effluent median concentrations are not statistically significantly different. One interesting general observation from the scatter matrix is that the studies in the BMPDB that have larger drainage area ratios also tend to have larger media depths. While the number of studies are too few to statistically analyze, at least two of the studies having both relatively high area ratios and relatively high media depths achieved relatively low median total phosphorus effluent concentrations.

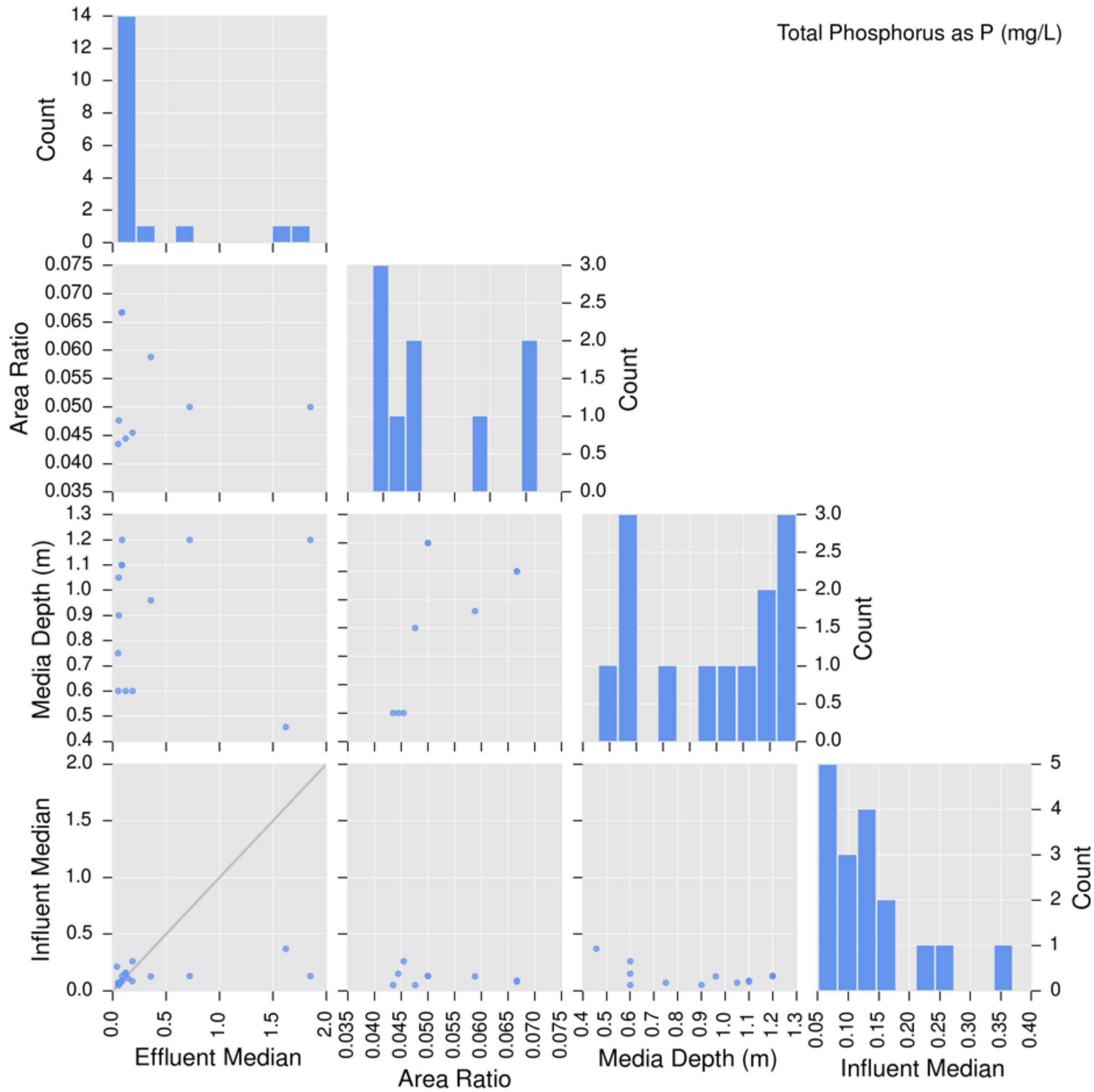

Figure 2. Scatter matrix of median total phosphorus concentration in the influent and effluent with selected design parameters for bioretention.

Figure 3 shows a side-by-side boxplot of the effluent total phosphorus concentration with and without internal storage. The difference is not statistically significant as measured by Mann-Whitney analysis (p=0.24); however, the sample size for each group (n = 6) is relatively small.

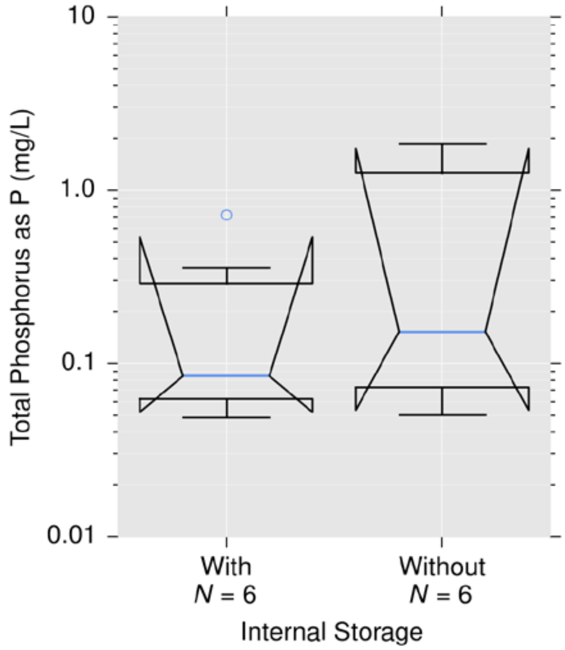

Figure 3. Side-by-side box-plot of effluent total phosphorus concentrations for bioretention BMPs with and without internal storage.

2.1.2 NOx

Figure 4 does not indicate a relationship between effluent NOx concentration and either of the design parameters, which agrees with the hypothesis test results presented in Table 4. Net removal of NOx is indicated for several of the studies analyzed, but with the small number of data points and the highly variable median effluent concentrations among studies, concentration reductions are not statistically significant (i.e., p=0.12 in Table 3).

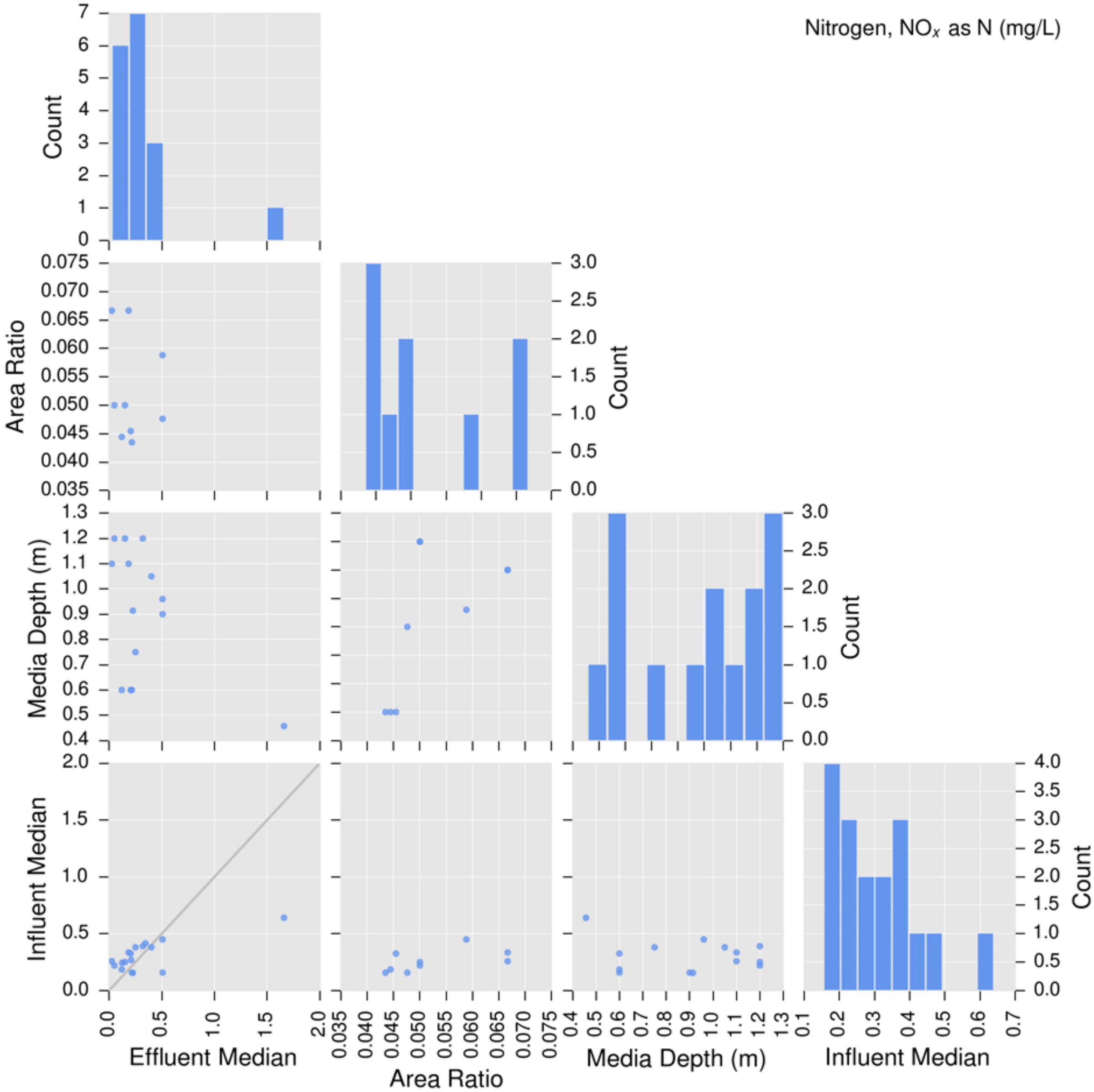

Figure 4. Scatter matrix of median NOx concentration in the influent and effluent with selected design parameters for bioretention.

Figure 5 shows a side-by-side boxplot of the effluent NOx concentration with and without internal storage. The difference is not statistically significant as measured by Mann-Whitney analysis (p=0.31). However, the boxplots do indicate that the highest median effluent NOx concentrations (~1.7 mg/L) occurred for a study that did not have internal storage. Based on the 25^{th} percentiles and lower fence values, the lowest median effluent NOx concentrations occurred for studies with internal storage. While more data are needed to show statistical significance, the use of internal storage for NOx removal appears promising and research by Brown and Hunt

(2011a, 2011b) indicate improved nitrogen species removal when internal water storage is incorporated into bioretention.

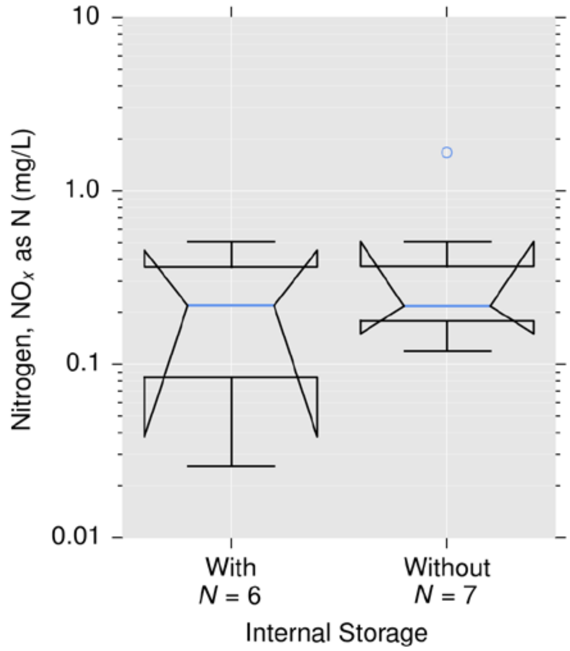

Figure 5. Side-by-side box-plot of effluent NOx concentrations with and without internal storage.

2.1.3 Total Suspended Solids

Figure 6 does not indicate a relationship between median effluent total suspended solids and either of the design parameters. However, the design parameter data sets are small, especially for the area ratio (n=5), so the lack of relationship is inconclusive. The effluent concentrations do not appear to be dependent on the influent concentrations (p=0.37 in Table 4), with the scatterplot indicating a relatively consistent discharge TSS concentration below 50 mg/L.

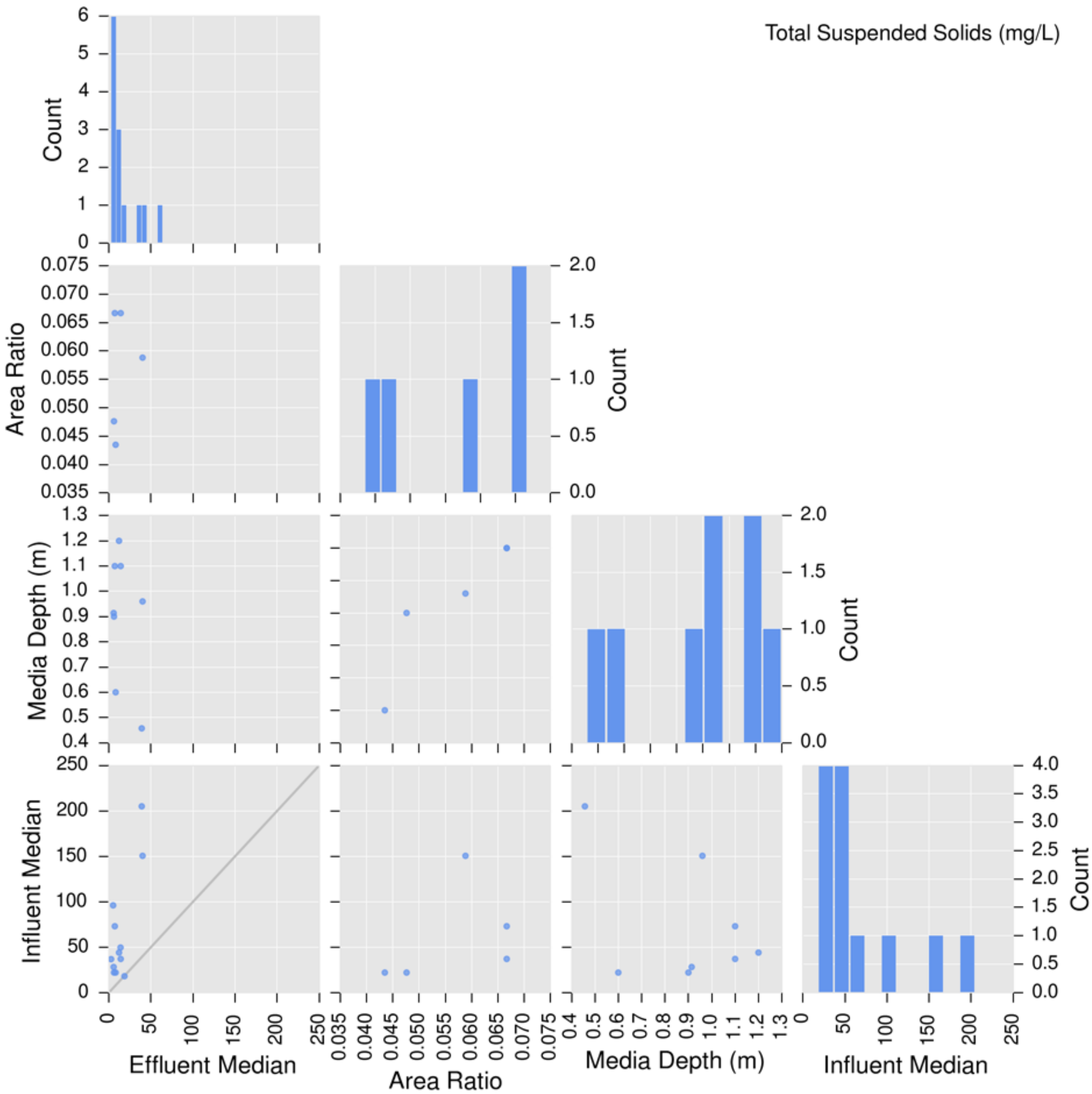

Figure 6. Scatter matrix of median total suspended solids in the influent and effluent with selected design parameters for bioretention.

Figure 7 shows a side-by-side dot-plot of the effluent total suspended solids concentration with and without internal storage. The difference is not statistically significant as measured by Mann-Whitney analysis (p=0.19); however, the sample size for each group is very small, limiting the conclusions that can be drawn. While internal storage may reduce the interstitial flow rates and thereby improve sedimentation and filtration, the majority of TSS removal in bioretention systems is likely occurring at or near the surface, as described by Li and Davis (2008). Therefore, even with additional studies, the internal storage may still not be found to affect TSS effluent concentrations.

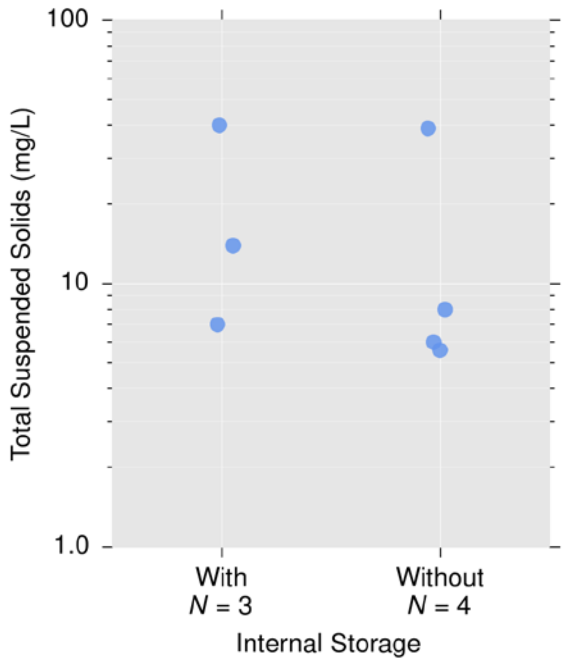

Figure 7. Side-by-side dot-plot of effluent total suspended solids for bioretention BMPs with and without internal storage.

2.2 Detention Basins

The primary design variables expected to influence performance of detention basins are those that affect the hydraulic residence time, such as the total storage volume, discharge rate, and flow path length. Since most of these variables are scale dependent, they were normalized before analysis of the available studies. The analyzed parameters included design storm depth to average storm depth ratio (DSD to ASD), brim-full emptying time (BFET), and length-to-width ratio (L to W) as shown in Table 5.

Table 5. Detention basin design parameters analyzed

Design Parameter	Analysis Performed
Design storm/ average storm depth (DSD to ASD)	Non-parametric correlation of median effluent concentration vs. design storm ratio
Length/width ratio (L to W)	Non-parametric correlation of median effluent concentration vs. length-to-width ratio
Brim full emptying time (BFET)	Non-parametric correlation of median effluent concentration vs. emptying time bins

Table 6 presents the number of available studies for analysis of each parameter. Analysis was not conducted on dissolved copper because it had fewer than six available data points for all design parameters investigated.

Table 6. Number of detention basin studies available for indicated constituent and parameter.

Constituent	DSD to ASD	BFET (hr)	L to W	Influent Median
Phosphorus as P, Total	7	10	10	9
Phosphorus as P, Dissolved	6	6	6	6
NOx as N	6	6	6	6
Total suspended solids	7	10	10	9
Copper, Total	6	6	6	6
Copper, Dissolved	5	5	5	5

Table 7 presents the results of Mann-Whitney analysis of the median influent and effluent concentrations for the studies with available design information. The effluent concentrations are statistically significantly lower than the influent concentrations for total suspended solids and total copper, and nearly significant (p=0.11) for total phosphorus. The differences in concentration are not statistically significant at the p=0.1 level for dissolved phosphorus or nitrate.

Figure 8 and Figure 9 show side-by-side boxplots of the median influent and effluent concentrations. The figures show that the 95 percent confidence intervals overlap for all constituents, with the degree of overlap corresponding to the hypothesis test results. For example, the p-values are largest for dissolved phosphorus and NOx where there is substantial overlap, and the p-values are the smallest for TSS where the confidence intervals only partially overlap. The p-values and the boxplots indicate that detention basins provide statistically significant reduction for total suspended solids and total copper concentrations and nearly statistically significant reductions for total phosphorus. Based on the available data, detention basins do not appear to effectively reduce dissolved phosphorus or NOx concentrations.

Table 7. p-values from Mann-Whitney analysis of influent and effluent concentrations for detention basins.

Constituent	MW p-value
Phosphorus as P, Total	0.11
Phosphorus as P, Dissolved	0.29
NOx as N	0.29
Total suspended solids	**0.012**
Copper, Total	**0.06**

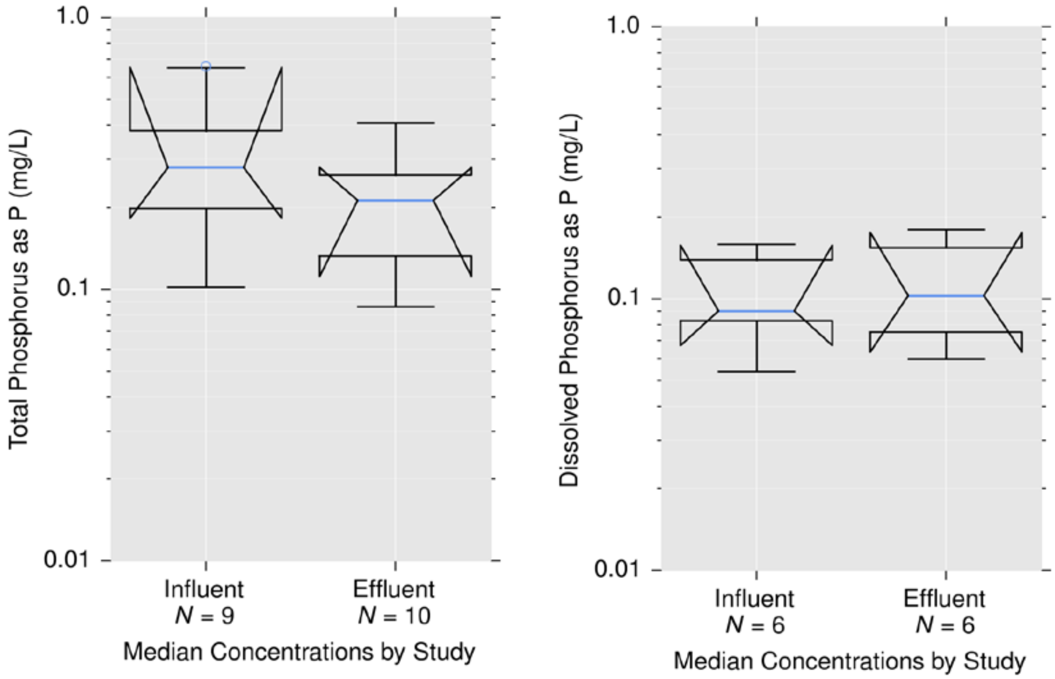

Figure 8. Side-by-side boxplots of median influent and effluent concentrations for TP and DP for detention basins.

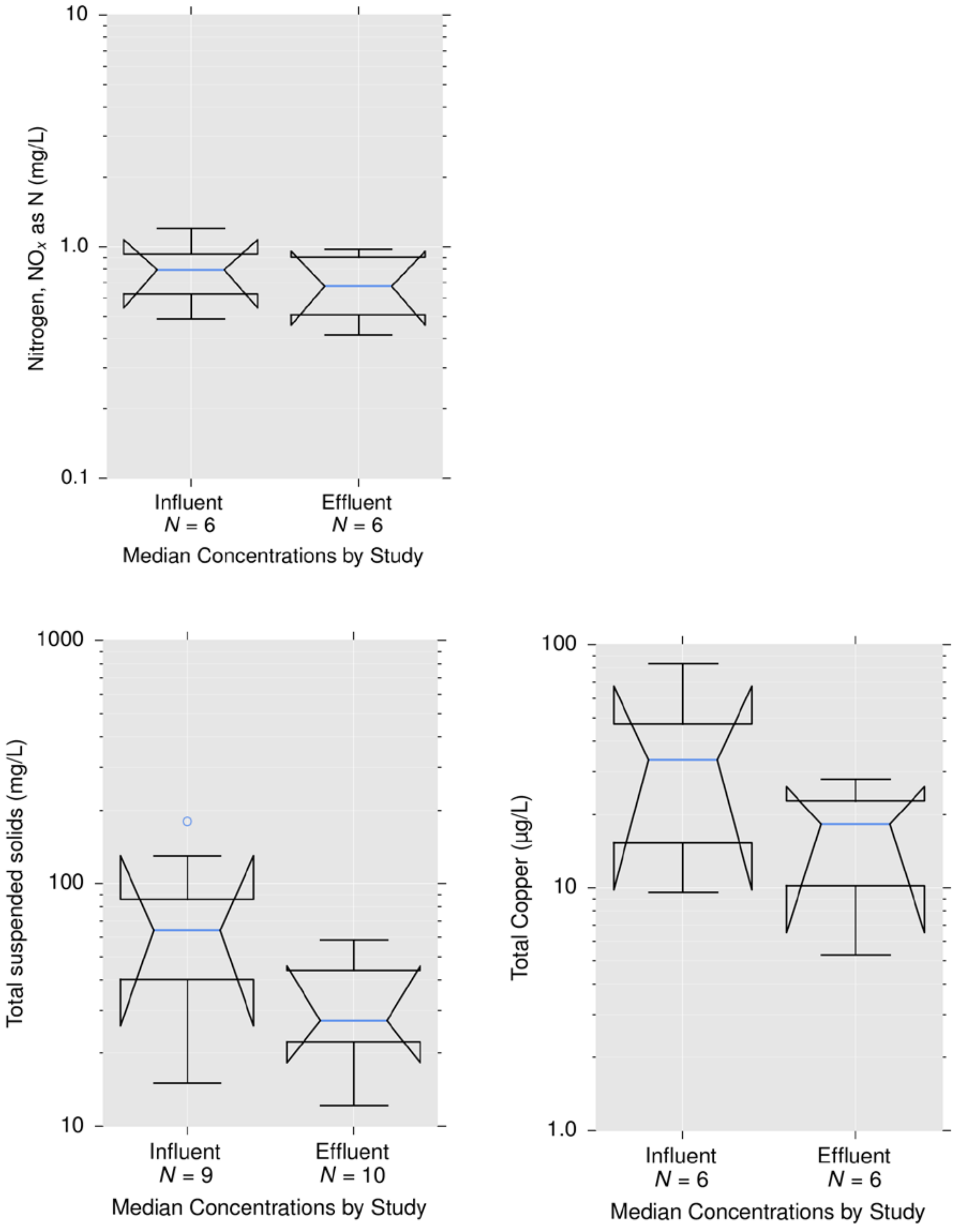

Figure 9. Side-by-side boxplots of median influent and effluent concentrations NOx, TSS, and TCu for detention basins.

Table 8 indicates that there is a significant correlation, defined as $p<0.1$ and shown in bold in the table, for some of the combinations of design parameters and constituents. These results are discussed along with the scatterplot matrices provided in the sections below for each analyzed constituent.

Table 8. Spearman's rho correlation coefficients (p-values) between median effluent concentration and the listed parameters for detention basins.

Constituent	DSD to ASD	BFET (hr)	L to W	Influent Median
Phosphorus as P, Total	-0.32 (0.48)	**0.76 (0.01)**	-0.10 (0.77)	**0.63 (0.07)**
Phosphorus as P, Dissolved	-0.54 (0.27)	0.17 (0.75)	0.60 (0.21)	0.52 (0.29)
NOx as N	-0.37 (0.47)	0.68 (0.14)	-0.09 (0.87)	**0.77 (0.07)**
Total suspended solids	**0.75 (0.05)**	0.17 (0.64)	-0.44 (0.20)	0.35 (0.36)
Copper, Total	-0.14 (0.79)	**0.78 (0.07)**	-0.49 (0.33)	**0.89 (0.02)**

2.2.1 Total Phosphorus

Figure 10 and the Spearman's rho correlation coefficient in Table 8 indicate a strong and statistically significant positive correlation between the emptying time of the detention basin and the median effluent phosphorus concentration. However, the scatterplot displays a similar relationship between emptying time and the influent median concentrations. Increased emptying time would be expected to improve pollutant removal performance since a major removal mechanism for total phosphorus is sedimentation. Therefore, the observed positive correlation between median effluent concentration and emptying time is suspect, given the strong correlation between influent and effluent concentrations that confounds the analysis. While there are limited data points to fully evaluate, the highest median TP concentration reduction achieved occurred for a study with a 72 hour emptying time. Multi-regression analysis is needed to isolate the effects of emptying time from the effects of the influent concentrations.

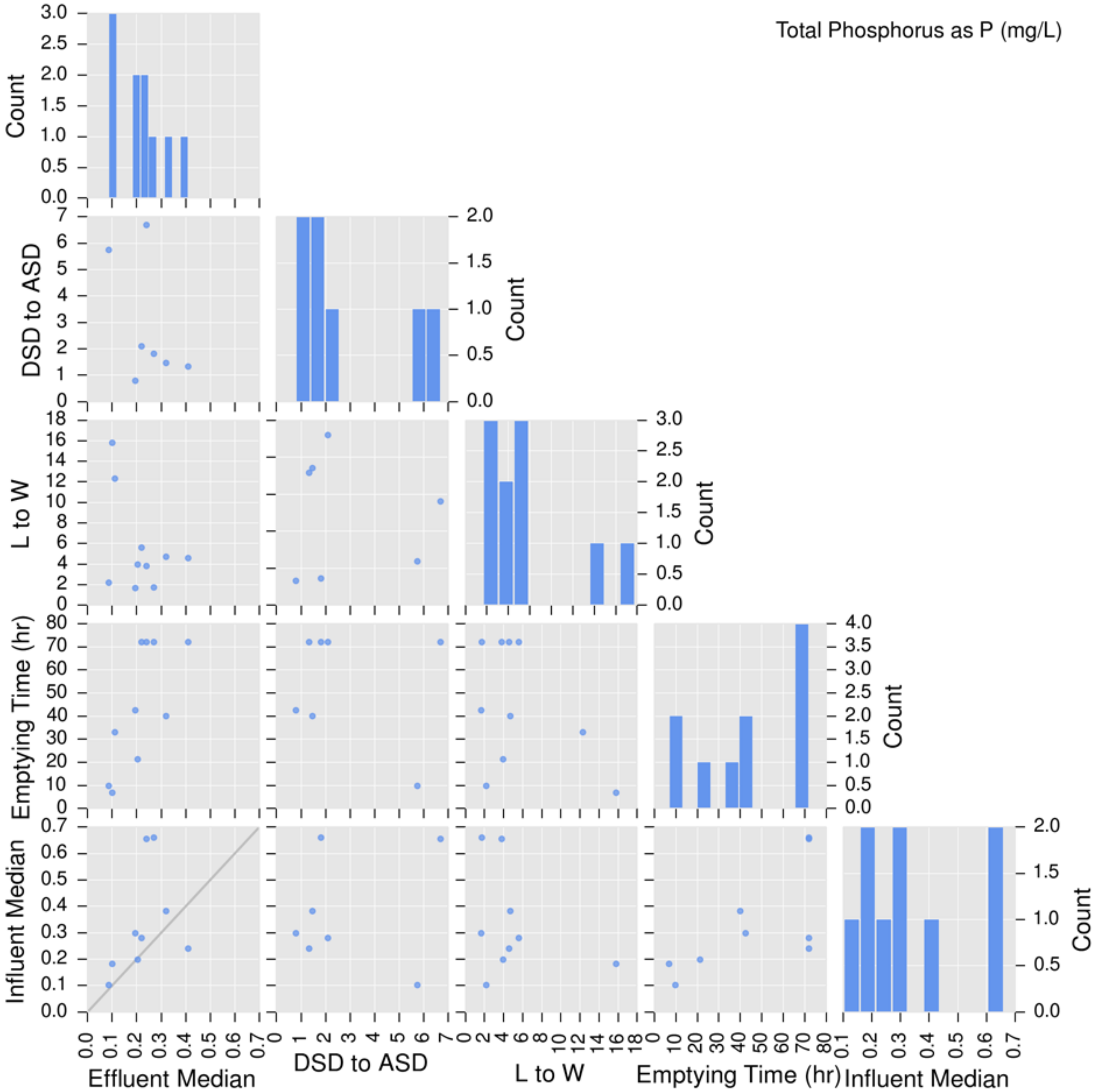

Figure 10. Scatter matrix of median total phosphorus in the influent and effluent with selected design parameters for detention basins.

2.2.2 Dissolved Phosphorus

The scatter matrix shown in Figure 11 and the Spearman's rho correlation coefficients in Table 8 indicate no significant correlation between the design variables and the median effluent concentration. The release of dissolved phosphorus appears to occur for several of the analyzed studies, but this relationship was not found to be significant (Spearman's rho p=0.29) and the differences between the median influent and effluent concentrations were also not significant (Mann-Whitney p=0.29). These results make sense, given that sedimentation is the primary unit treatment process provided by detention basins. Release of DP may occur if phosphorus-rich sediment or detritus (i.e., leaves, grass clippings, etc.) captured within the detention basin begins to decay. Because the total organic cumulative load into the system is not sampled and tracked, it is not possible to evaluate whether the increases in storm event concentrations is due to a net export of phosphorus or due to sampling bias. Understanding/quantifying the complete mass balance of nutrients in and out of BMPs is an area of needed research.

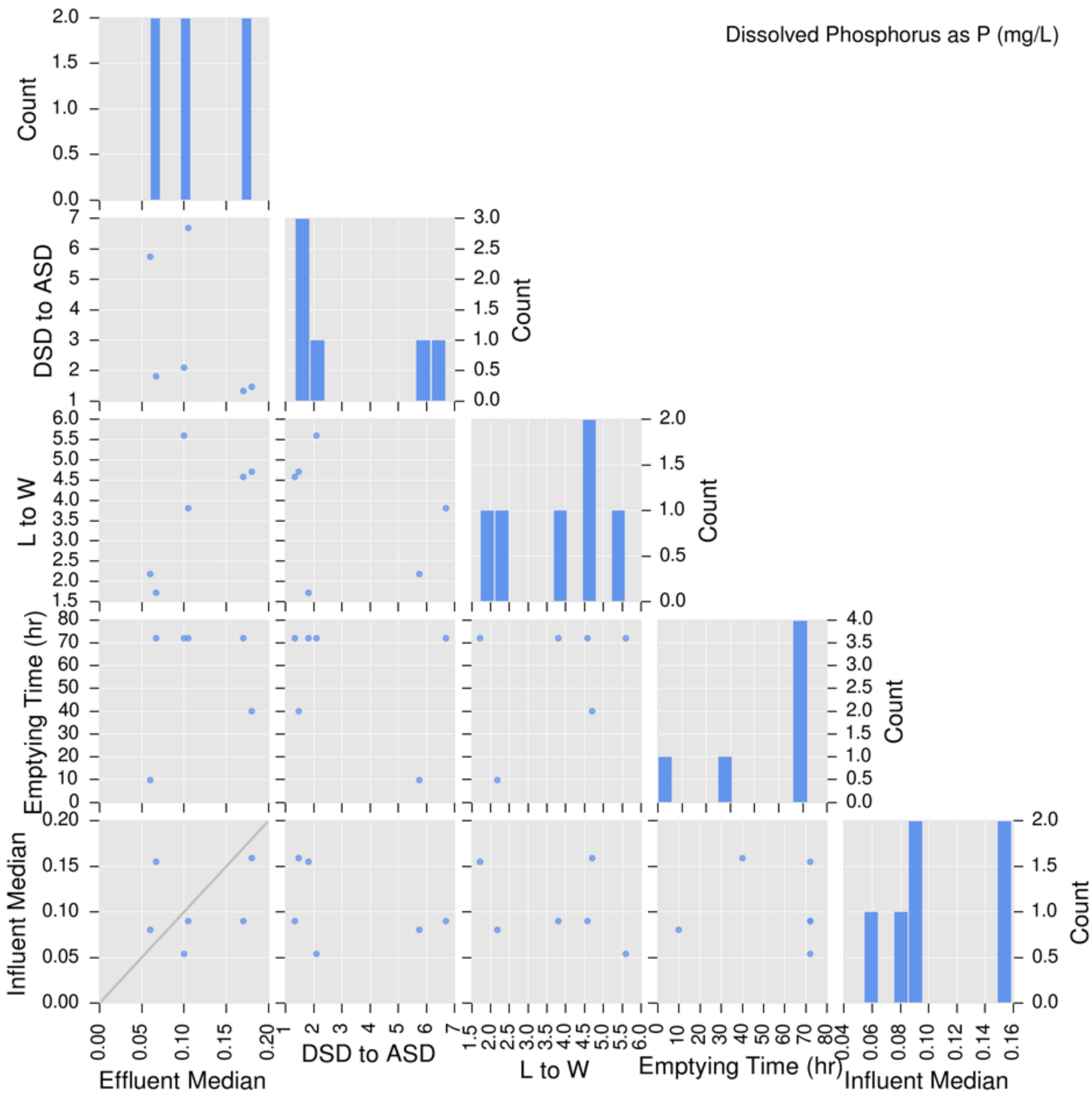

Figure 11. Scatter matrix of median dissolved phosphorus concentration in the influent and effluent with selected design parameters for detention basins.

2.2.3 NOx

Similar to dissolved phosphorus, the scatter matrix shown in Figure 12 and the Spearman's rho correlation coefficients shown in the Table 8 indicate no significant correlation between the design variables and the median effluent concentration. Mann-Whitney results in Table 7 indicate that there is no significant difference between influent and effluent medians. This result along with the high Spearman's rho coefficient provides a strong indication that detention basins generally do not provide significant reduction or release of nitrate.

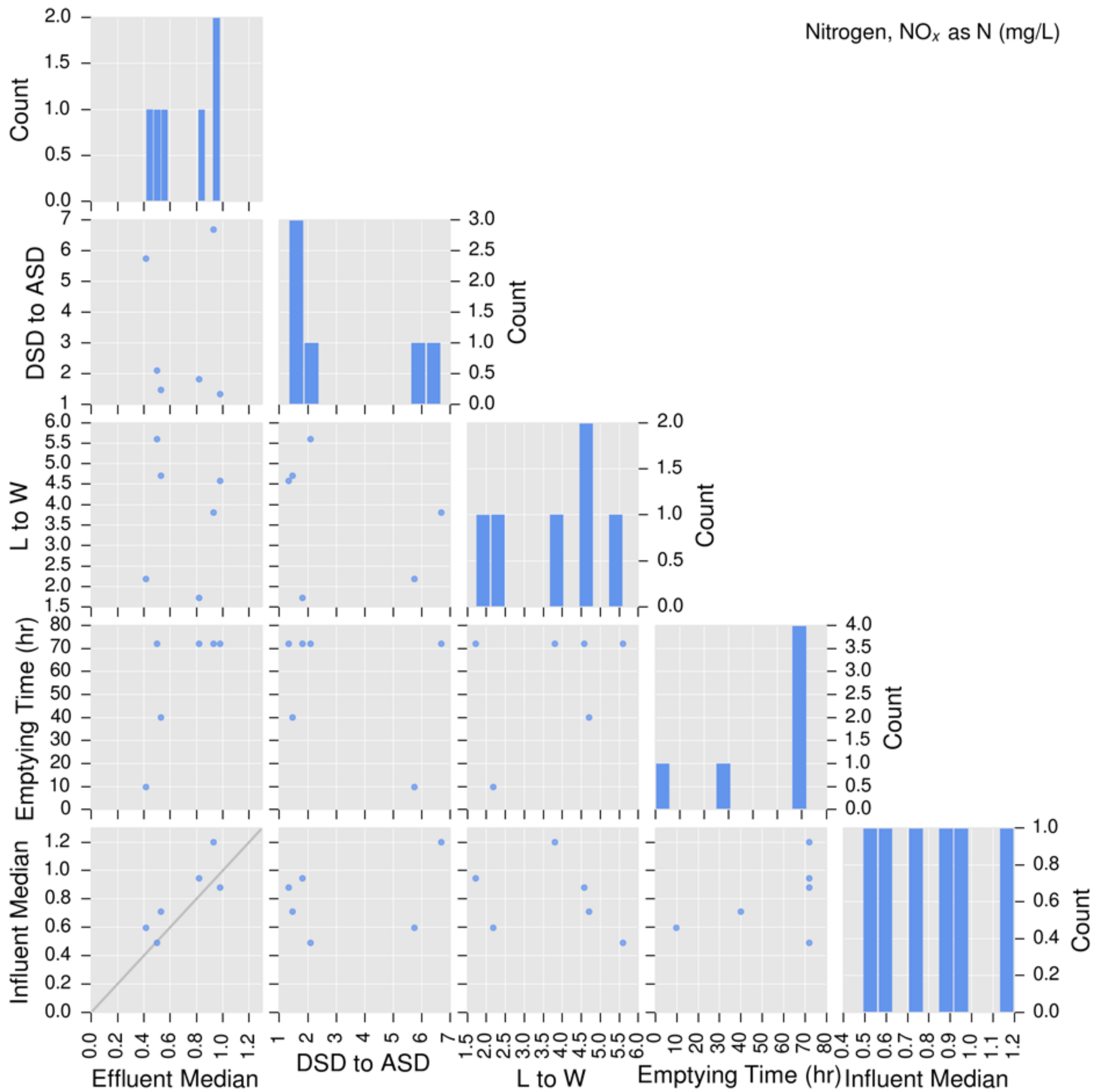

Figure 12. Scatter matrix of median NOx concentration in the influent and effluent with selected design parameters for detention basins.

2.2.4 Total Suspended Solids

The scatter matrix in Figure 13 and the Spearman's rho correlation coefficient in Table 8 indicate a statistically significant positive relationship between DSD/ASD and median effluent concentrations. This is counterintuitive because a larger DSD/ASD would be expected to achieve lower effluent concentrations, resulting in a negative correlation. As with total phosphorus, the findings are confounded by the influent concentration, which has a similar (albeit not statistically significant) relationship with DSD/ASD. Influent concentrations may also affect the results of the analysis for the other design parameters too. As shown in Figure 13, the highest L to W ratio is associated with the lowest influent concentration and the longest drain time is associated with the largest influent concentration.

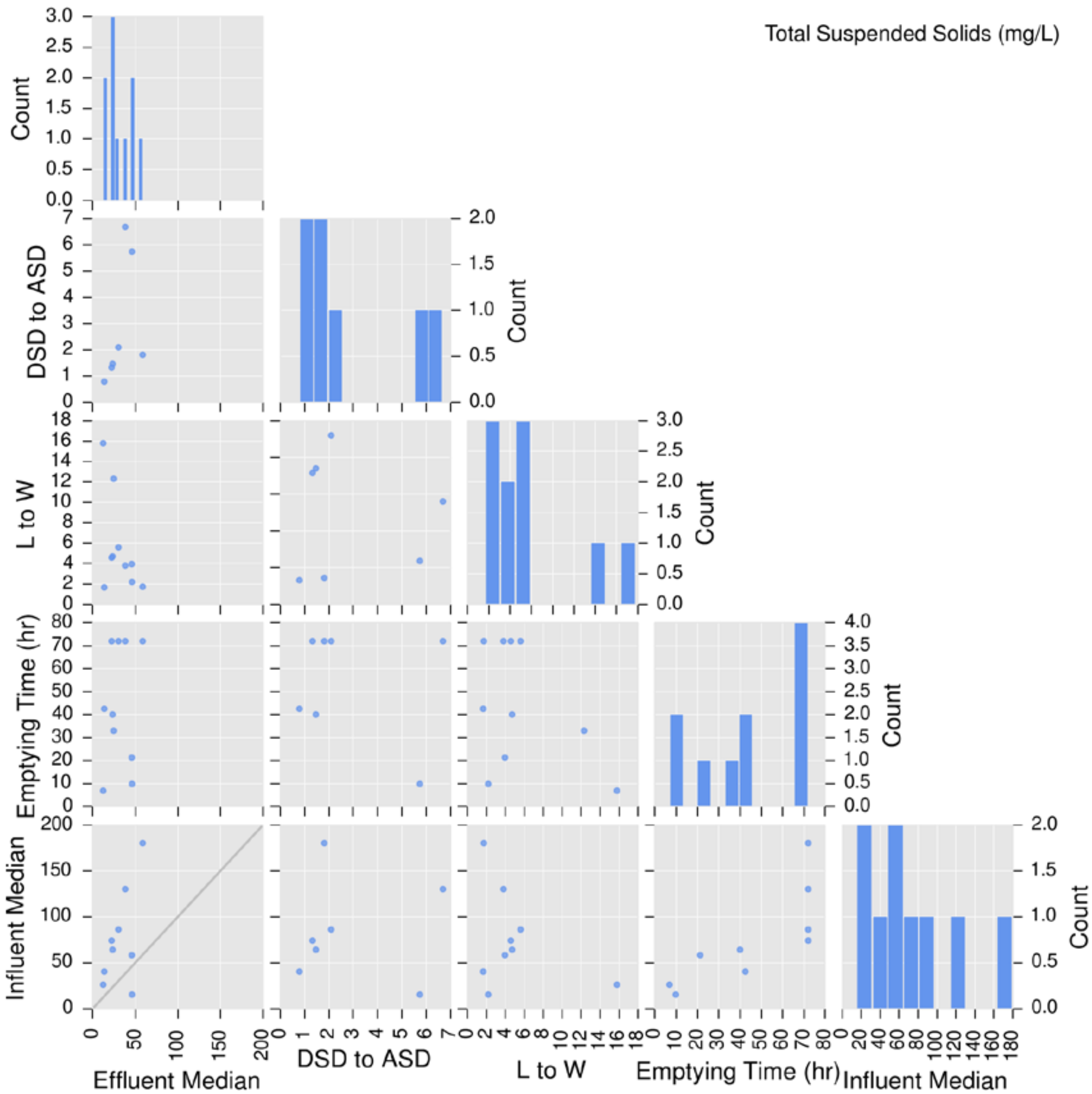

Figure 13. Scatter matrix of median total suspended solids in the influent and effluent with selected design parameters for detention basins.

2.2.5 Total Copper

In agreement with the hypothesis test results (Table 8), Figure 14 indicates that there is a positive correlation between the emptying time of the detention basin and the median effluent total copper concentration. However, as with total phosphorus and TSS, this correlation is considered spurious since the emptying time displays a similar pattern with the influent median concentration. Additionally, it should again be noted that the number of studies available for analysis is relatively small, making it difficult to identify causal relationships between design parameters and constituent removal.

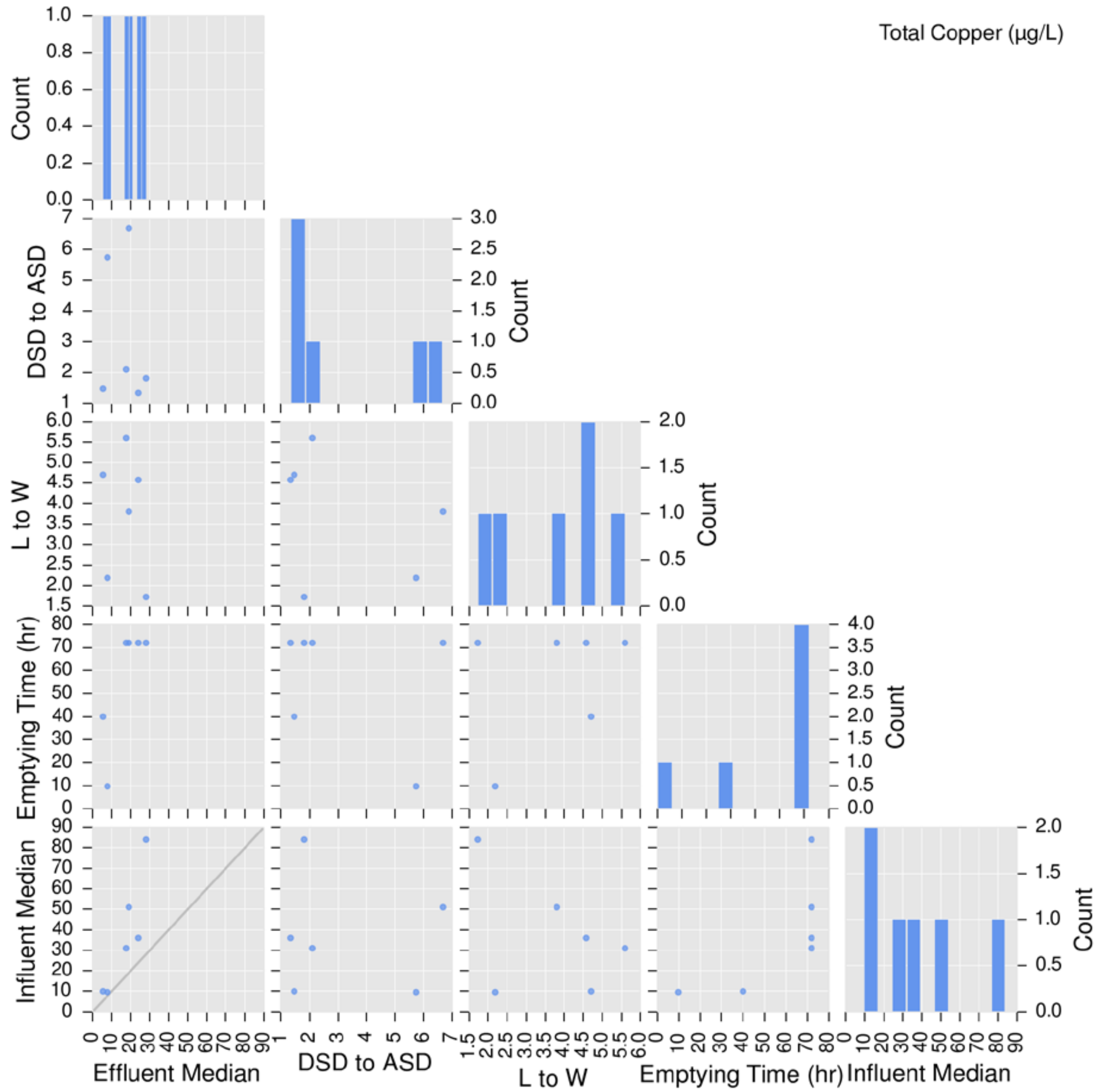

Figure 14. Scatter matrix of median total copper concentration in the influent and effluent with selected design parameters for detention basins.

2.3 Grass Strips

Two design parameters expected to influence performance of grass strips include the flow path length and slope. Other parameters, such as soil type, grass type and density may also be important, but these parameters are not widely available or consistently reported in the BMPDB to permit meaningful analysis at this time. Table 9 summarizes the parameters analyzed for grass strips.

Table 9. Grass strip design parameters analyzed.

Design Parameter	Analysis Performed
Length	Non-parametric correlation of median effluent concentration vs. length
Slope	Non-parametric correlation of median effluent concentration vs. length

Table 10 presents the number of available studies for analysis of each parameter. No statistical tests were performed when there were fewer than six BMPs available for analysis; therefore, dissolved phosphorus was not analyzed.

Table 10. Number of grass strip studies available for indicated constituent and parameter.

Constituent	Length (m)	Slope	Influent Median
Phosphorus as P, Total	30	30	29
Phosphorus as P, Dissolved	3	3	3
NOx as N	30	30	29
Total suspended solids	30	30	29
Copper, Total	23	23	22
Copper, Dissolved	22	22	21

Table 11 presents the results of Mann-Whitney analysis of the median influent and effluent concentrations for the studies with available design information. The effluent concentrations are statistically significantly lower than the influent concentrations for total suspended solids, NOx and total copper (and nearly significantly lower for dissolved copper), and significantly higher for total phosphorus, indicating that these BMPs often export phosphorus. Figure 15 and Figure 16 show side-by-side boxplots comparing the median influent and effluent concentrations for each analyzed constituent. Only TSS and TCu have confidence intervals that do not overlap, indicating that filter strips are very reliable for removing these constituents.

Table 11. p-values from Mann-Whitney analysis of influent and effluent concentrations for grass strips.

Constituent	MW p-value
Phosphorus as P, Total	**0.01**
NOx as N	**0.06**
Total suspended solids	**<0.0001**
Copper, Total	**0.007**
Copper, Dissolved	0.12

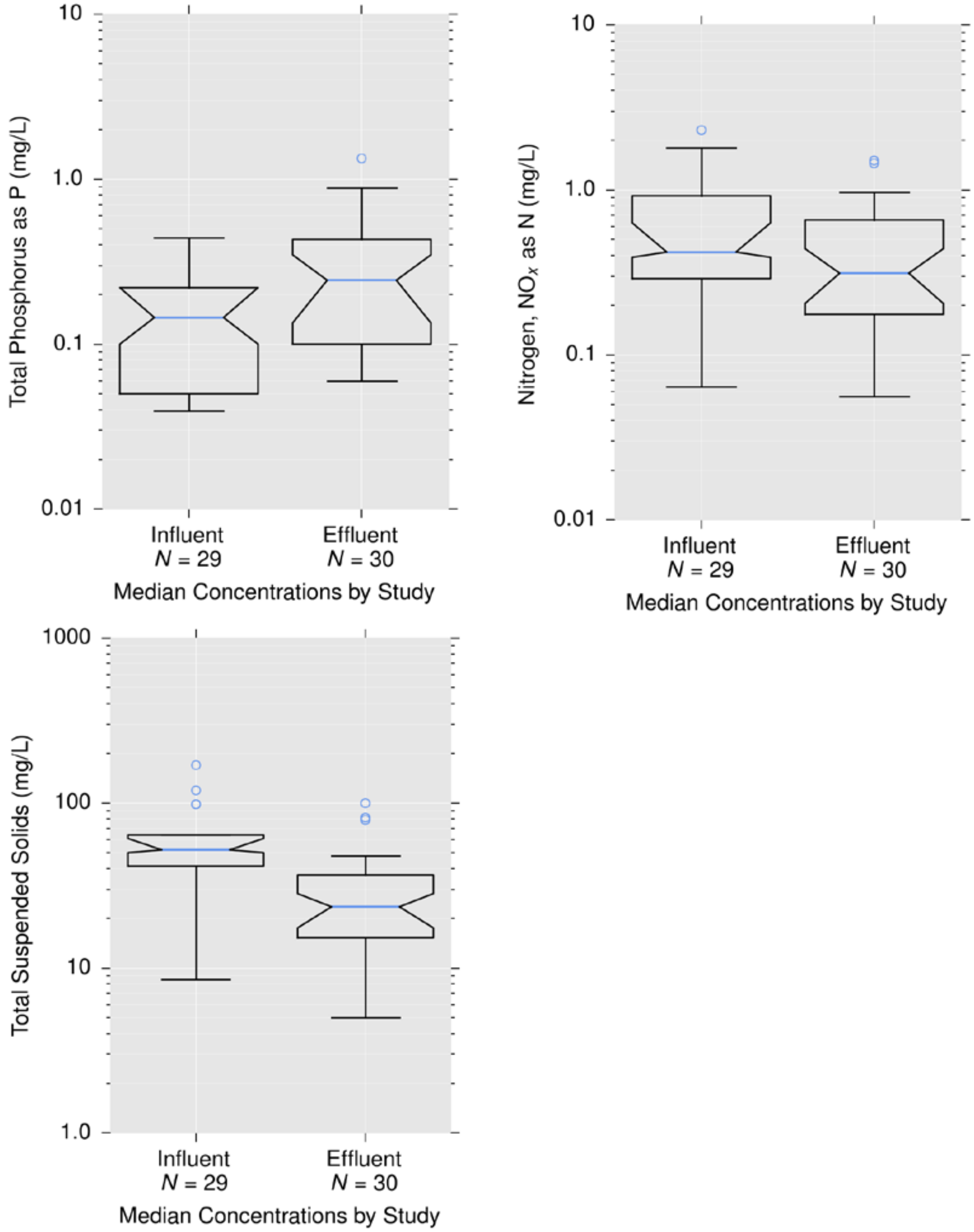

Figure 15. Side-by-side boxplots of influent and effluent concentrations for TP, NOx, and TSS for grass strips.

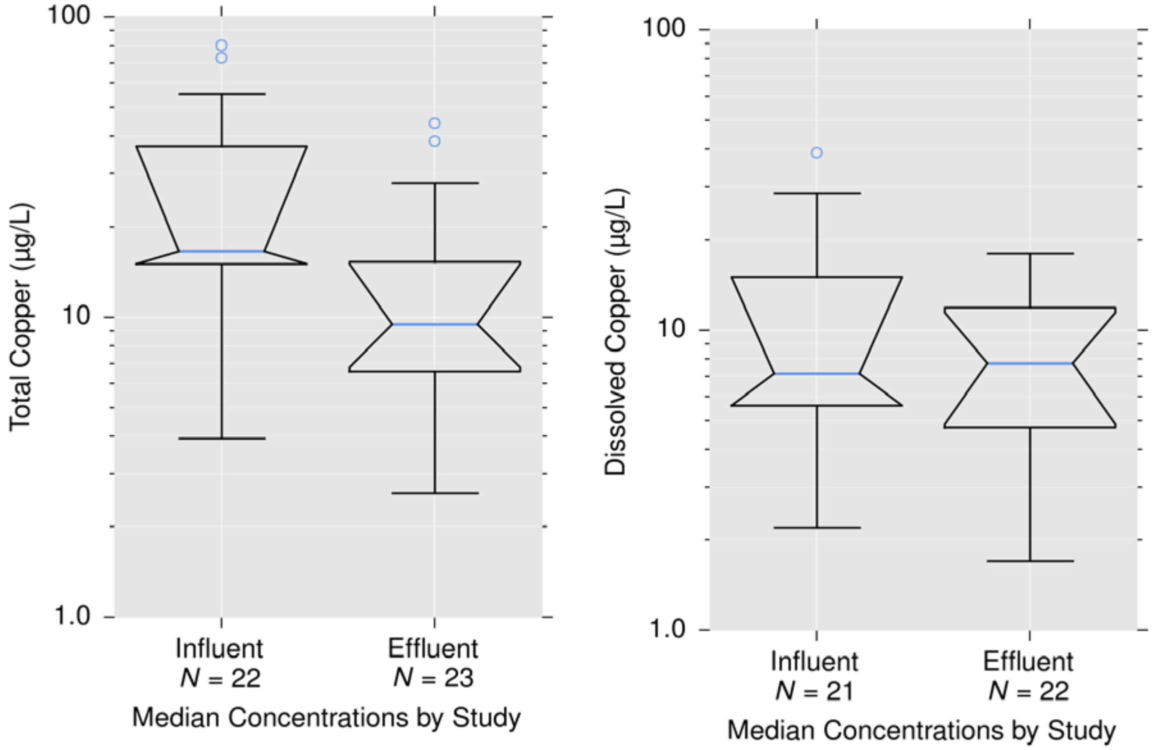

Figure 16. Side-by-side boxplots of influent and effluent concentrations for TCu and DCu for grass strips.

Table 12 indicates that BMP length did not have a statistically significant correlation with effluent median concentration for any of the analyzed constituents as measured by Spearman's rho tests. However, the results of this analysis should not be interpreted to mean that a short grass strip would be as effective as a long grass strip. Rather, there is enough scatter in the relationship due to variables other than length to affect the statistical significance of the analysis. The filter strip study by Caltrans (2003) found that when slopes are less than 10% and the vegetation cover exceeds 80%, then an irreducible concentration is achieved at a strip length less than 5 meters. In other words, a longer strip would not provide additional water quality benefit unless slopes are higher or the vegetation is sparse. The slope of the BMP does have a statistically significant positive correlation with effluent NOx—a gentler slope is associated with lower effluent concentrations for this constituent. There is a strong correlation between influent and effluent concentrations for all constituents. Scatterplots are presented below and discussed in conjunction with these correlation coefficients for the analyzed constituent below.

Table 12. Spearman's rho correlation coefficients (p-values) between median effluent concentration and the listed parameters for grass strips.

Constituent	Length (m)	Slope	Influent Median
Phosphorus as P, Total	0.11 (0.57)	0.07 (0.72)	**0.72 (<0.0001)**
NOx	-0.13 (0.48)	**0.34 (0.06)**	**0.79 (<0.0001)**
Total suspended solids	-0.20 (0.29)	0.001 (0.99)	**0.82 (<0.0001)**
Copper, Total	-0.16 (0.46)	0.16 (0.45)	**0.76 (<0.0001)**
Copper, Dissolved	-0.016 (0.94)	0.04 (0.86)	**0.62 (0.002)**

2.3.1 Total Phosphorus

Figure 17 and the Spearman's rho correlation coefficients in Table 12 do not indicate a correlation between effluent total phosphorus concentration and either of the design parameters. However, there is a relatively strong and statistically significant correlation (rho = 0.72, $p<0.0001$) between median influent and effluent concentrations. The scatterplot indicates that net export of total phosphorus occurs for several of the studies in the BMPDB. Phosphorus export from filter strips may be due to a number of factors including the soil types, the amount of interflow, and the characteristics influencing erosion (e.g., vegetation type and density, concentrated flow paths, etc.). Additionally, as discussed above, the apparent exporting of phosphorus could also be due to decomposing grass clippings or other plant matter not sampled with the influent.

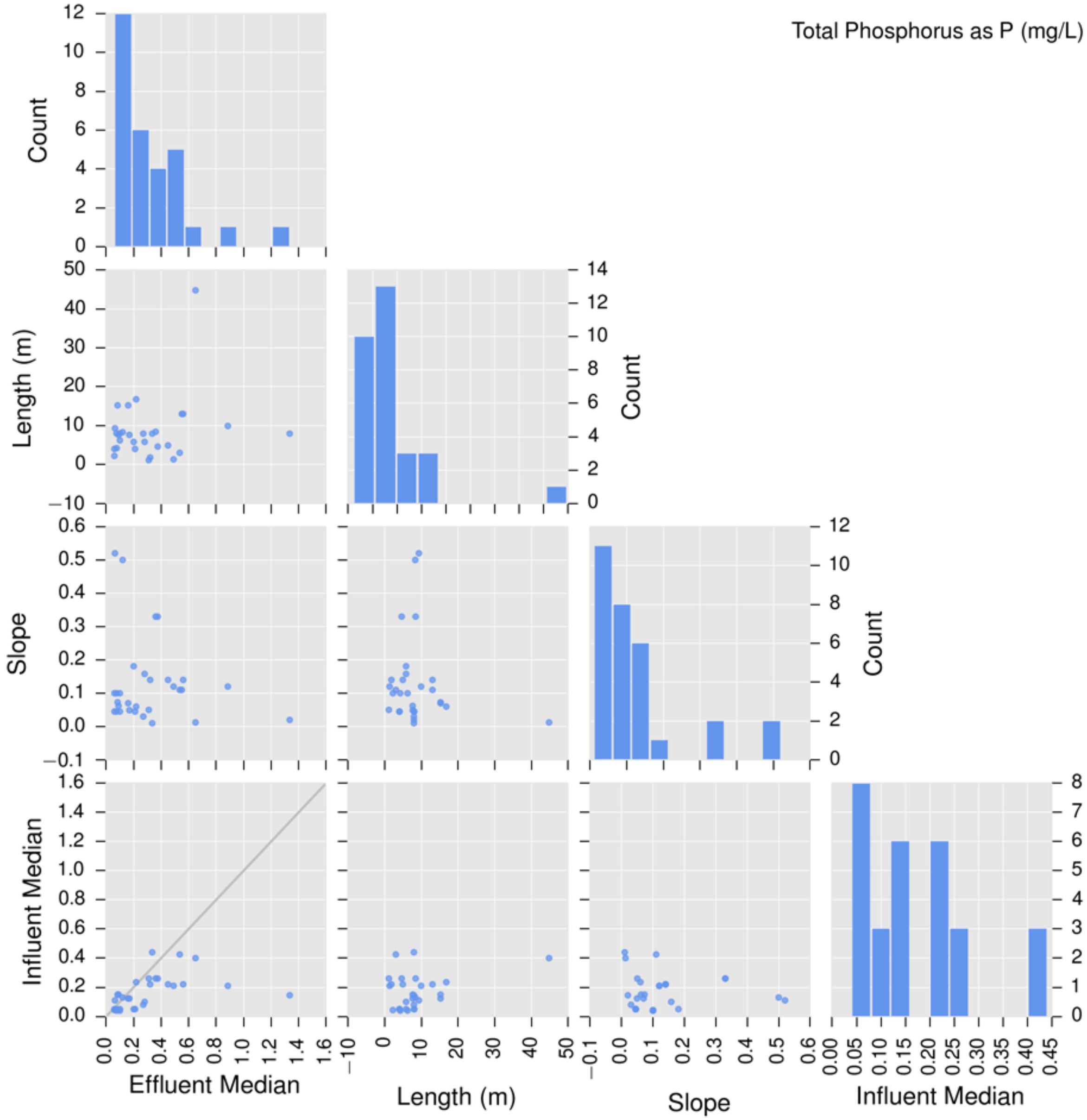

Figure 17. Scatter matrix of median total phosphorus concentration in the influent and effluent with selected design parameters for grass strips.

2.3.2 NOx

Figure 18 reaffirms the correlation between slope and effluent NOx concentration noted in Table 12. However, the scatter matrix also shows that some of the steepest sloped BMPs also had the highest influent NOx concentration, indicating that gentle slopes may not be the cause of the lower effluent NOx concentrations for some of the BMPs. Nonetheless, grass strips show mildly statistically significant reductions in NOx when comparing influent and effluent medians (Mann-Whitney p-value = 0.06).

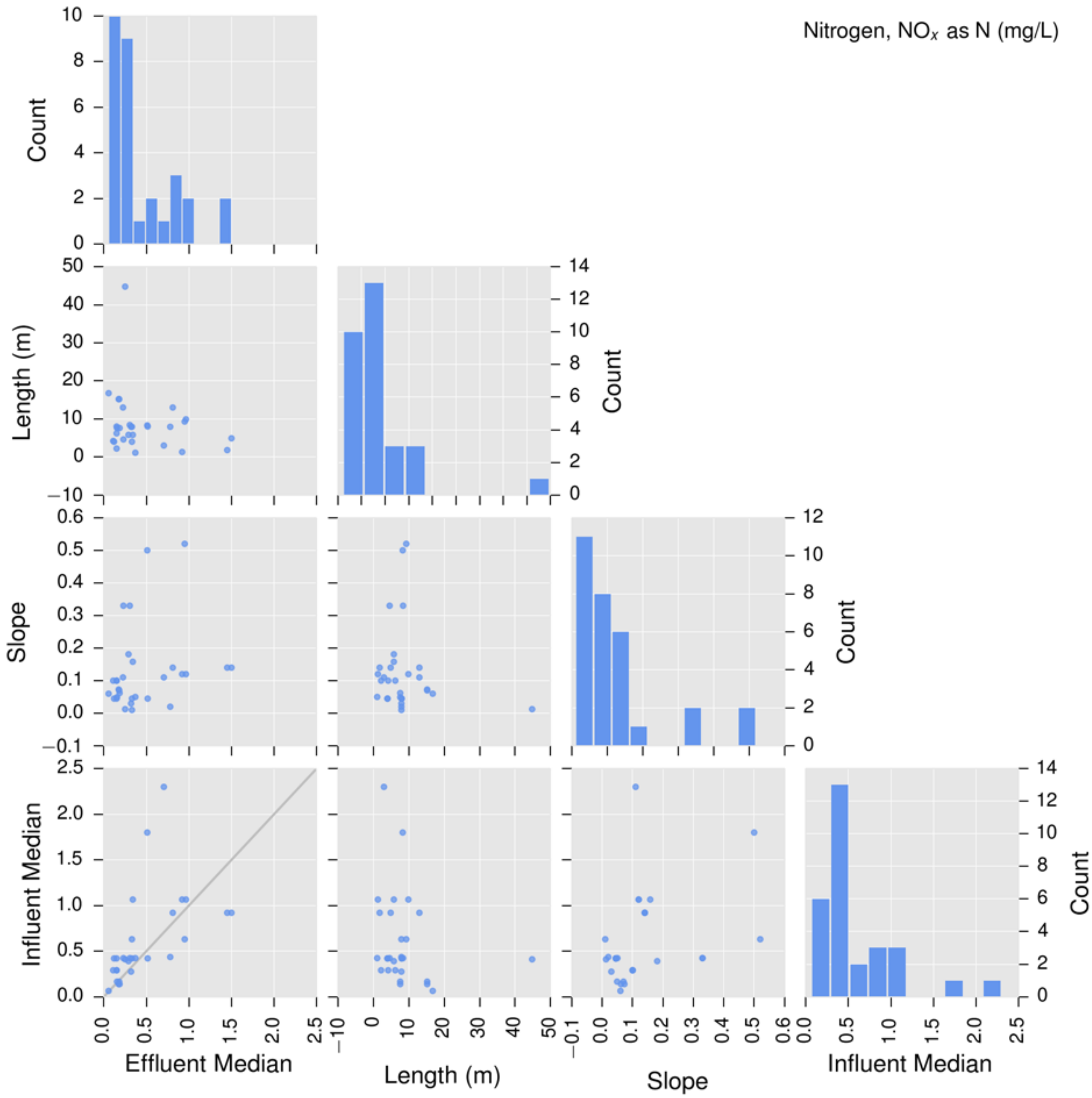

Figure 18. Scatter matrix of median NOx concentration in the influent and effluent with selected design parameters for grass strips

2.3.3 Total Suspended Solids

Figure 19 and the Spearman's rho correlation coefficients in Table 12 do not indicate a correlation between effluent total suspended solids concentration and either of the design parameters. However, there is a strong and statistically significant correlation between median influent and effluent TSS concentrations. Since net removals are also significant, as indicated by the Mann-Whitney test results shown in Table 11 ($p < 0.0001$), a potential functional relationship between influent and effluent TSS concentrations may exist.

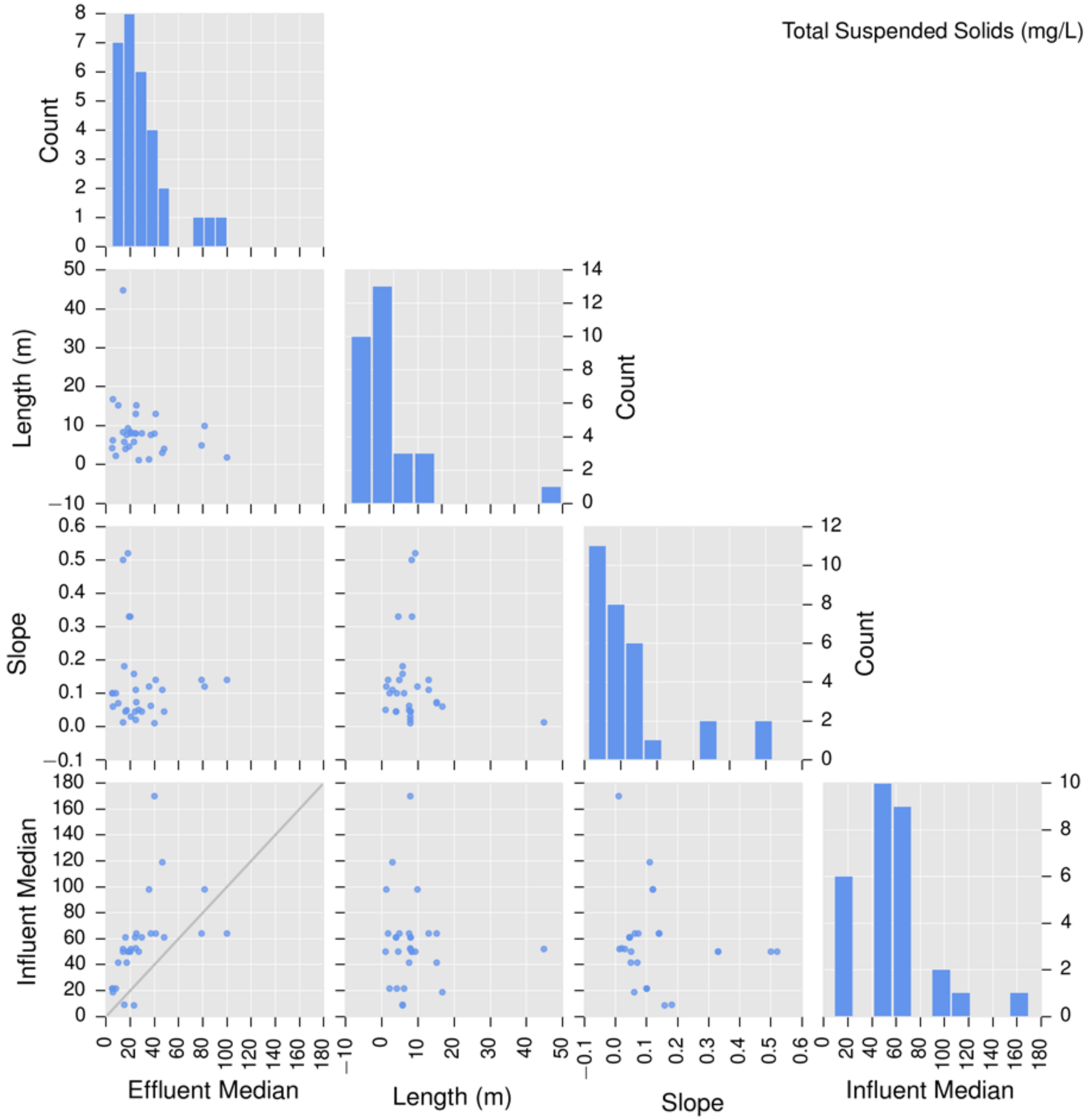

Figure 19. Scatter matrix of median total suspended solids in the influent and effluent with selected design parameters for grass strips.

2.3.4 Total Copper

Figure 20 and the Spearman's rho correlation coefficients in Table 12 do not indicate a correlation between effluent total copper concentration and either of the design parameters. The correlation between the median influent and effluent concentrations are statistically significant, but the scatterplot indicates that effluent concentrations are somewhat resilient to increases in influent concentrations. For example, nearly all effluent concentrations are near or below 30 µg/L, whereas almost half of the studies have median influent concentrations greater than 30 µg/L.

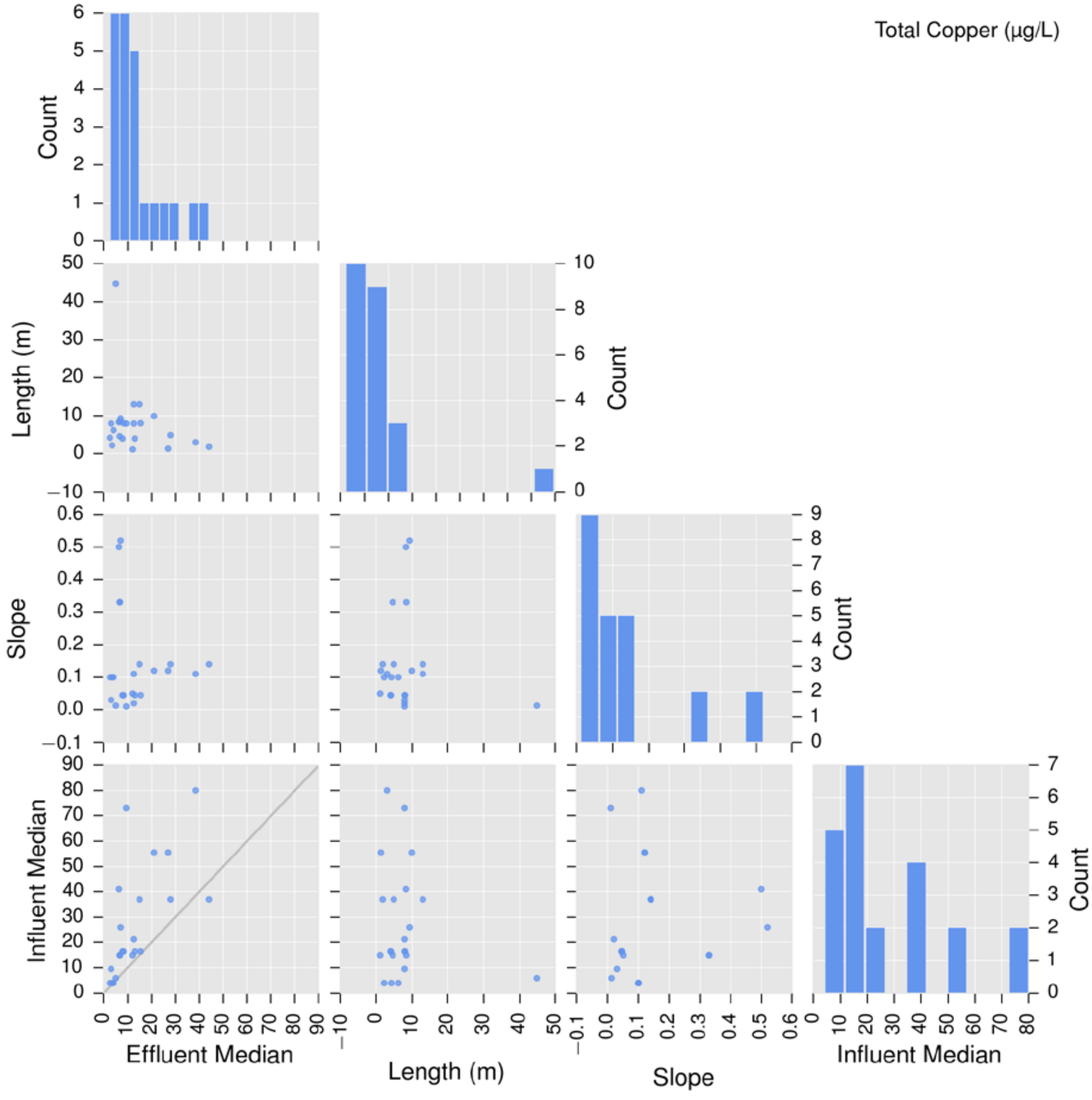

Figure 20. Scatter matrix of median total copper concentration in the influent and effluent with selected design parameters for grass strips.

2.3.5 Dissolved Copper

Figure 21 and the Spearman's rho correlation coefficients in Table 12 do not indicate a correlation between effluent dissolved copper concentration and either of the design parameters.

There is a statistically significant correlation between median influent and effluent concentrations ($p=0.002$). The Mann-Whitney test indicates grass strips do not provide statistically significant reductions in dissolved copper ($p = 0.12$ as shown in Table 11); however, based on the scatterplot, removals appear to occur when median influent concentrations are greater than approximately 10 µg/L.

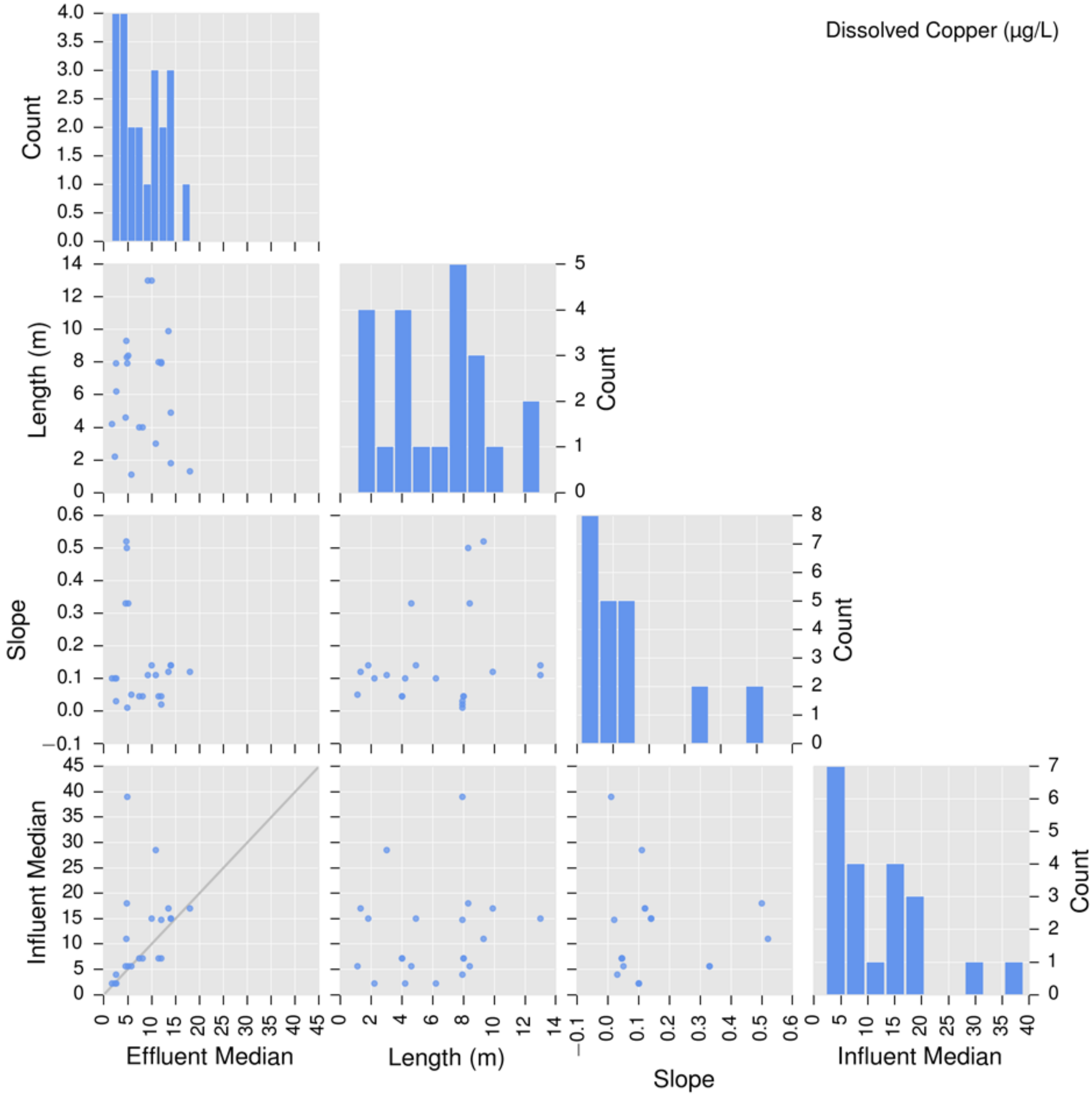

Figure 21. Scatter matrix of median dissolved copper concentration in the influent and effluent with selected design parameters for grass strips.

2.4 Grass Swales

Grass swale BMPs were analyzed similarly to grass strips, but the design depth during a 2-year storm was also added because this parameter was available for some studies and was hypothesized to influence performance, since shallower design depths would be expected to provide better performance. Table 13 summarizes the analyzed parameters.

Table 13. Grass swale design parameters analyzed.

Design Parameter	Analysis Performed
Length	Non-parametric correlation of median effluent concentration vs. length
Slope	Non-parametric correlation of median effluent concentration vs. length
2-year Design Depth	Non-parametric correlation of median effluent concentration vs. design depth

Table 14 presents the number of available studies for analysis of each parameter. No statistical tests were performed for dissolved phosphorus due to limited data. Analysis results for dissolved copper for the two-year depth are presented, but flagged as unreliable.

Table 14. Number of grass swale studies available for indicated pollutant and design parameter.

Constituent	Length (m)	Slope	Two-Year Depth (m)	Influent Median
Phosphorus as P, Total	19	17	7	15
Phosphorus as P, Dissolved	5	5	0	5
NOx as N	19	17	7	15
Total suspended solids	20	18	8	15
Copper, Total	17	15	7	13
Copper, Dissolved	13	11	3	13

Table 15 presents the results of Mann-Whitney analysis on the median influent and effluent concentrations for the studies with available design information. The effluent concentrations are statistically significantly lower than the influent concentrations of TSS and TCu. The differences in concentration are not statistically significant at the p=0.1 level for NOx, TP, and DCu. Although with a p-value of 0.13, DCu concentration reductions are nearly significant. Figure 22 and Figure 23 show side-by-side boxplots of the median influent and effluent concentrations of each constituent and generally agree with the Mann-Whitney p-value results. Total copper, which has the lowest p-value, is the only constituent without overlapping influent/effluent confidence intervals.

Table 15. p-values from Mann-Whitney analysis of influent and effluent concentrations for grass swales.

Constituent	MW p-value
Phosphorus as P, Total	0.24
NOx as N	0.21
Total suspended solids	**0.02**
Copper, Total	**0.003**
Copper, Dissolved	0.13

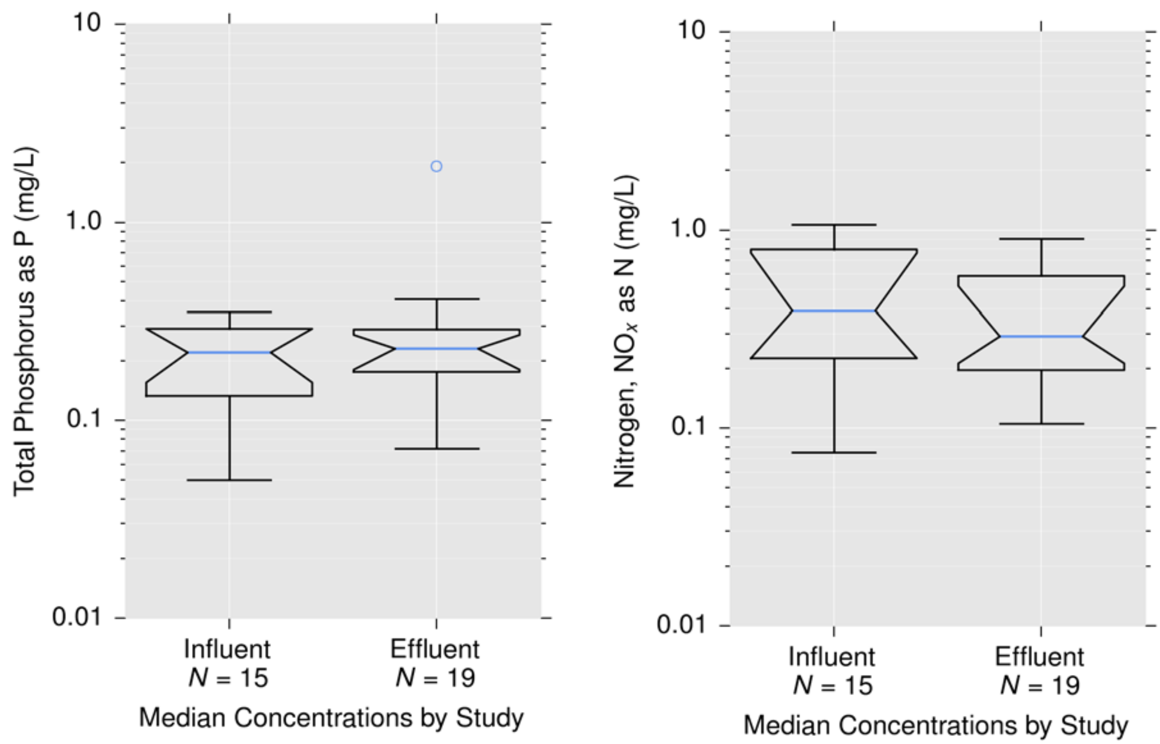

Figure 22. Side-by-side boxplots of influent and effluent concentrations for TP and NOx for grass swales.

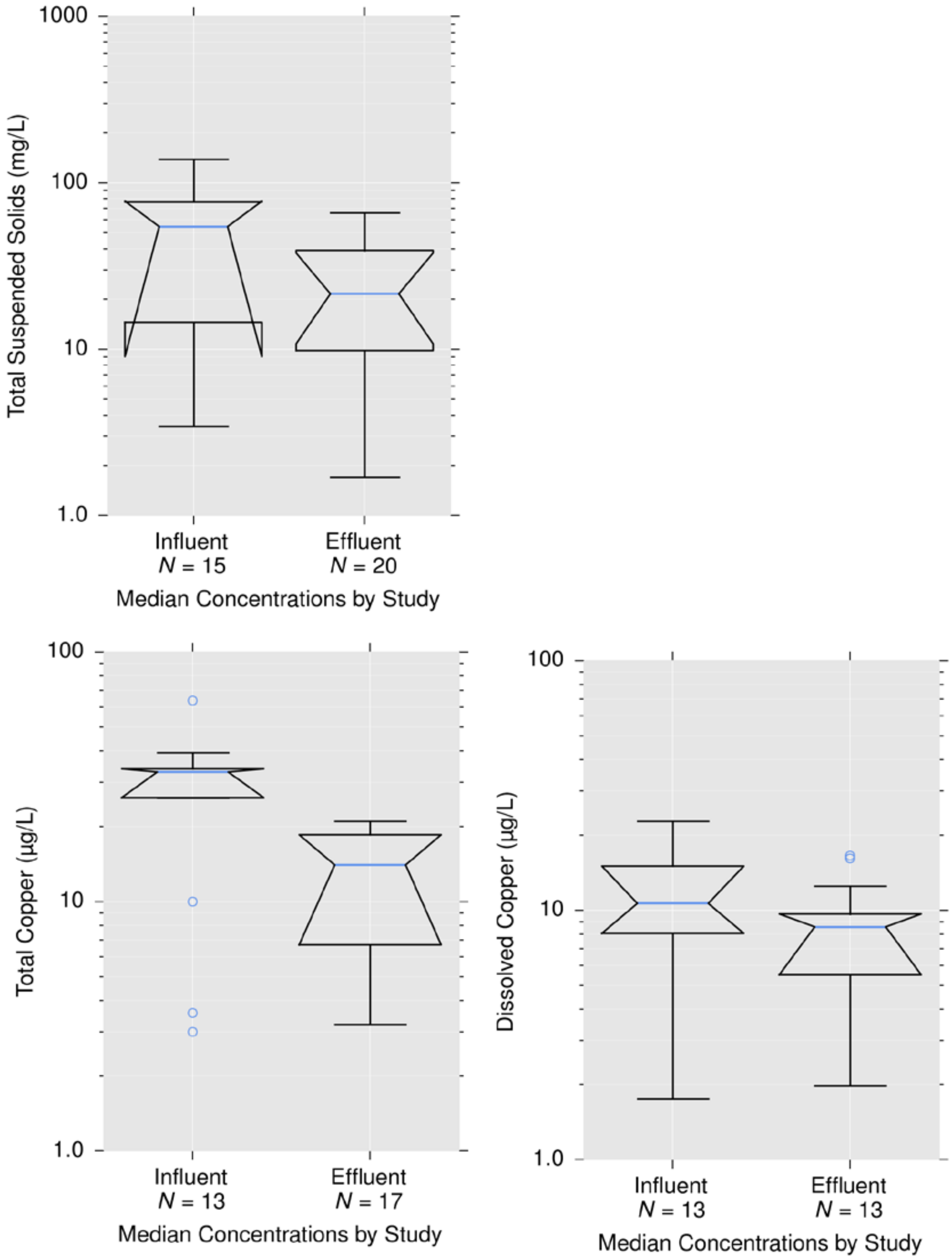

Figure 23. Side-by-side boxplots of influent and effluent concentrations for TSS, TCu, and DCu for grass swales.

Table 16 indicates that two-year depth negatively correlates with effluent NOx and total copper and that swale length negatively correlates with effluent dissolved copper. The decrease in effluent concentration with increasing swale length makes sense, but the statistically significant correlations for the two-year depth are counterintuitive (i.e., decreasing design depth would be expected to result in decreasing concentrations). The next section presents scatterplots for further analysis of these results and to explore the extent to which they are explained by correlations with influent concentration.

Table 16. Spearman's rho correlation coefficients (p-values) between median effluent concentration and the listed parameters for grass swales.

Constituent	Length (m)	Slope	Two-Year Depth (m)	Influent Median
Phosphorus as P, Total	-0.14 (0.57)	0.21 (0.41)	-0.39 (0.38)	0.24 (0.40)
NOx as N	0.01 (0.97)	0.22 (0.41)	**-0.70 (0.08)**	**0.53 (0.04)**
Total suspended solids	0.01 (0.96)	-0.36 (0.14)	-0.55 (0.16)	**0.50 (0.06)**
Copper, Total	-0.19 (0.46)	0.16 (0.58)	**-0.70 (0.08)**	**0.76 (0.003)**
Copper, Dissolved	**-0.54 (0.06)**	0.42 (0.20)	-0.87 (0.33)	**0.81 (0.001)**

2.4.1 Total Phosphorus

Figure 24 and the Spearman's rho correlation coefficients in Table 16 indicate no statistically significant correlation between effluent total phosphorus concentration and any of the design variables. There is also no significant relationship between median influent and effluent TP concentrations. As with grass filter strips, export is evident in the scatterplot for several of the studies, but the Mann-Whitney results in Table 15 indicates that export is not statistically significant. Together, the analyses indicate that grass swales are not generally effective at reducing phosphorus concentrations, but as noted previously, the export could be due to decaying detritus (e.g., grass clippings, leaves, etc.) rather than export from the planting media.

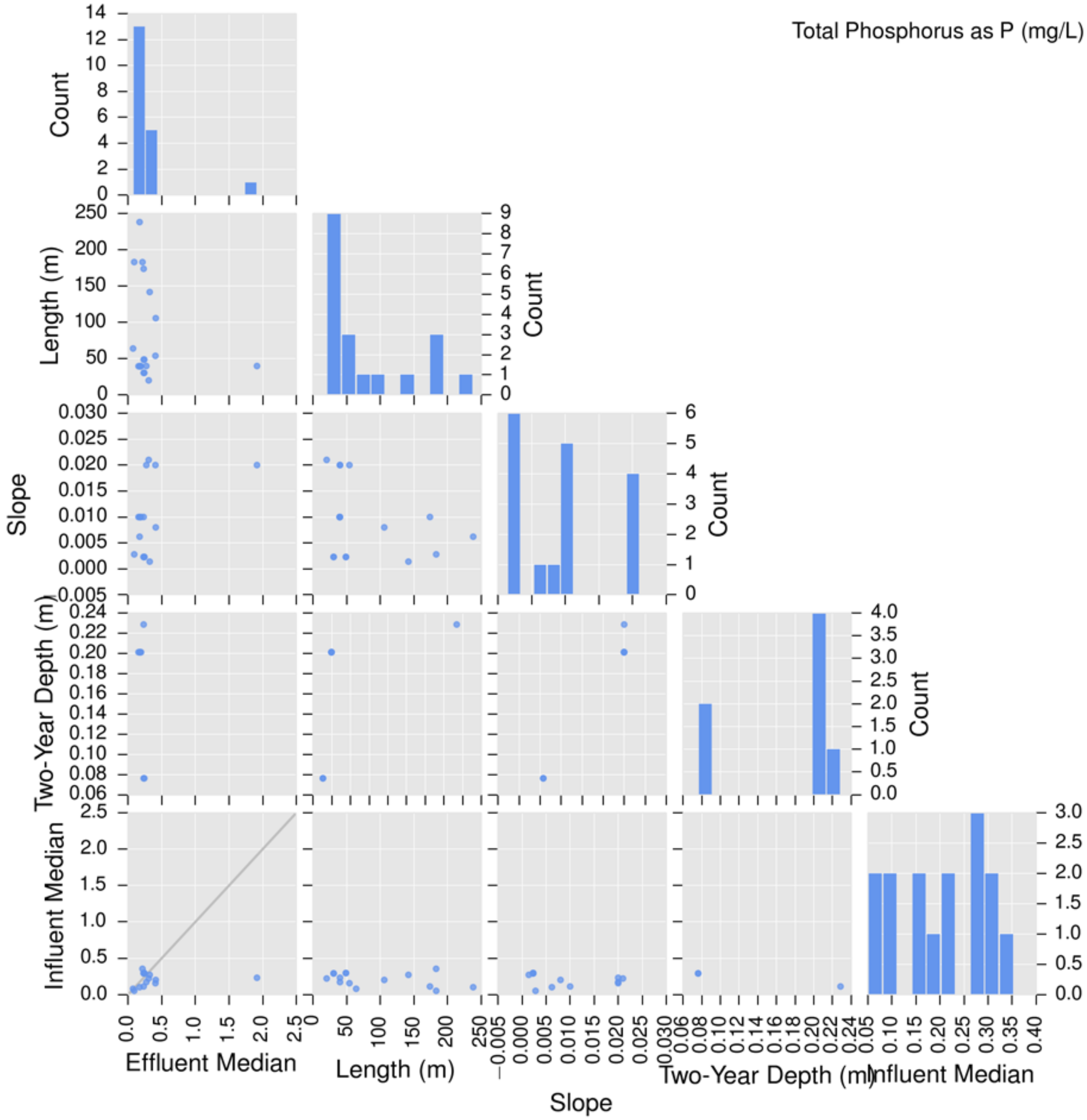

Figure 24. Scatter matrix of median total phosphorus as P in the influent and effluent with selected design parameters for grass swales.

2.4.2 NOx

Figure 25 indicates a slightly negative relationship between the two-year depth and effluent concentration of NOx. However, despite having seven data pairs, there is not adequate variability in this design parameter to validate the statistical significance indicated by the Spearman's rho correlation coefficient of -0.70 and p-value of 0.08 (Table 16). The relationship between influent and effluent concentrations is statistically significant ($p=0.04$) and the Mann-Whitney indicates insignificant differences between medians ($p=0.24$), which reinforces the observation that swales are not effective at removing NOx.

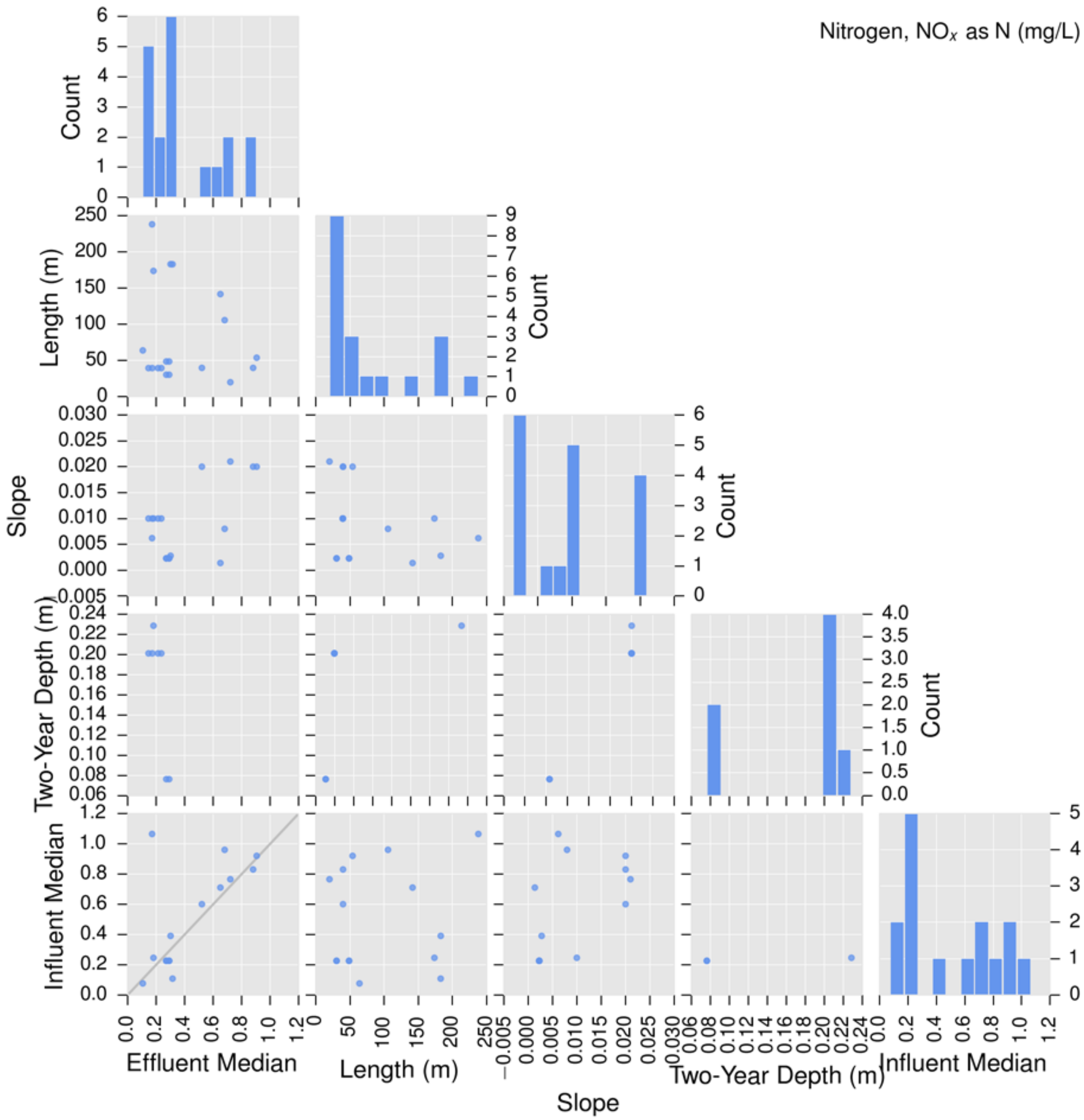

Figure 25. Scatter matrix of median NOx concentration in the influent and effluent with selected design parameters for grass swales.

2.4.3 Total Suspended Solids

Figure 26 and the Spearman's rho correlation coefficient in Table 16 indicate that none of the design parameters are statistically related to effluent concentrations. A statistically significant correlation between median influent and effluent concentrations was identified, and since the Mann-Whitney results indicate statistically significant differences, it may be possible to develop a functional relationship between influent and effluent concentrations.

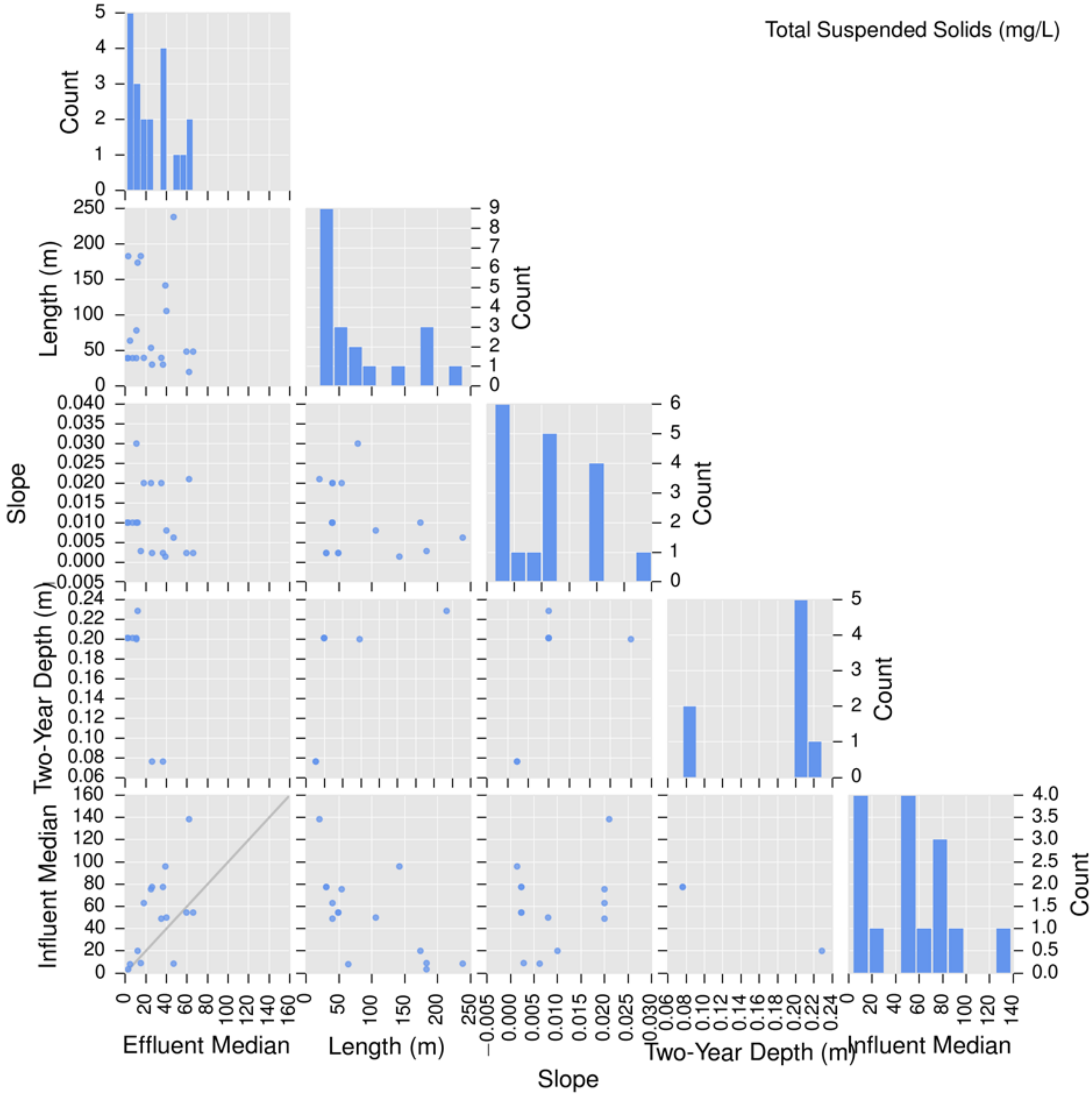

Figure 26. Scatter matrix of median total suspended solids in the influent and effluent with selected design parameters for grass swales.

2.4.4 Total Copper

As shown in Figure 27 and Table 16, median effluent total copper concentration is negatively correlated with the 2-year design depth, but as with NOx, this correlation is not considered to be meaningful due to the small number of discrete design depths. Also, the median influent concentrations are also similarly related to 2-year design depth, which further discounts the significance of this design parameter for the group of analyzed studies. The scatter matrix does indicate consistent total copper concentration reductions and, with a statistically significant

Spearman's rho, it may be possible to develop an empirical relationship between influent and effluent total copper concentrations.

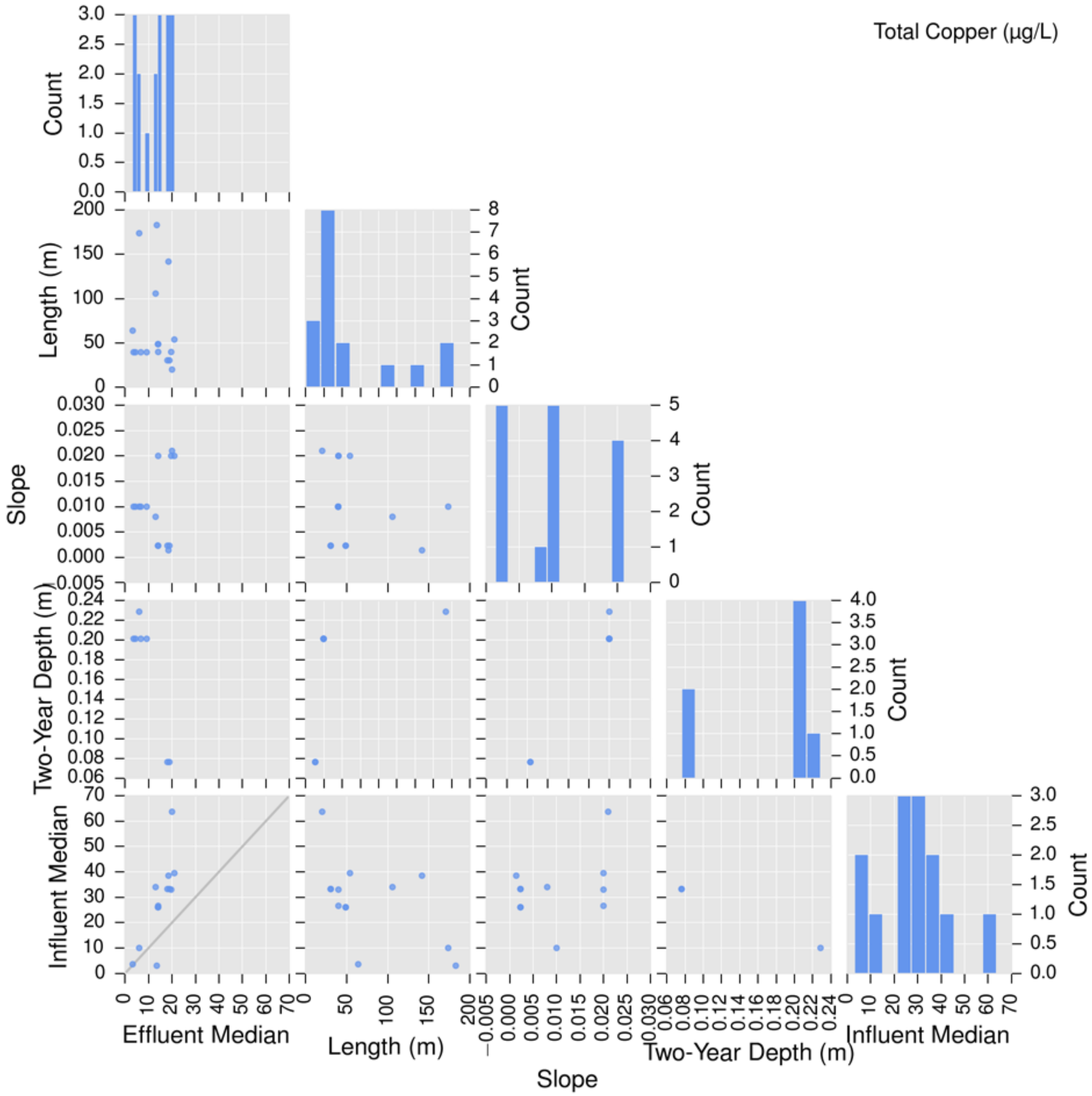

Figure 27. Scatter matrix of median total copper concentration in the influent and effluent with selected design parameters for grass swales.

2.4.5 Dissolved Copper

Figure 28 and the Spearman's rho correlation coefficient in Table 16 shows an inverse relationship between the length of the swale and the median effluent concentration ($p = 0.06$). However, a similar relationship is observed in the scatterplot between the length and the influent concentration, so this does not represent a causal link between length and effluent concentration. The median influent and effluent concentrations are significantly correlated, and the scatterplot generally indicates dissolved copper reductions. However, additional studies are needed to justify the development of a functional relationship between influent and effluent concentrations since the Mann-Whitney results indicate that the differences are not quite statistically significant (p=0.13).

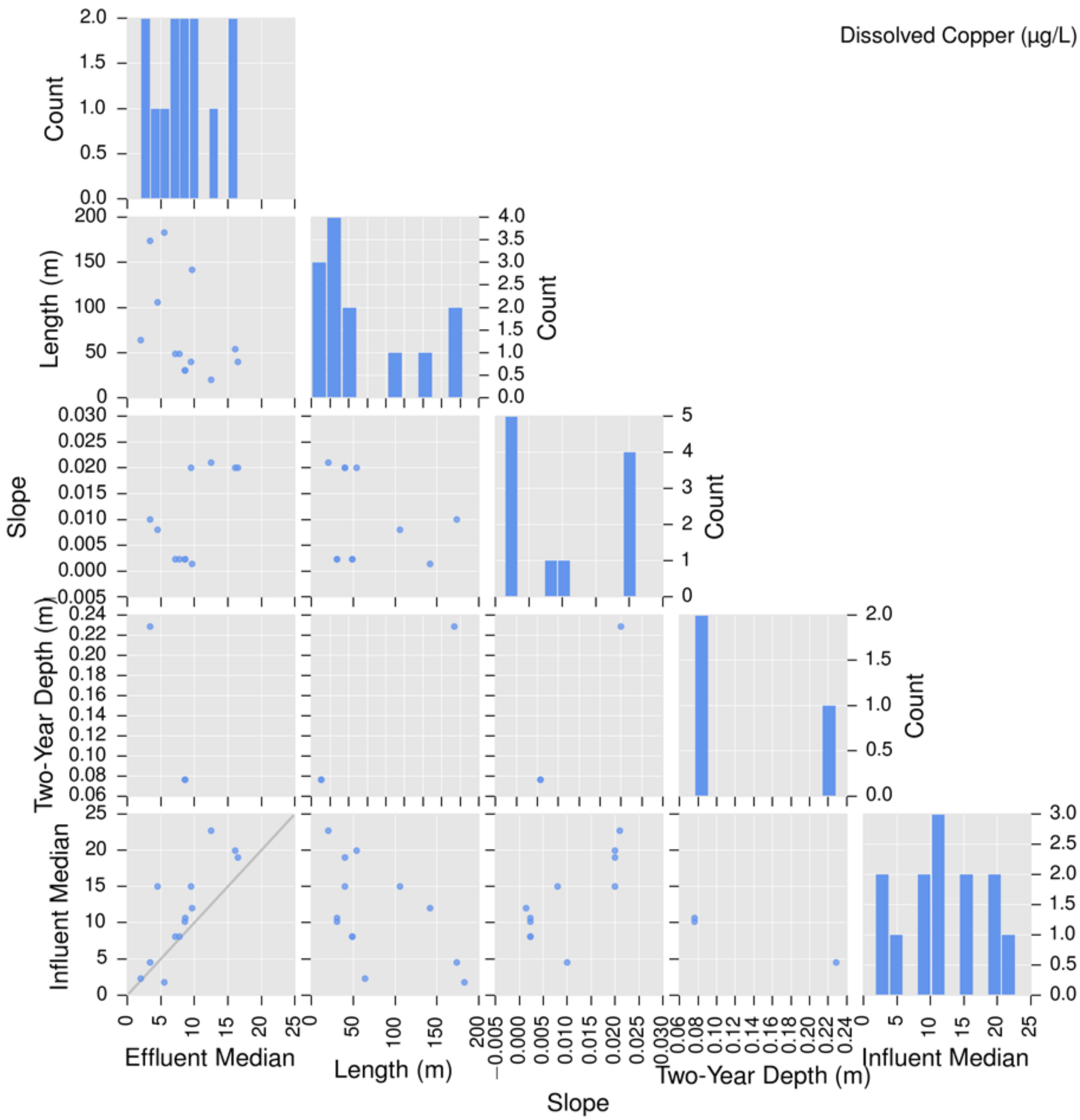

Figure 28. Scatter matrix of median dissolved copper in the influent and effluent with selected design parameters for grass swales.

2.5 Media Filters

Due to the limited number of studies for media types other than sand filters, the analysis effort focused on sand filters only. The features analyzed were the presence/absence of a sedimentation basin preceding the filter, the footprint area relative to the drainage area (FA/DA ratio), and the media depth. Although the design infiltration rate and the maintenance frequency are also expected to be major factors in performance, this information was not readily available in the BMPDB. Table 17 summarizes the parameters analyzed for media filters.

Table 17. Media filter design parameters analyzed.

Design Parameter	Analysis Performed
Sedimentation Basin (presence/absence)	Side-by-side boxplots; hypothesis tests on difference between median effluent concentrations
Footprint/drainage area ratio (FA/DA)	Non-parametric correlation of median effluent concentration vs. footprint/drainage area ratio
Media depth	Non-parametric correlation of median effluent concentration vs. media depth

Table 18 presents the number of available studies for analysis of each parameter. Adequate data are available for the design parameters evaluated except for the presence/absence of sedimentation basins. Consequently, this design feature is only discussed qualitatively.

Table 18. Number of media filter studies available for indicated pollutant and design parameter.

Constituent	FA/DA ratio	Media Depth (m)	Has Sed. Basin	No Sed. Basin	Influent Median
Phosphorus as P, Total	13	13	10	3	13
Phosphorus as P, Dissolved	7	7	-	-	7
NOx as N	13	13	10	3	13
Total suspended solids	13	13	10	3	13
Copper, Total	13	13	10	3	13
Copper, Dissolved	10	10	8	2	10

Table 19 presents the results of Mann-Whitney analysis of the median influent and effluent concentrations for the studies with available design information. The effluent concentrations are statistically significantly lower than the influent concentrations of total suspended solids, total copper and total phosphorus. Effluent concentrations are significantly higher for NOx, which may be due to oxidation of total Kjeldahl nitrogen (TKN) within the filter media, resulting in nitrate release. The differences in concentration are not statistically significant at the p=0.1 level for dissolved phosphorus and dissolved copper. Figure 29 and Figure 30 show side-by-side boxplots of the median influent and effluent concentrations of each analyzed constituent and the plots generally agree with the hypothesis test results. TSS is the only constituent without overlapping confidence intervals, but there is only partial overlap for TP and TCu indicating relatively reliable reductions in concentrations for all three of these constituents.

Table 19. p-values from Mann-Whitney analysis of influent and effluent concentrations for media filters.

Constituent	MW p-value
Phosphorus as P, Total	**0.04**
Phosphorus as P, Dissolved	0.47
NOx as N	**0.02**
Total suspended solids	**<0.0001**
Copper, Total	**0.006**
Copper, Dissolved	0.48

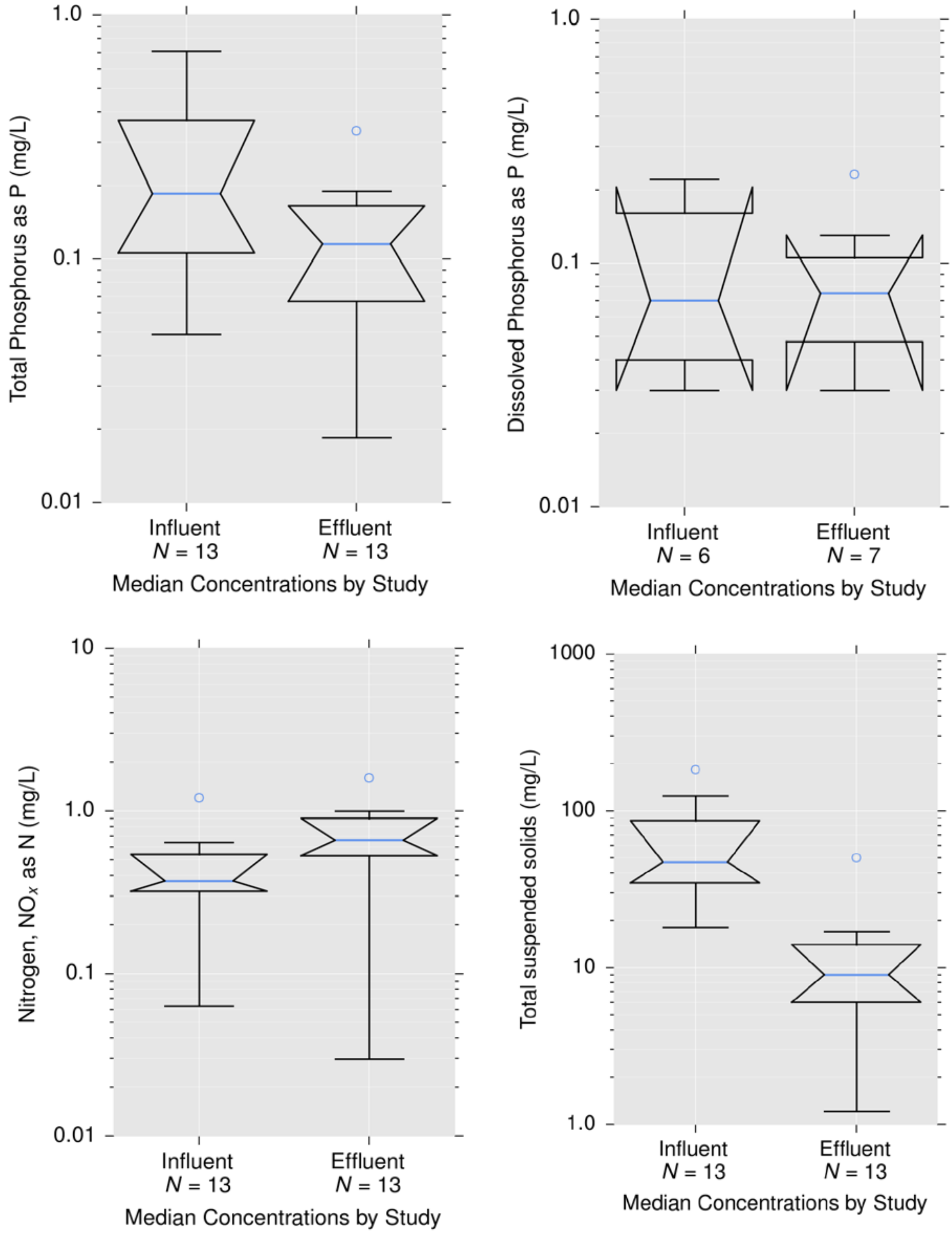

Figure 29. Side-by-side boxplots of influent and effluent concentrations of TP, DP, NOx, and TSS for media filters.

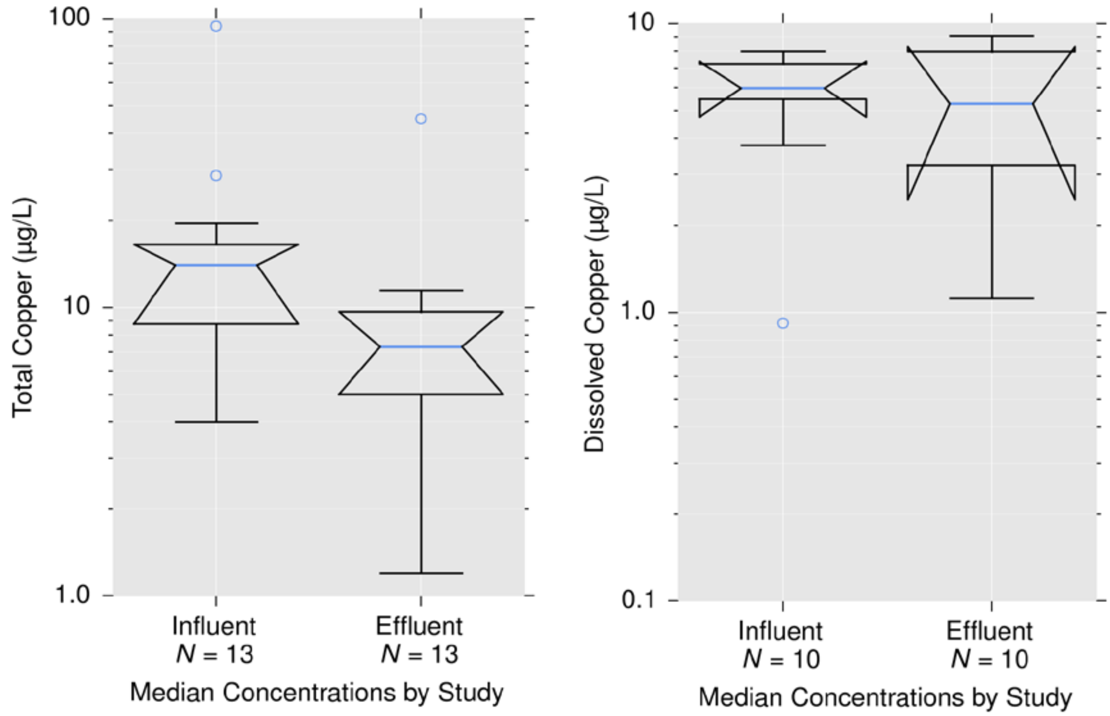

Figure 30. Side-by-side boxplots of influent and effluent concentrations for TCu and DCu for media filters.

Table 20 indicates there is a strong correlation between influent concentration and effluent concentration (as measured by the p-value from Spearman's rho tests), but no statistically significant correlation between the two design parameters and effluent concentration except for the footprint area to drainage area (FA/DA) ratio for total and dissolved copper. Scatterplots along with these correlation analysis results are discussed for each analyzed constituent in the sections below. Dot plots are also presented comparing effluent concentrations for BMPs with and without sedimentation basins.

Table 20. Spearman's rho correlation coefficients (p-values) between median effluent concentration and the listed parameters for media filters.

Constituent	FA/DA ratio	Media Depth (m)	Influent Median
Phosphorus as P, Total	-0.10 (0.75)	-0.03 (0.93)	**0.95 (<0.0001)**
Phosphorus as P, Dissolved	0.59 (0.16)	0.21 (0.66)	**0.99 (0.0003)**
NOx as N	-0.31 (0.30)	-0.17 (0.59)	**0.88 (<0.0001)**
Total suspended solids	0.03 (0.91)	-0.09 (0.79)	**0.65 (0.02)**
Copper, Total	**-0.54 (0.06)**	0.25 (0.44)	**0.84 (0.0004)**
Copper, Dissolved	**-0.58 (0.08)**	-0.01 (0.97)	**0.83 (0.003)**

2.5.1 Total Phosphorus

Figure 31 and the Spearman's rho correlation results shown in Table 20 indicate no significant correlation between effluent total phosphorus concentration and either of the design parameters. However, there is a strong and statistically significant correlation with the influent median concentration and consistent removals are indicated in the scatterplot indicating that a potential functional relationship between influent and effluent may exist.

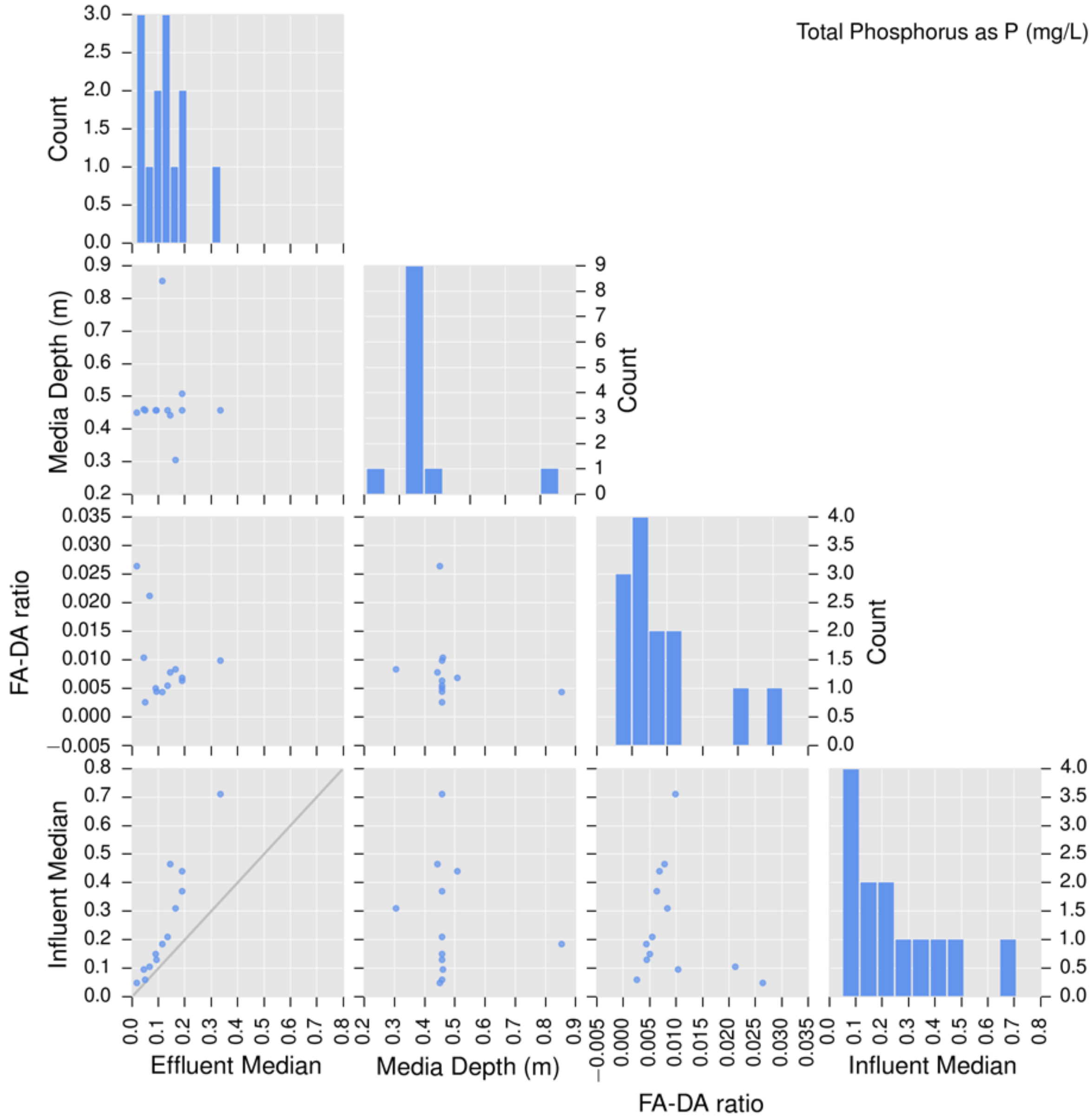

Figure 31. Scatter matrix of median total phosphorus concentration in the influent and effluent with selected design parameters for media filters.

Figure 32 shows a comparison between effluent concentrations with and without a sedimentation basin. Few studies were available without a sedimentation basin, so no conclusions could be made with regard to the water quality performance benefits of having a sedimentation basin upstream of a sand filter. Nonetheless, pretreatment is considered critical for the longevity of the filter bed.

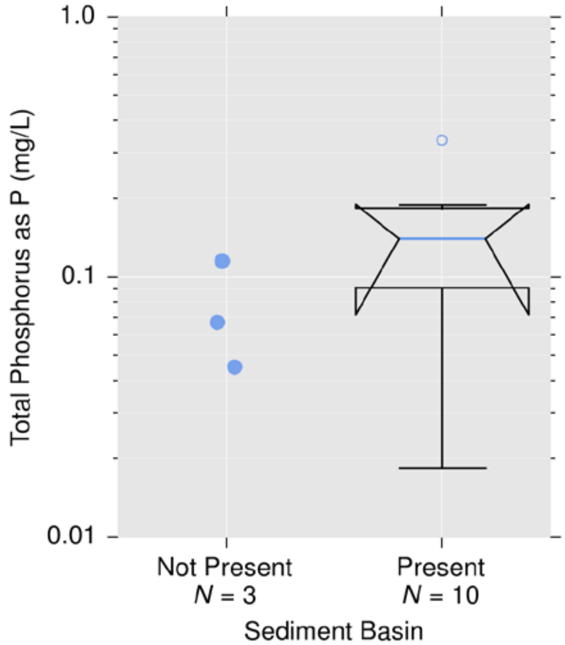

Figure 32. Box and dot plots respectively showing effluent total phosphorus concentrations for media filters with and without a sediment basin.

2.5.2 Dissolved Phosphorus

Table 20 and Figure 33 show no apparent correlation between effluent dissolved phosphorus concentration and either of the design parameters, but data are sparse. The correlation between FA-DA ratio and effluent concentration is nearly statistically significant (p=0.16); however, a confounding relationship is also observed between FA-DA ratio and influent concentration. All of the media filters for which dissolved phosphorus data were available included a sedimentation basin, so the importance of the presence of a sedimentation basin could not be evaluated. Despite the low number of available studies, the plots and analysis indicate that sand filters may not be reliable for removing dissolved phosphorus.

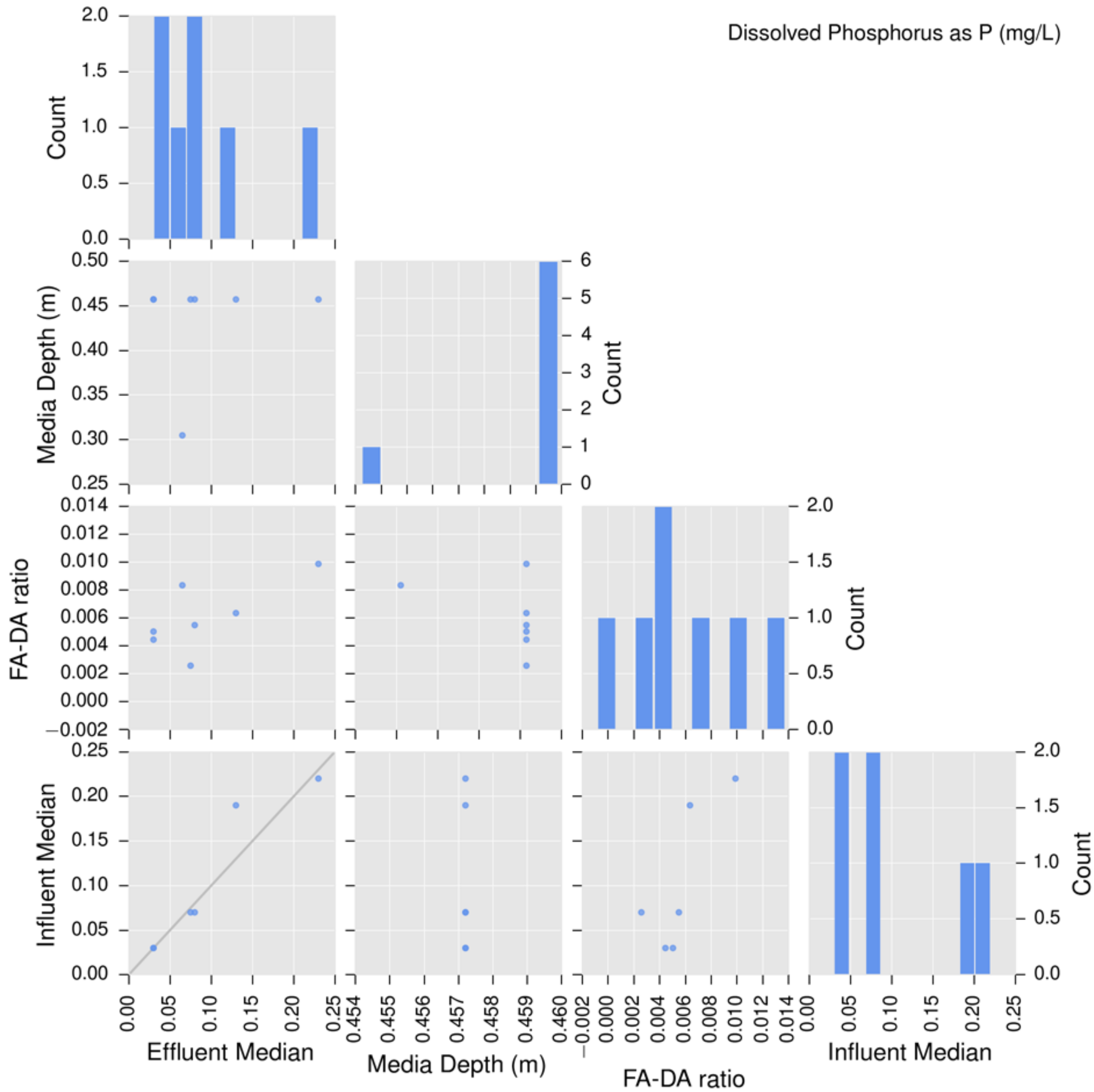

Figure 33. Scatter matrix of median dissolved phosphorus concentration in the influent and effluent with selected design parameters for media filters.

2.5.3 NOx

Table 20 and Figure 34 show no significant correlation between effluent NOx concentration and either of the design parameters, but a net increase in NOx is observed for nearly all studies evaluated. This likely reflects oxidation of total Kjeldahl nitrogen (TKN) within the filter media, resulting in increased nitrate. For other BMP types, similar total nitrogen levels may be discharged to the receiving water where the nitrogen could be oxidized and cause the same net impact. However, depending on receiving water conditions and regulatory considerations, it may still be preferable for oxidation to take place within the water body as opposed to in the BMP, so these findings indicate that sand filters should be selected with caution if nitrate is a target pollutant of concern.

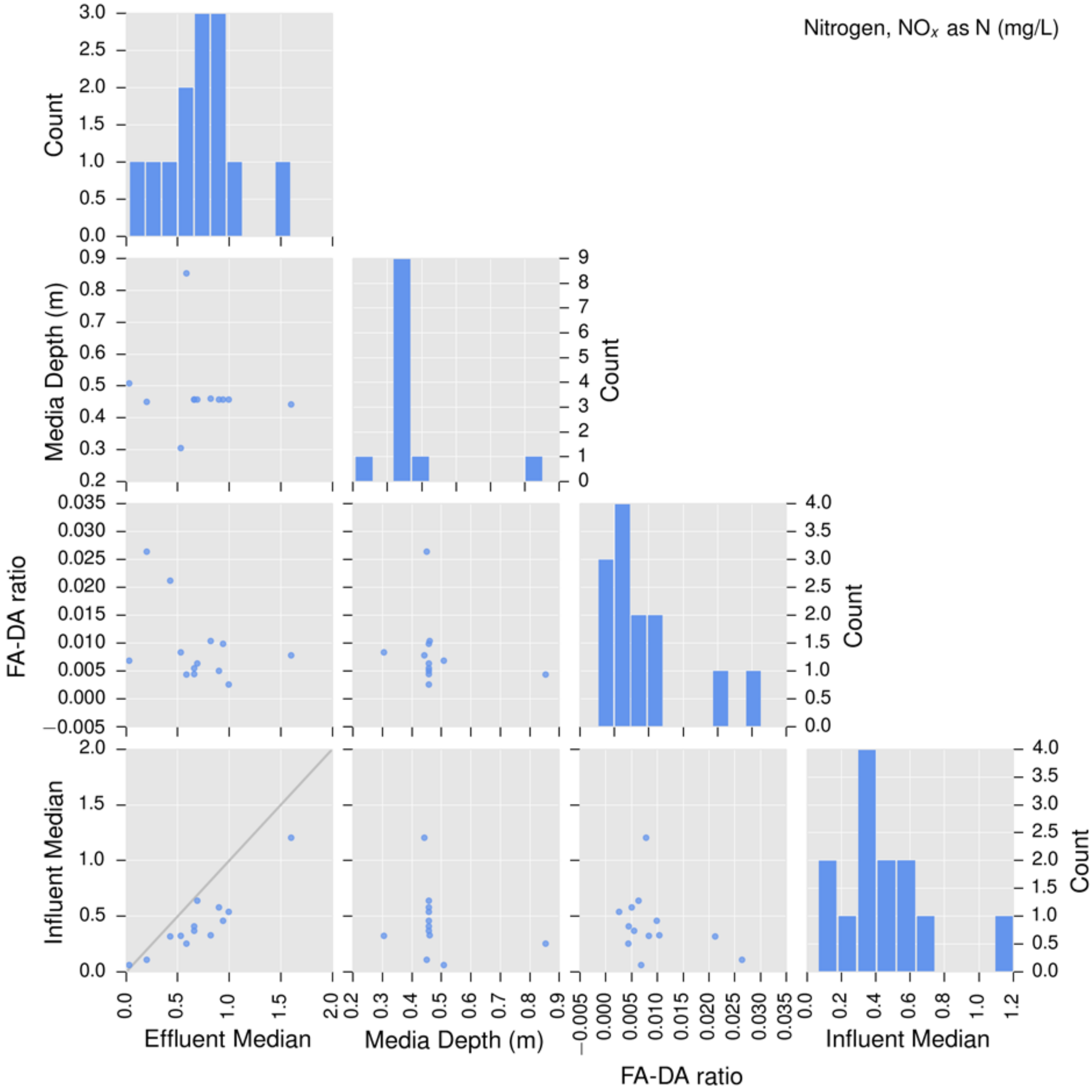

Figure 34. Scatter matrix of median NOx concentration in the influent and effluent with selected design parameters for media filters.

Figure 35 shows a comparison between effluent concentrations with and without a sedimentation basin. Few studies were available without a sedimentation basin, so hypothesis testing could not be reliably conducted.

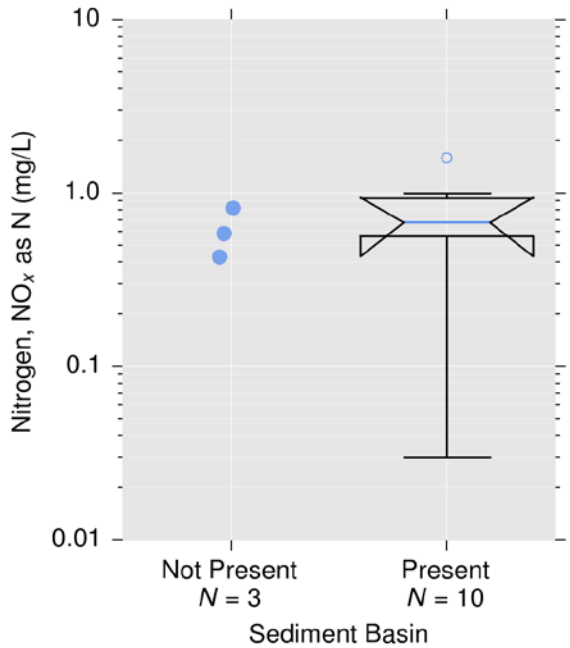

Figure 35. Box and dot plots respectively showing effluent NOx concentrations for media filters with and without a sediment basin.

2.5.4 Total Suspended Solids

Table 20 and Figure 36 show no significant correlation between effluent total suspended solids concentration and either of the design parameters, but there is consistent removal of total suspended solids among the analyzed studies. In fact, most studies achieve median effluent concentrations less than 20 mg/L. The Spearman's rho correlation coefficient between median influent and effluent concentrations is statistically significant indicating that a functional relationship could potentially be developed.

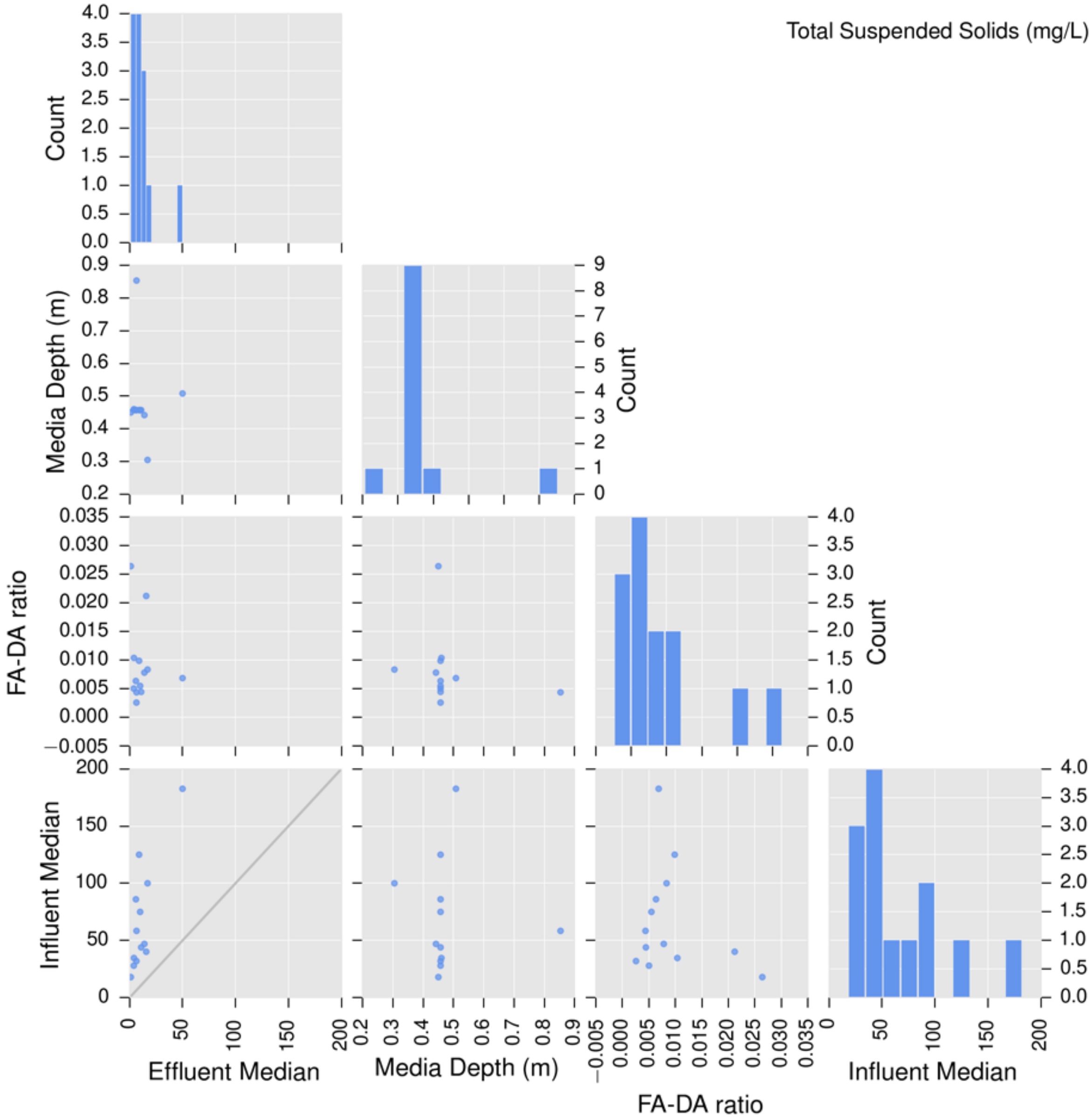

Figure 36. Scatter matrix of median total suspended solids in the influent and effluent with selected design parameters for media filters.

Figure 37 shows a comparison between effluent concentrations with and without a sedimentation basin. Few studies were available without a sedimentation basin, so hypothesis testing could not be reliably conducted.

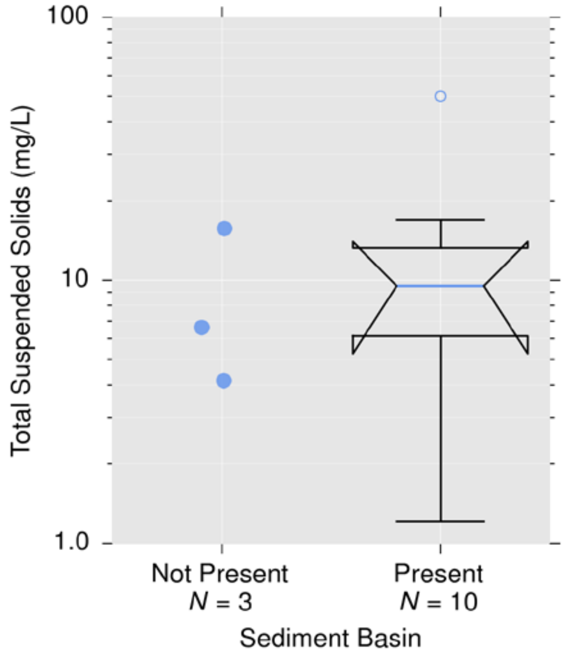

Figure 37. Box and dot plots respectively showing effluent total suspended solids for media filters with and without a sediment basin.

2.5.5 Total Copper

Figure 31 and the Spearman's rho correlation results shown in Table 20 indicate an inverse correlation between FA-DA ratio and effluent total copper concentration (p=0.06), but a similar correlation is also observed between FA-DA ratio and influent total copper concentration. Therefore, this may not indicate a causal link between higher FA-DA ratio and better removal of total copper. There is a strong and statistically significant correlation between median influent and effluent concentrations and consistent removals are indicated both in the scatterplot and the Mann-Whitney test results shown in Table 19. Therefore, it may be possible to develop a statistically valid functional relationship between influent and effluent total copper concentrations for media filters.

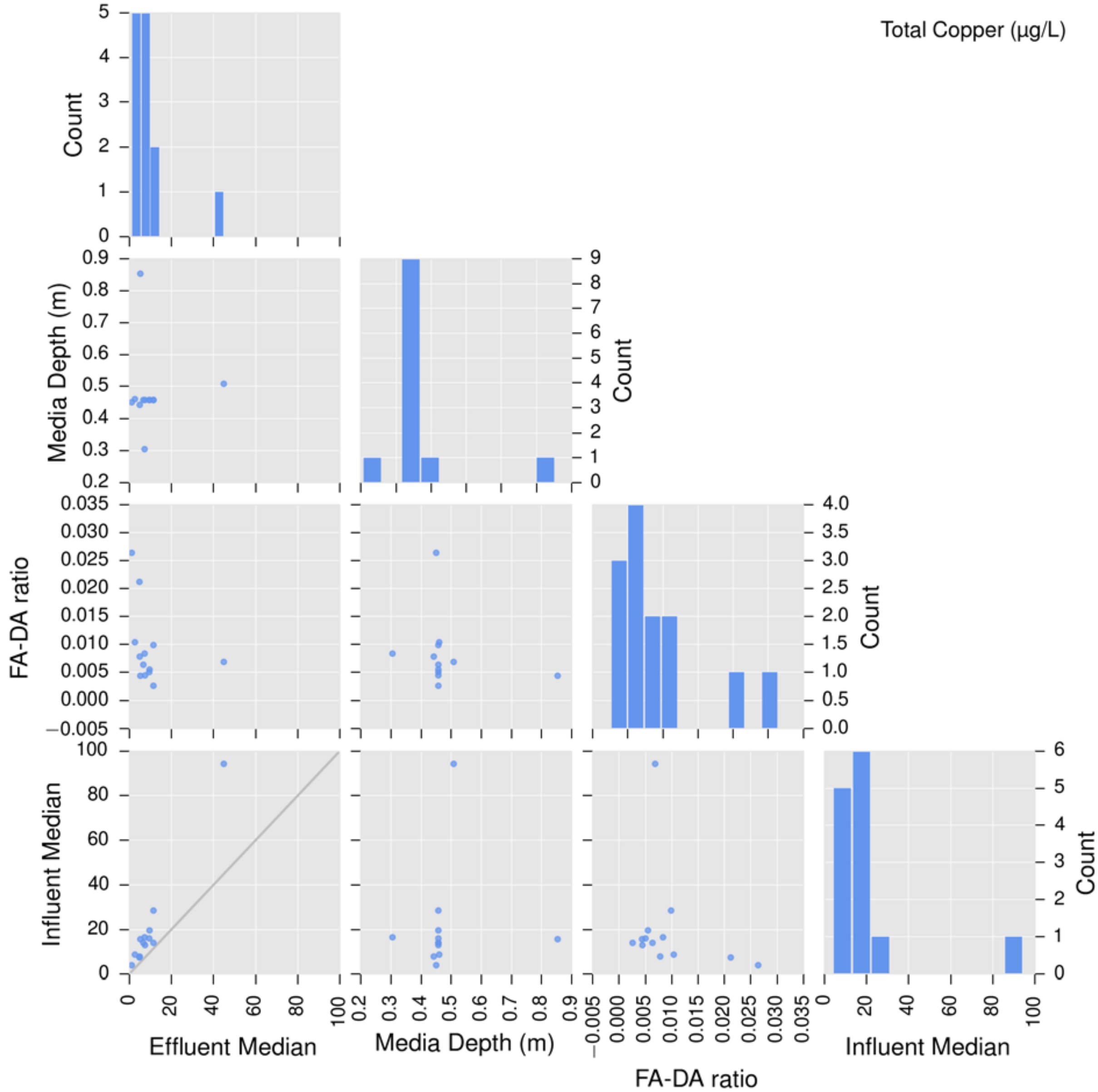

Figure 38. Scatter matrix of median total copper concentration in the influent and effluent with selected design parameters for media filters.

Figure 39 shows a comparison between effluent concentrations with and without a sedimentation basin. Few studies were available without a sedimentation basin, so hypothesis testing could not be reliably conducted.

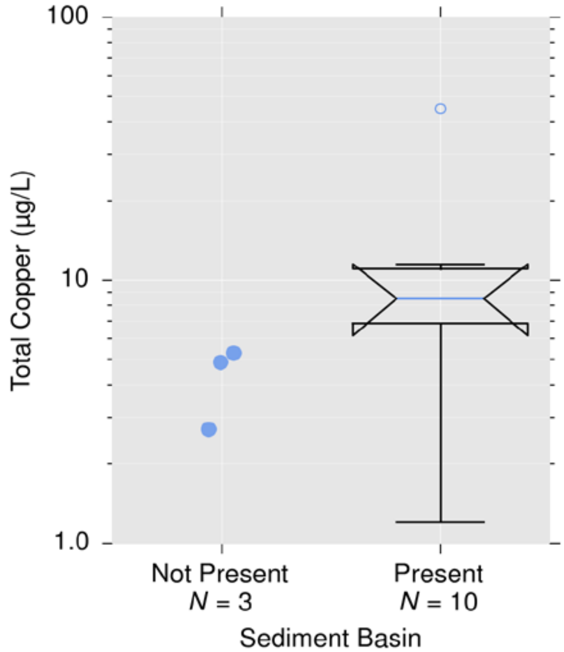

Figure 39. Box and dot plots respectively showing effluent total copper concentrations for media filters with and without a sediment basin.

2.5.6 Dissolved Copper

Figure 40 and the Spearman's rho correlation results shown in Table 20 (p=0.08) indicate an inverse correlation between FA-DA ratio and effluent dissolved copper concentration, but a similar correlation is also observed between FA-DA ratio and influent dissolved copper concentration. Therefore, this does not indicate there is a statistical relationship between higher FA-DA ratio and better removal of dissolved copper. While the influent/effluent Spearman's rho is statistically significant, the influent/effluent scatterplot and the Mann-Whitney test results shown in Table 19 do not indicate consistent dissolved copper removal by sand filters.

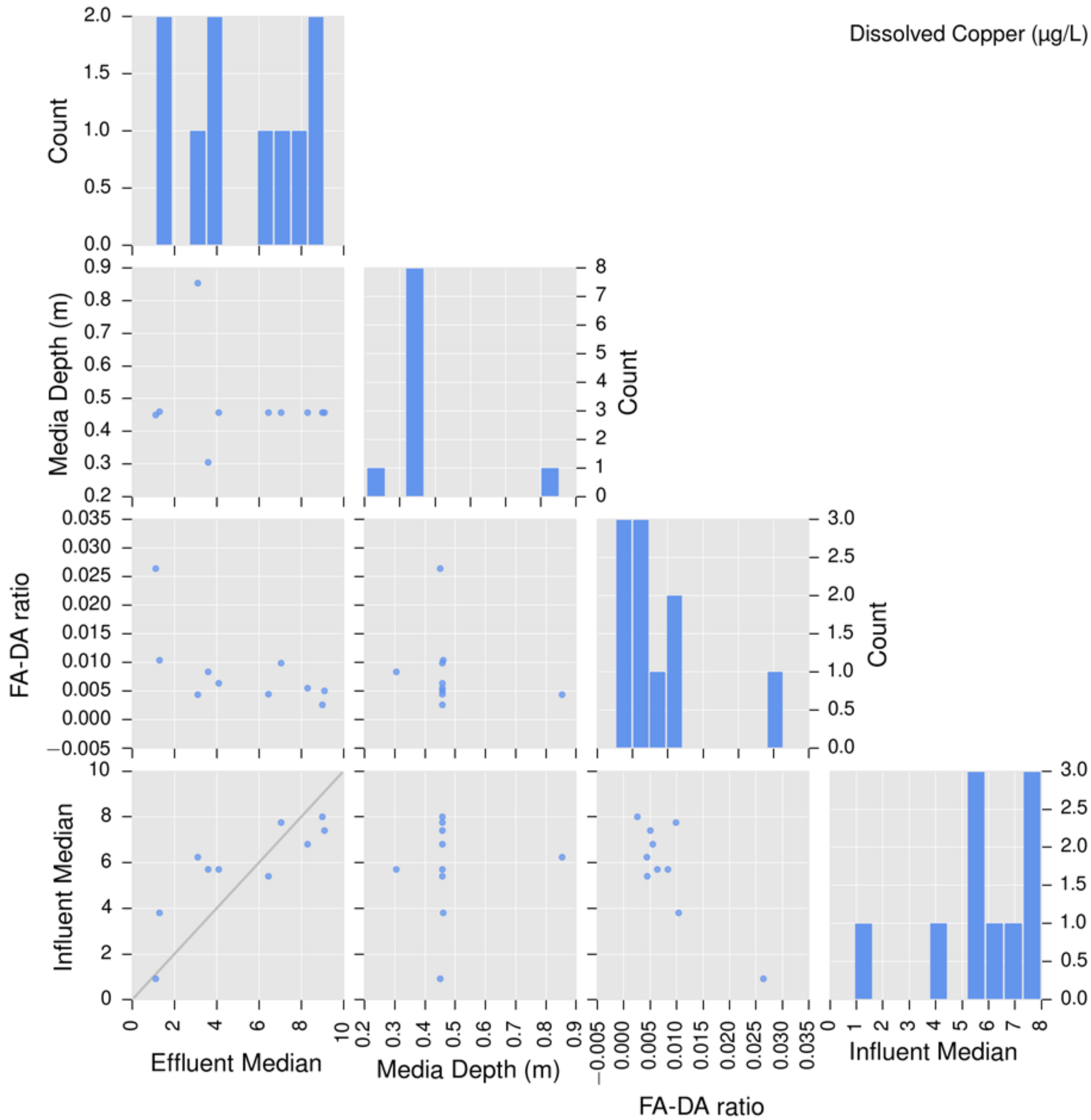

Figure 40. Scatter matrix of median dissolved copper concentration in the influent and effluent with selected design parameters for media filters.

Figure 41 shows a comparison between effluent concentrations with and without a sedimentation basin. More data would be needed to conduct meaningful statistical analysis because few studies were available without a sedimentation basin.

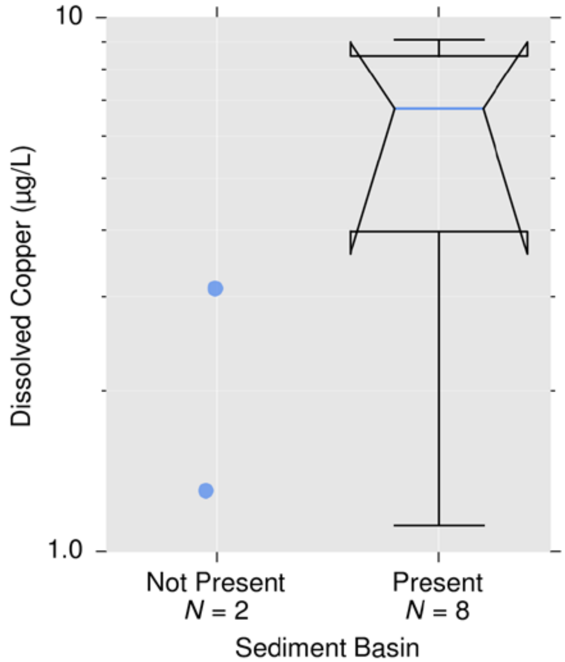

Figure 41. Box and dot plots respectively showing effluent dissolved copper concentrations for media filters with and without a sediment basin.

2.6 Retention Ponds

Table 21 summarizes the key retention pond parameters that were analyzed. While the density of wetland vegetation and/or the percentage of open water are also expected to influence performance, this information is not consistently reported in the database to support this type of factorial analysis. For example, only six studies report the area of the vegetated littoral zone.

Table 21. Retention pond design parameters analyzed.

Design Parameter	Analysis Performed
Water quality surcharge volume/permanent pool volume (WQSV/PPV)	Non-parametric correlation of median effluent concentration vs. surcharge volume to permanent pool ratio
Permanent pool volume/average storm depth (PPV/ASV)	Non-parametric correlation of median effluent concentration vs. permanent pool design storm ratio
Length/width ratio of permanent pool (L/W)	Non-parametric correlation of median effluent concentration vs. length-to-width ratio

Table 22 shows the number of available studies for analysis of each parameter.

Table 22. Number of retention pond studies available for indicated pollutant and design parameter.

Constituent	L / W	PPV / ASV	WQSV / PPV	Influent Median
Phosphorus as P, Total	34	34	34	34
Phosphorus as P, Dissolved	14	14	14	14
NOx as N	26	26	26	26
Total suspended solids	35	35	35	35
Copper, Total	22	22	22	22
Copper, Dissolved	10	10	10	10

Table 23 presents the results of Mann-Whitney analysis of the median influent and effluent concentrations for the studies with available design information. The median effluent concentrations are statistically significantly lower than the median influent concentrations of all of the analyzed constituents except for dissolved phosphorus, which is nearly significant ($p=0.14$). Figure 42 and Figure 43 show side-by-side boxplots of the median influent and effluent concentrations of each constituent. While all of the boxplots indicate median concentration reductions, only the TSS boxplot has confidence intervals that do not overlap. Overall, the data indicate that retention ponds can be effective at reducing concentrations of all of the pollutants analyzed.

Table 23. p-values from Mann-Whitney analysis of influent and effluent concentrations for retention ponds.

Constituent	MW p-value
Phosphorus as P, Total	**0.0009**
Phosphorus as P, Dissolved	0.14
NOx as N	**0.007**
Total suspended solids	**<0.0001**
Copper, Total	**0.01**
Copper, Dissolved	**0.07**

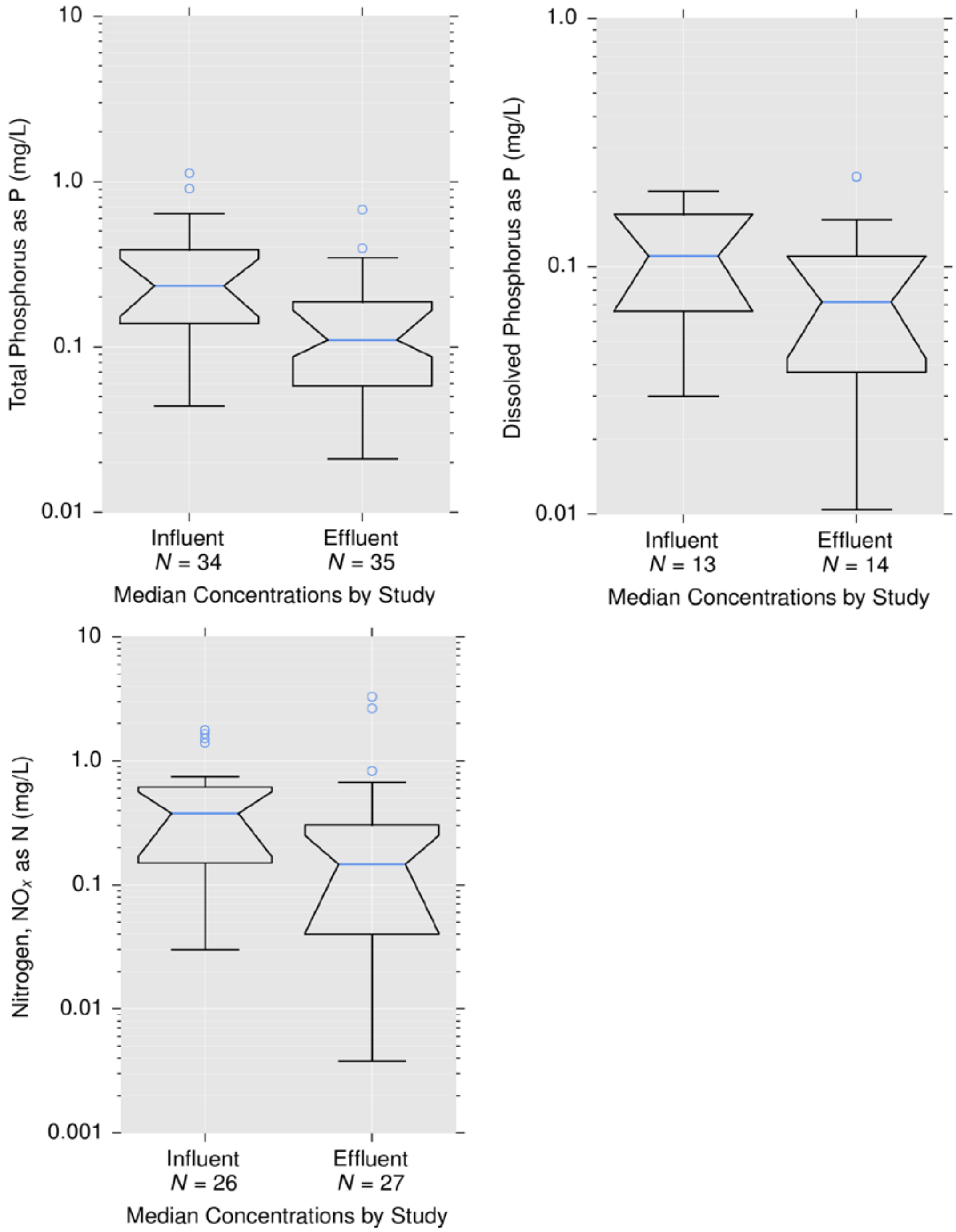

Figure 42. Side-by-side boxplots of influent and effluent concentrations of indicated constituents for retention ponds.

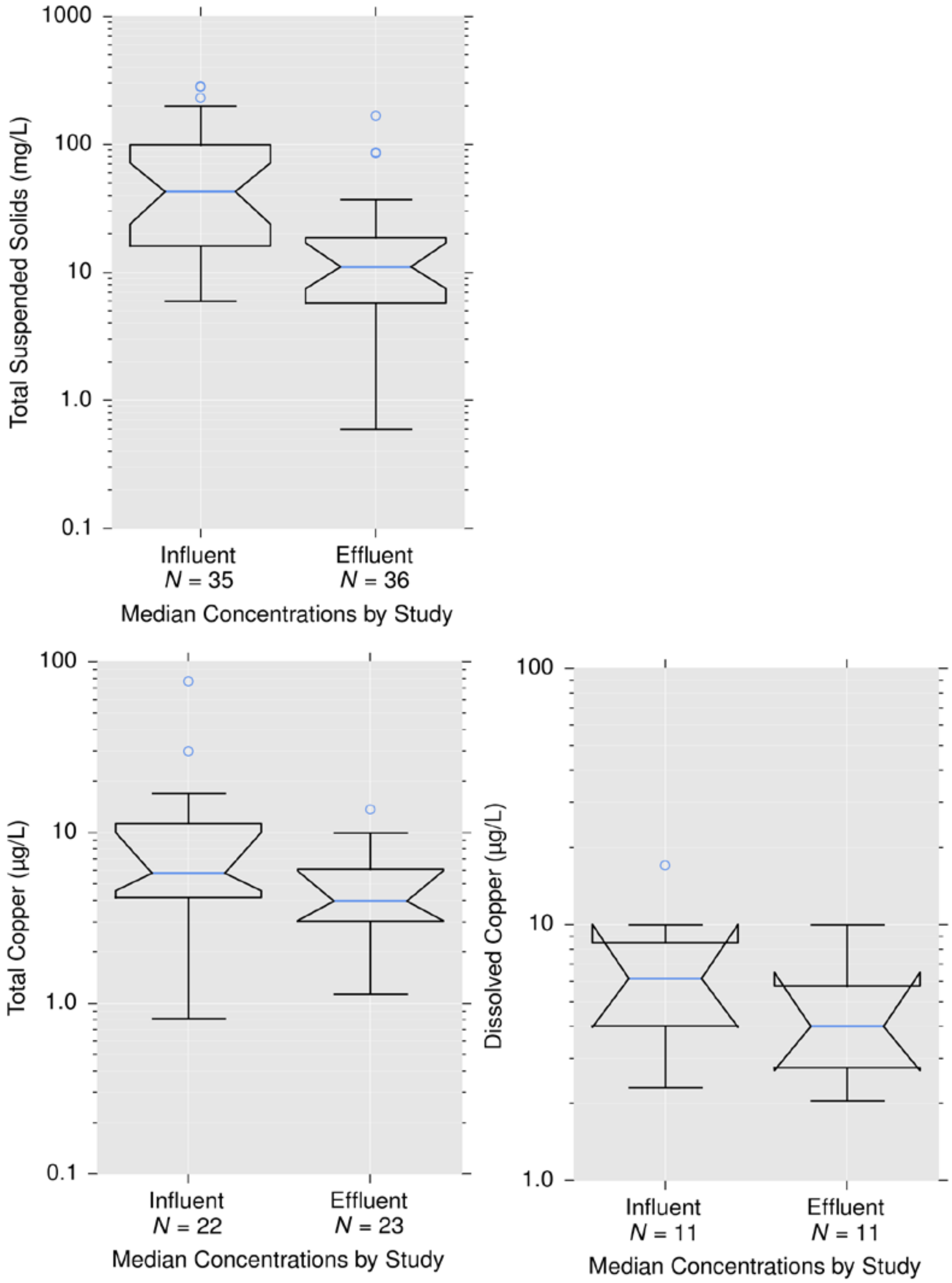

Figure 43. Side-by-side boxplots of influent and effluent concentrations of indicated constituents for retention ponds.

Table 24 indicates that the design parameters correlate with effluent concentrations for a few of the constituents considered. The next section presents scatterplots for further analysis of these results and to explore whether they are confounded by correlations with influent concentration.

Table 24. Spearman's rho correlation coefficients (p-values) between median effluent concentration and the listed parameters for retention ponds.

Constituent	L / W	PPV / ASV	WQSV / PPV	Influent Median
Phosphorus as P, Total	**-0.53 (0.05)**	-0.31 (0.11)	**-0.64 (0.09)**	**0.78 (<0.0001)**
Phosphorus as P, Dissolved	-0.32 (0.43)	-0.01 (0.97)	-0.61 (0.15)	**0.47 (0.10)**
NOx as N	0.35 (0.32)	-0.35 (0.14)	0.13 (0.73)	**0.74 (<0.0001)**
Total suspended solids	-0.18 (0.55)	**-0.54 (0.003)**	0.24 (0.53)	**0.41 (0.02)**
Copper, Total	0.09 (0.79)	-0.31 (0.24)	0.28 (0.47)	**0.45 (0.04)**
Copper, Dissolved	-0.23 (0.52)	-0.15 (0.68)	-0.20 (0.70)	**0.87 (0.001)**

2.6.1 Total Phosphorus

Figure 44 and the Spearman's rho correlation results shown in Table 24 indicate statistically significant negative correlations between effluent concentrations and the L/W and WQSV/PPV ratios. Both of these relationships are also confounded by similar relationships with influent concentration. Median concentration reductions are noted in the scatter plot for nearly all studies and the Spearman's rho indicates a statistically significant influent/effluent correlation. Therefore, it may be possible to develop a statistically valid functional relationship between median influent and effluent concentrations.

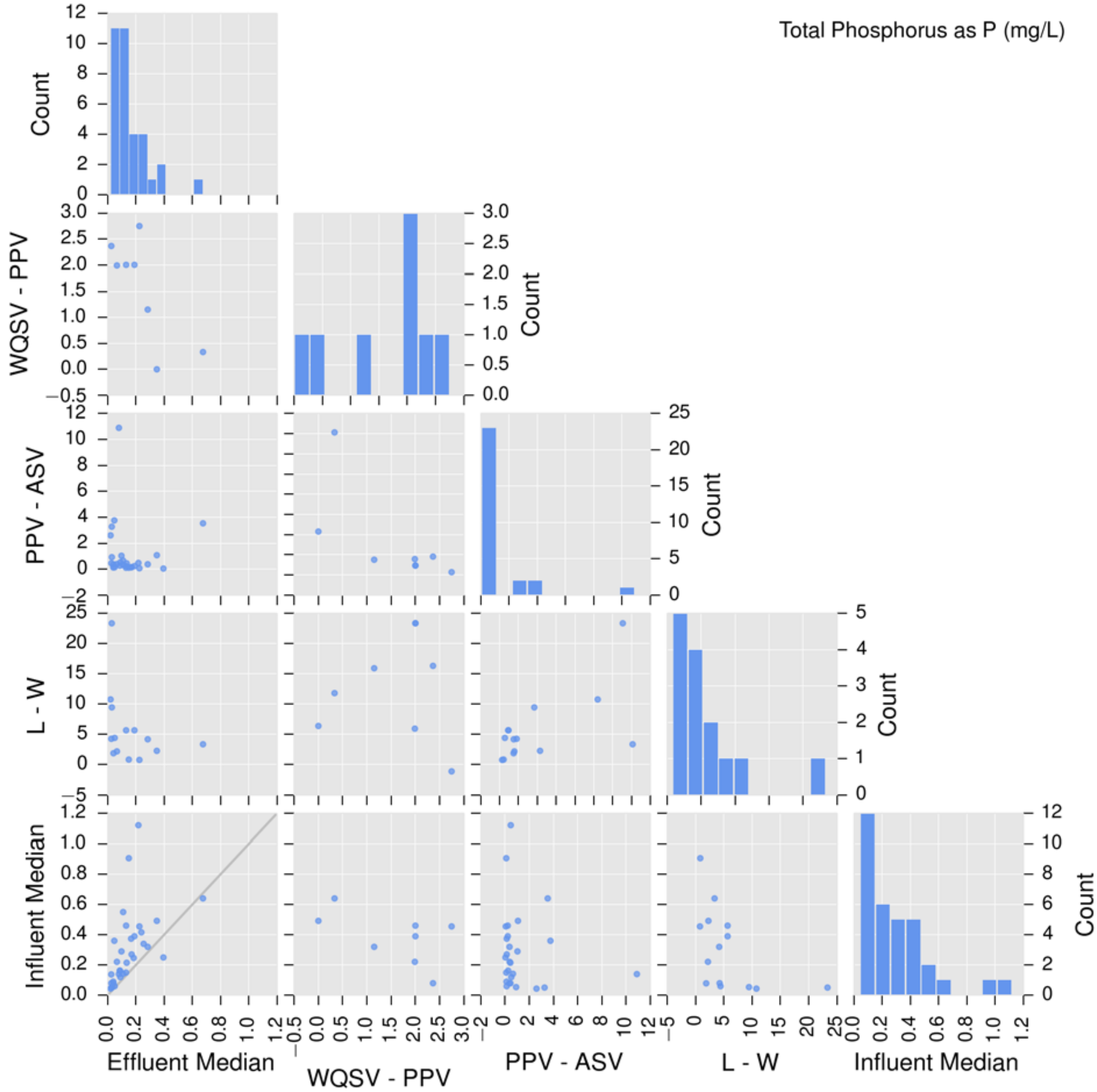

Figure 44. Scatter matrix of median total phosphorus concentration in the influent and effluent with selected design parameters for retention ponds.

2.6.2 Dissolved Phosphorus

Figure 45 suggests a trend where higher WQSV/PPV values result in lower dissolved phosphorus concentrations. While this suggested relationship is not quite statistically significant based on the Spearman's rho correlation results (p=0.15), a similar relationship is not identified for the influent concentrations, indicating that there may be a causal relationship between this design parameter and effluent concentration that could be validated with additional data.

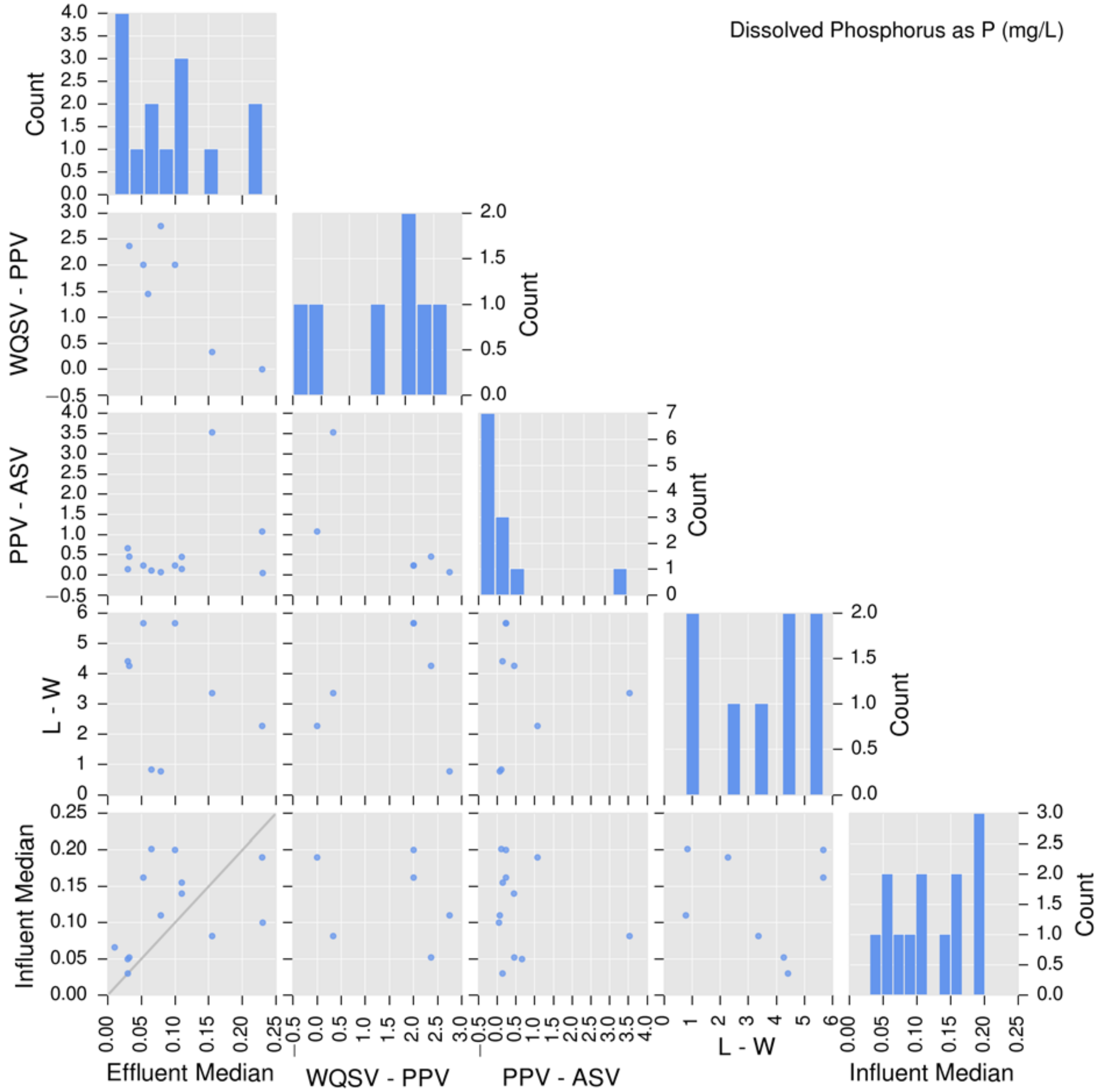

Figure 45. Scatter matrix of median dissolved phosphorus concentration in the influent and effluent with selected design parameters for retention ponds.

2.6.3 NOx

Figure 46 and the Spearman's rho correlation results shown in Table 24 indicate that the effluent concentration is inversely related to the PPV/ASV ratio. The plot of influent concentrations versus PPV/ASV ratios has a different pattern (shapes). Considering this suggested relationship is almost statistically significant (p=0.14), there may be a causal relationship between higher PPV/ASV and lower effluent NOx concentrations that could be validated with additional data. The scatterplot and the Mann-Whitney result indicate consistent reduction of NOx, and since there is a strong correlation between influent and effluent concentrations shown in Table 24 ($p<0.0001$), it may be possible to develop a statistically valid functional relationship.

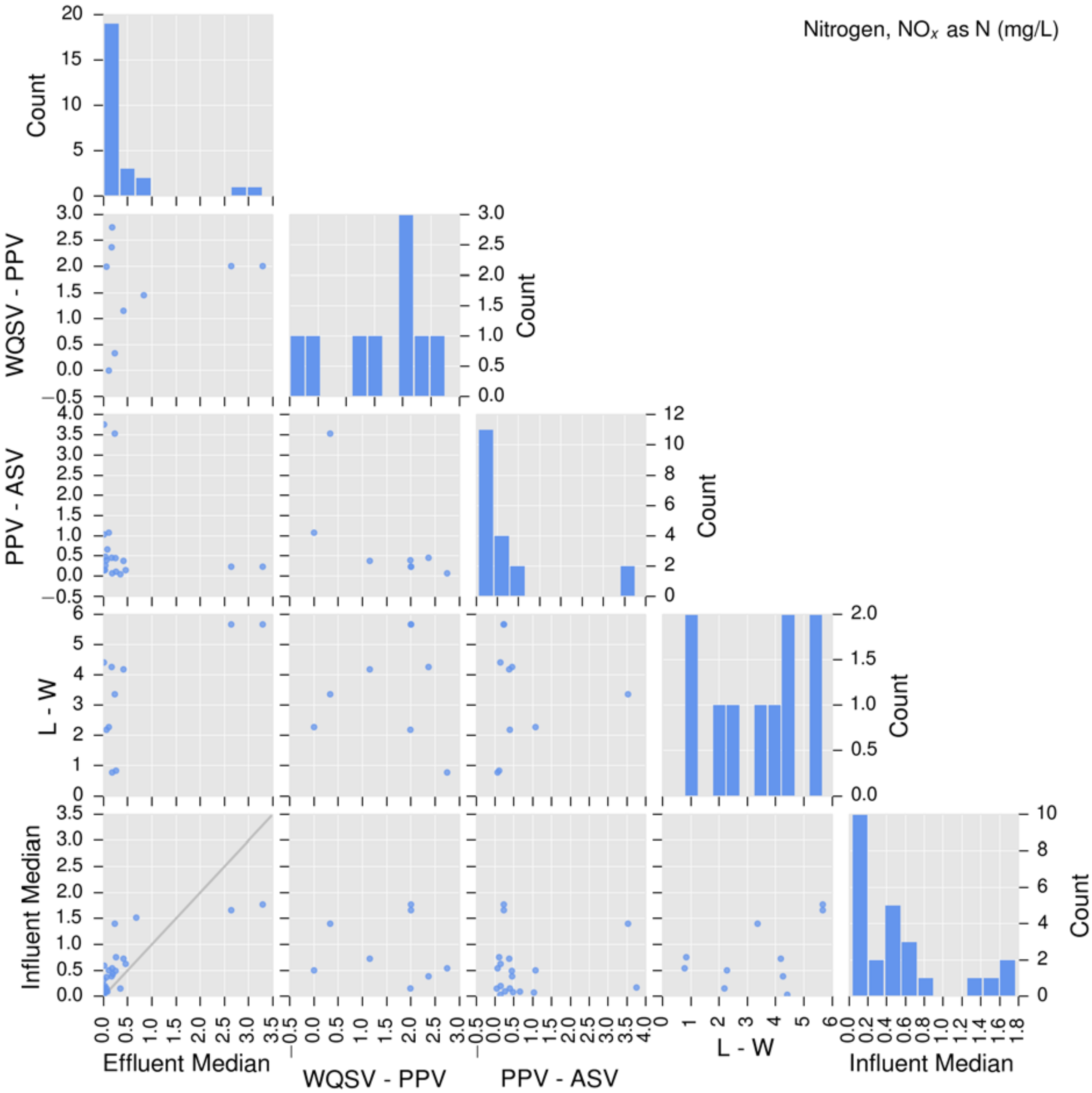

Figure 46. Scatter matrix of median NOx concentration in the influent and effluent with selected design parameters for retention ponds.

2.6.4 Total Suspended Solids

Figure 47 and the Spearman's rho correlation results shown in Table 24 indicate a negative correlation between median effluent total suspended solids concentration and PPV/ASV ratio. This relationship is not fully explained by the influent concentrations, suggesting that a higher

PPV/ASV ratio may be associated with greater reductions in total suspended solids concentration in retention ponds. However, all except one of the retention ponds in the BMPDB show significant total suspended solids reductions, so additional research is needed to evaluate the point of diminishing returns in total suspended solids reduction relative to permanent pool size. Nevertheless, the data suggest an intuitive negative correlation—a large pool volume relative to the size of the storm results in good removal of total suspended solids.

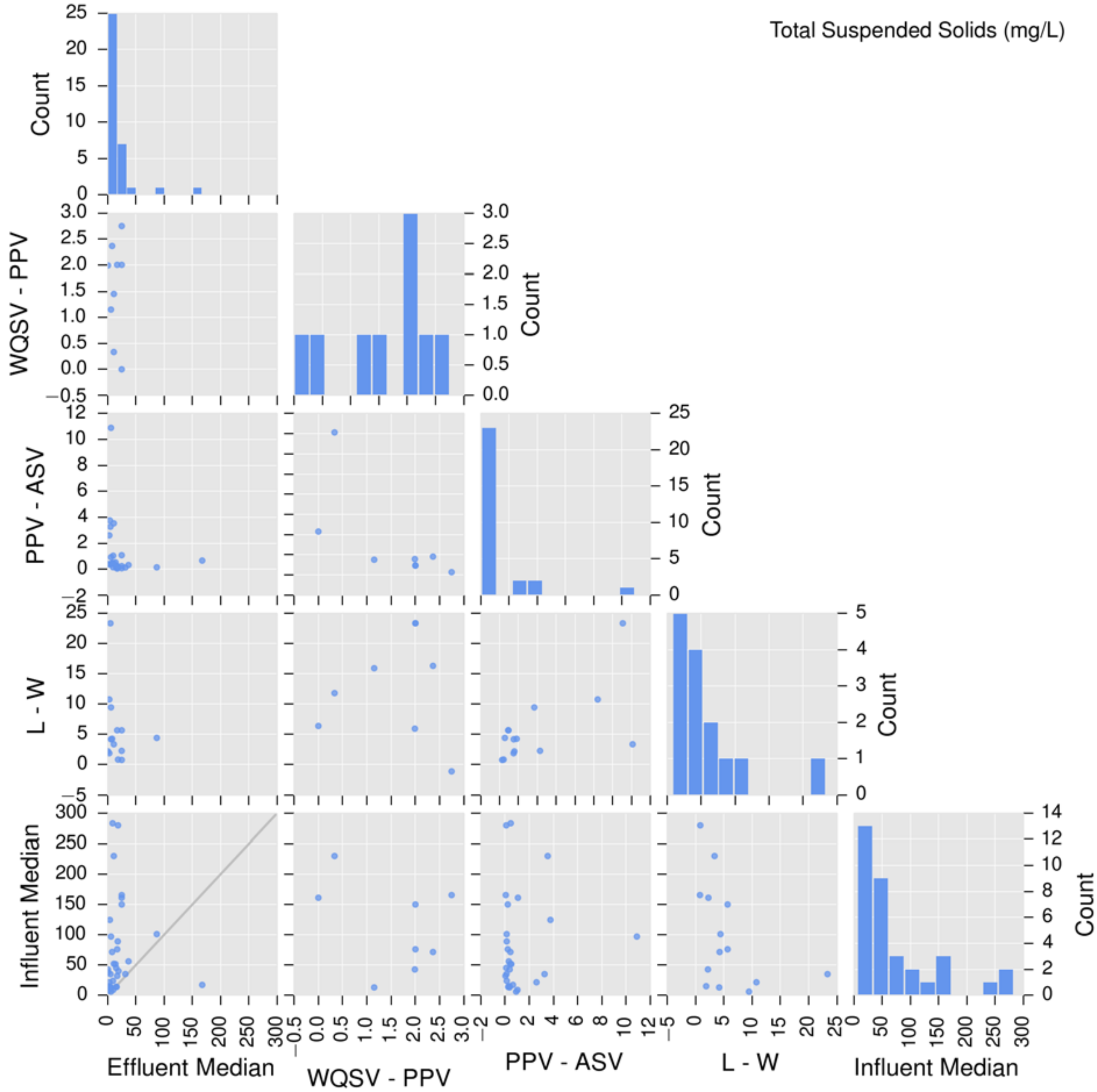

Figure 47. Scatter matrix of median total suspended solids in the influent and effluent with selected design parameters for retention ponds.

2.6.5 Total Copper

Figure 48 and the Spearman's rho correlation results shown in Table 24 indicate that the effluent concentration is not related to the design parameters evaluated. However, statistically significant reductions are indicated in both the influent/effluent scatterplot and the Mann-Whitney results shown in Table 23, so additional research is needed to identify which design parameters and/or environmental conditions may contribute to better total copper removal. The statistically significant correlation between influent and effluent concentrations indicates that it may be possible to develop a functional relationship.

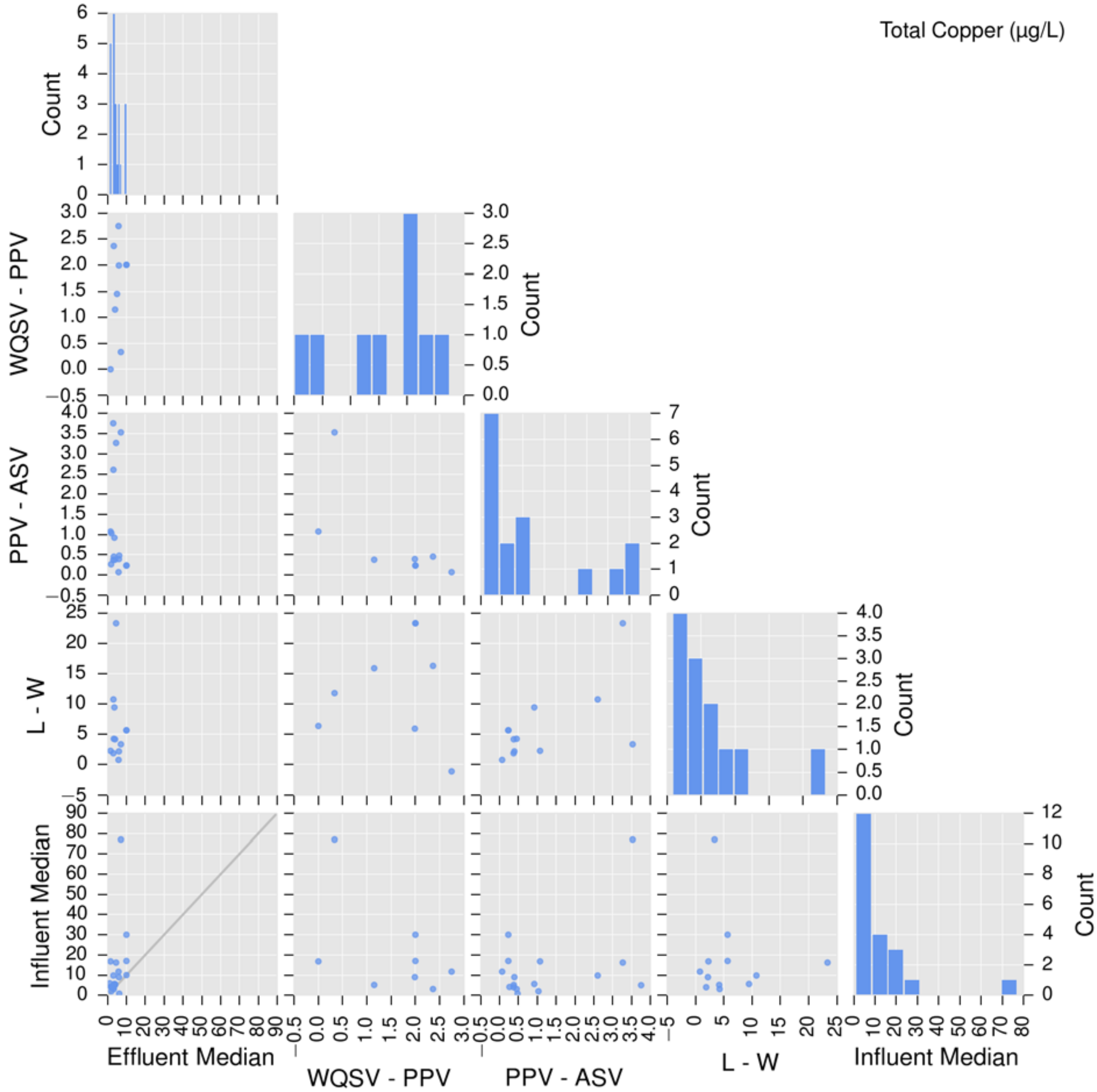

Figure 48. Scatter matrix of median total copper concentration in influent and effluent with selected design parameters for retention ponds.

2.6.6 Dissolved Copper

As shown in Figure 49 and Table 24, the results for dissolved copper are similar to those for total copper. Median effluent concentrations are not significantly correlated with the retention pond design parameters evaluated; however, statistically significant reductions are indicated in both the influent/effluent scatterplot and the Mann-Whitney results shown in Table 23. The influent/effluent correlation coefficient for dissolved copper is stronger than for total copper, indicating that reductions in dissolved copper concentrations are more dependent on influent quality and a statistically valid functional relationship may exist.

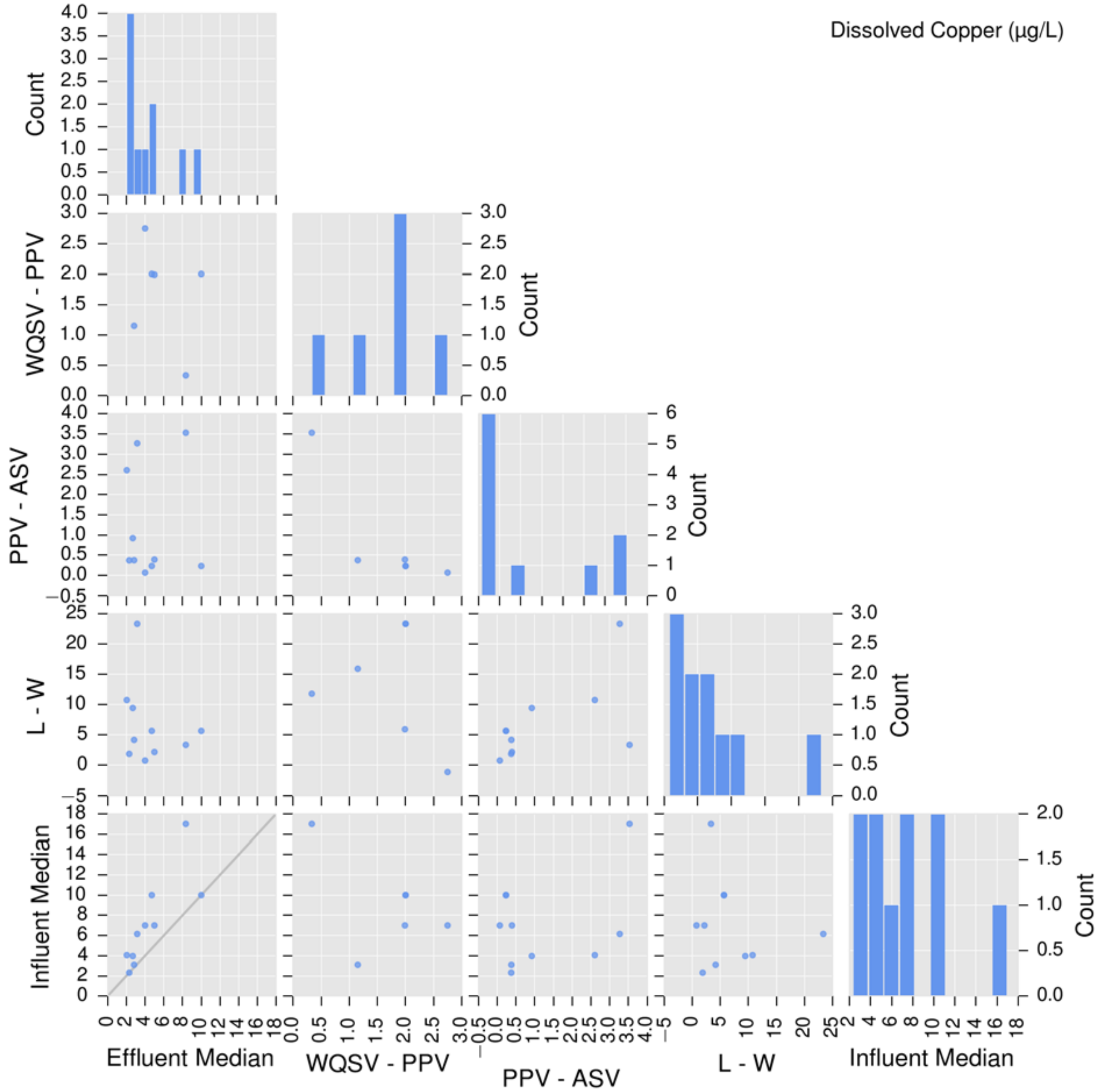

Figure 49. Scatter matrix of median dissolved copper concentration in the influent and effluent with selected design parameters for retention ponds.

3 SUMMARY AND CONCLUSIONS

The BMPDB is a long-term project that has steadily grown to over 530 BMPs and has resulted in improved understanding of performance of various BMP types. For the most part, analyses to date have focused on summarizing influent and effluent concentration statistics, along with some limited analysis of volume reduction. However, a long-term objective of the project has always been to provide a source of information to practitioners on the relationship between performance and various BMP design parameters. Given significant growth of the BMPDB, the Project Team reviewed the available design information stored in the BMPDB for various BMP types and evaluated potential relationships between selected design parameters and performance for a subset of water quality parameters. As a result of this evaluation, a few design-related findings emerged; however, for the most part, the design-related content of the BMP Database is still relatively limited for many BMP categories. Additionally, this analysis showed that most of the BMP design parameters that were significantly correlated with effluent concentration often displayed a similar correlation with influent concentration. This finding confounds conclusions that can be drawn regarding causal relationships between BMP design parameters and removal of constituents, without applying more advanced statistical methods, such as analysis of covariance and multi-parameter regression. Also, the analysis of nutrient removal is difficult since monitoring may not capture all influent sources, including leaves and grass clippings, which may result in apparent nutrient export due to an incomplete mass balance analysis. Primary observations and conclusions reached for each BMP category analyzed include:

1. Retention Ponds: The retention pond (wet pond) category is one of the larger data sets in the BMP database, both in terms of number of studies, water quality data and design parameters. Based on statistical analysis in this report, retention ponds provide statistically significant removal of all constituents evaluated (i.e., total suspended solids, total and dissolved copper, total phosphorus, NOx) except for dissolved phosphorus. Analysis of the relationships between selected design parameters and median effluent concentrations showed that higher permanent pool volume (PPV) to average storm volume (ASV) ratios are associated with lower concentrations of total suspended solids and possibly total phosphorus and nitrate, but the relationships for these two constituents are not quite statistically significant ($p=0.11$ and 0.14, respectively). Additionally, a higher water quality surcharge volume (WQSV) to permanent pool volume (PPV) ratio may result in lower effluent total phosphorus and dissolved phosphorus; however, hypothesis test results were not quite statistically significant for dissolved phosphorus ($p=0.15$) and the influent concentration may be confounding the results for total phosphorus. Lower total phosphorus concentrations were also identified for higher length to width ratios, but, again, the influent concentrations showed a similar relationship. No other statistically significant relationships between design parameters and effluent concentrations were identified based on the available data set.

2. Detention Basins: The detention pond (extended detention dry pond) category is also relatively large in terms of number of studies and water quality data; however, reporting of design parameters is less consistent. Based on statistical analyses in this report, detention ponds provide statistically significant removal of total suspended solids, total copper, and nearly significant removal of total phosphorus, but not dissolved phosphorus or NOx. Analysis conducted showed no explainable, significant relationships between design storm depth (DSD) to average storm depth (ASD) ratio, brimful emptying time (BFET), or length to width ratios based on the available data set.

3. Media Filters: Several different types of media filters are included in the BMP Database. This analysis focused on sand filters. Sand filters showed statistically significant reductions of total suspended solids, total copper, and total phosphorus; however, they did not significantly reduce dissolved phosphorus or dissolved copper. Statistically

significant increases in NOx were present. Analysis of the relationships between selected design parameters and median effluent concentrations did not result in identification of statistically significant causal relationships between design variables and effluent concentrations.

4. Bioretention: The bioretention category is growing data set in the BMPDB, which tends to include more consistent reporting of design parameters in newer studies, but the data set overall remains smaller in terms of numbers of BMPs and constituents available. Additionally, this analysis focused on designs with underdrains, which further narrows the number of studies evaluated. Based on statistical analysis in this report, bioretention facilities with underdrains provide statistically significant removal of total suspended solids, but not total phosphorus or NOx. (Inadequate studies with design data were available to evaluate dissolved phosphorus and copper in this report.) The scatterplot matrices indicate that the combination of a large footprint to drainage area ratio and deep media bed may provide a higher water quality benefit than a smaller area ratio and shallower media bed, but additional data and research is needed to evaluate this relationship statistically. The composition of the media mix also is expected to play a significant role in pollutant removal, but with the variety of mixes reported in the BMPDB there currently are too few studies to meaningfully analyze this design parameter. Analysis of the relationships between selected design parameters and median effluent concentrations did not result in identification of statistically significant causal relationships between design variables and effluent concentrations. An important caveat for the bioretention findings is that volume reduction is typically a primary design objective and process for reducing pollutant loads. The analyses in this particular report do not consider volume reduction; however, bioretention has been shown to provide significant volume reduction in studies by other researchers, as well as in previous BMPDB analyses (see Geosyntec and WWE 2012c).

5. Grass Strips: Grass strips showed statistically significant reductions of total suspended solids, NOx, and total copper. Nearly significant reductions for dissolved copper were identified. A statistically significant increase in total phosphorus was noted. Volume reduction benefits may be present for grass strips, but were not addressed in this report. Analysis of the relationships between selected design parameters (length and slope) and median effluent concentrations did not result in identification of any statistically significant causal relationships. However, research by others (e.g., Caltrans, 2003) indicates that there may be an optimum length for any given slope and vegetation density to achieve consistently low effluent concentrations. Multi-regression analyses on the available BMPDB data could be used to better evaluate the effects these design parameters may have on performance.

6. Grass Swales: Grass swales showed statistically significant reductions of total suspended solids and total copper, but not NOx, total phosphorus or dissolved copper. However, dissolved copper removals were nearly statistically significant ($p=0.13$). Volume reduction benefits may also be present for grass swales, but were not addressed in this report. Analysis of the relationships between selected design parameters and median effluent concentrations showed that increasing swale lengths corresponded to better

removal of dissolved copper. However, a similar relationship was observed in the scatterplot between the length and the influent dissolved copper concentration, so this does not represent a causal link between length and performance. Although some potential relationships between effluent concentration and design parameters were identified, no other meaningful statistically significant findings were identified based on the available data set.

Although additional studies with more complete design information would enable more powerful statistical analysis in the future, covariation of influent-effluent concentrations is a complicating factor that will need to be addressed for some BMP categories (e.g., detention basins). Future statistical analyses conducted to evaluate the effects of design parameters on BMP performance should include an analysis of covariance and possibly multi-parameter regression. Power analyses could also be conducted to reasonably estimate the number of additional studies required to detect various statistically significant differences.

The number of studies in the BMPDB compared to the availability of design information discussed here indicates that there is a significant need for more complete and consistent reporting of the meta data requested for each BMP type with submissions to the BMPDB. Future project efforts could include identifying high quality studies currently included in the BMPDB where additional design information could be backfilled from available BMP reports and working with data providers to encourage more complete reporting of critical design parameters for new data sets.

Despite the limited findings for the particular design parameters evaluated in this analysis, previous unit-treatment based findings remain valid, as have been discussed in BMPDB technical summaries completed over the last several years. Examples of these findings include:

- Many BMP types can be effective for reducing total suspended solids concentrations in urban runoff. BMPs that provide sedimentation and filtration processes and are well designed, installed and maintained are expected to provide good removal of total suspended solids (Geosyntec and WWE 2011).

- Phosphorus in stormwater runoff is generally highly particulate-bound. As a result, BMPs with unit processes for removing particulates (i.e., sedimentation and filtration), will generally provide good removal for total phosphorus. In particular, BMPs with permanent pools appear to be effective at reducing the major forms of phosphorus. Similarly, BMPs with permanent pools appear to be able to reduce nitrate concentrations (Geosyntec and WWE 2010).

- Many BMP types provided good pollutant removal for total metals. Removal of dissolved metals is more challenging and may require selection of BMPs with more advanced unit treatment processes (WWE and Geosyntec 2011).

- When selecting BMPs to reduce pollutant loading, volume reduction should also be considered when site conditions are conducive. In particular, analysis of bioretention studies in the BMPDB has demonstrated significant volume reduction (Geosyntec and WWE 2012c).

- A treatment train incorporating different unit processes that target different pollutant characteristics is a robust pollutant removal strategy (WWE and Geosyntec 2011; WERF 2005). These unit treatment processes can be targeted and refined to meet site-specific pollutant reduction objectives. To maintain proper functioning of unit treatment process, long-term operations and maintenance are necessary.

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