PACIFIC NORTHWEST BIORETENTION PERFORMANCE STUDY SYNTHESIS REPORT

Prepared for City of Redmond

Prepared by
Herrera Environmental Consultants, Inc.

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Prepared for
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Herrera. 2016. Pacific Northwest Bioretention Performance Study Synthesis Report. Prepared for City of Redmond Department of Public Works by Herrera Environmental Consultants, Inc., Seattle, Washington.

EXECUTIVE SUMMARY

This report summarizes and reviews the data from five studies in the Puget Sound region that evaluated the hydraulic and water quality treatment performance of various bioretention soil mixes (BSMs). Bioretention is currently classified in the *Stormwater Management Manual for Western Washington* (SWMMWW) (Ecology 2012b) as a basic (solids removal) and enhanced (copper and zinc removal) treatment best management practice (BMP). (Note: The *Stormwater Manual for Eastern Washington* has equivalent guidance for bioretention media specification. When the SWMMWW is referenced herein, a reference to both manuals is inferred.)

The default bioretention mix in Washington State is 60 percent sand and 40 percent compost (60/40 Mix). Findings from a 2013 study of roadside bioretention performance in the City of Redmond (Herrera 2014a) and from the Washington State University Low Impact Development (LID) Research Facility (WSU 2014) found that bioretention systems were actually exporting copper instead of reducing it. These findings called into question bioretention's enhanced treatment BMP classification and precipitated further studies of bioretention performance in the region. In addition, a number of recent regional studies have documented nitrogen and phosphorus flushing from bioretention systems built with the 60/40 Mix, although the duration and magnitude of metals and nutrient flushing were not fully documented in each of those studies. Furthermore, it was unclear which media components were contributing to pollutant export and if alternate media compositions would, on average, perform better than 60/40 Mix.

The meta-analysis presented in this report was conducted to help ascertain the duration and magnitude of metals and nutrient flushing from bioretention systems using the 60/40 Mix, to determine which media components contributed to pollutant export, and to establish whether other media compositions would perform better than the 60/40 Mix in bioretention systems. This report identifies common trends among the following five studies of various bioretention mixes (including the 60/40 Mix and others) that were conducted in the Puget Sound region within the past 5 years:

- Tacoma Salishan Study (City of Tacoma 2015)
- WSU Mesocosm Study (WSU 2014)
- Redmond 185th Avenue Northeast Study (Herrera 2014a)
- Redmond Six Swales Study (Herrera 2015b)
- Kitsap Column Study (Herrera 2015a)

METHODS

In the five studies listed above, 19 separate BSMs were tested in either the lab or field and more than 70 parameters were analyzed. To streamline the data and explore trends among BSMs with different components the 19 BSMs were grouped into four categories:

1. 60/40 Mix (n = 7)
2. Sand/Compost + Additives (n = 5)
3. Loamy Sands (n = 2)
4. Sand/Coir + Additives (n = 5)

Additives for the BSMs included one or more of the following: activated alumina, biochar, diatomaceous earth, granular activated carbon, high carbon wood ash, shredded bark, and water treatment residuals.

To characterize the temporal nature of bioretention performance, the effluent concentrations for select parameters from each BSM category were plotted against the amount of water that had been introduced to each system since it went online. In addition, the mean influent and effluent concentrations, and median percent reductions were calculated for each BSM category. Across the studies, all influent and effluent water samples were collected using either flow-weighted composite samples or full composite samples. To assess hydraulic performance, infiltration testing results were summarized across BSM categories and were compared with effluent concentrations. Finally, the physical and chemical properties of each media component were summarized across the studies and trends were identified. Conclusions and recommendations were then drawn based on the analyses.

RESULTS

Infiltration

The infiltration rates for the 60/40 Mix were, on average, a minimum of 12 inches per hour (in/hr). They were as high as 200 in/hr, which is higher than the Washington State Department of Ecology (Ecology) specification of 2 to 12 in/hr for an initial or measured rate. On average, the Sand/Compost + Additive exhibited lower infiltration rates than the 60/40 Mixes. The Loamy Sands exhibited the lowest infiltration rates among the BSMs tested, while the Sand/Coir + Additives exhibited the highest infiltration rates in every test except permeability testing. Relationships between infiltration rates and effluent concentrations were only evident for total suspended solids (TSS), where a noted increase in TSS effluent concentrations was associated with increased infiltration rates.

Water Quality Treatment

As indicated above, 70 parameters were analyzed among the five studies to evaluate the water quality treatment performance of the various BSMs. To simplify the discussion, 8 parameters of interest were selected out of the 70 for detailed analysis: TSS, total phosphorus, ortho-phosphate, nitrate + nitrite, dissolved copper, dissolved zinc, fecal coliform bacteria, and total petroleum hydrocarbons (TPH-oil).

TSS flushing from the BSMs was essentially complete by one water year (100%WY) and effluent values for all BSM categories converged on a value of less than 10 milligrams per liter (mg/L) TSS after 100%WY. Sand/Coir + Additives (using relatively uniform sands with high infiltration rates) flush significantly more TSS than the other BSMs, the 60/40 Mixes perform the best, and the Sand/Compost + Additives and Loamy Sands fall somewhere in between. One of the 19 BSMs tested used a sandy drainage layer, as opposed to a type-26 (a course sand with gravel) drainage layer, which seemed to improve TSS performance.

The best performers for total phosphorus removal were the Loamy Sands and the Sand/Coir + Additives. One Compost/Sand + Additives BSM from the Kitsap Column Study had a polishing layer containing activated alumina. This BSM exhibited high levels of solids retention. The total phosphorus performance of this BSM can be attributed to the reduction in solids export as well as sorption of ortho-phosphorus to the activated alumina in the polishing layer. The total phosphorus performance of the Sand/Coir + Additives can be attributed primarily to ortho-phosphate reduction. The 60/40 Mix performed the worst for total phosphorus removal, with an average effluent concentration of 0.6 mg/L and a flushing period that may last at least 3 water years (300%WY).

Both the 60/40 Mix and the Sand/Compost + Additives exported significantly more ortho-phosphate than the Loamy Sands and the Sand/Coir + Additives. The Sand/Compost + Additives and the Sand/Coir + Additives exhibited a slight flush that was complete by 25 percent of the water year (25%WY). The 60/40 Mix exhibited a different flushing pattern with a peak at 50 percent of the water year (50%WY) and then a gradual flush (average effluent = 0.45 mg/L ortho-phosphate) that may last more than 300%WY.

Nitrate + nitrite exhibited a flushing pattern similar to ortho-phosphate, with the 60/40 Mix performing the worst and the Sand/Coir + Additives performing significantly better than the other BSMs. The 60/40 Mix exhibited a peak effluent concentration at 50%WY and then decreased by 200%WY to an equilibrated effluent concentration of ~0.4 mg/L as nitrogen. The Sand/Compost + Additives and the Loamy Sands performed similarly, flushing to ~0.4 mg/L by 50%WY. The Sand/Coir + Additives flushed very little nitrogen and equilibrated to ~0.1 mg/L as nitrogen by 25%WY.

Dissolved copper dynamics were similar to those of total phosphorus. The 60/40 Mix exported the highest initial concentrations and then the effluent equilibrated after 200%WY to approximately 5 micrograms per liter (µg/L). The Sand/Compost + Additives and Loamy Sands BSMs performed slightly better but were still outperformed by the Sand/Coir + Additives. The

Sand/Coir + Additives were significantly better performers than the other BSM categories, beginning with a low level flush and then equilibrating after 25%WY to an effluent concentration of approximately 1 µg/L.

Each BSM tended to reduce influent concentrations of dissolved zinc. In addition, there was a slight flushing pattern observed from the 60/40 Mix, the Sand/Compost + Additives, and the Loamy Sands, which was complete by 50%WY. Overall, after flushing was complete, effluent concentrations among all the BSM categories averaged 5 µg/L (near the detection limit).

A fecal coliform flush by 100%WY was evident in each BSM category. The flush from the Sand/Coir + Additives was more rapid; however, because only one study analyzed fecal coliform for the Sand/Coir + Additives, this analysis cannot determine if that trend is site-specific or more pervasive.

There was no strong flushing trend for TPH-oil in any of the BSM categories. The Loamy Sands and Sand/Coir + Additives BSMs exhibited the lowest effluent concentrations; however, similar to fecal coliform bacteria, only one study analyzed TPH-oil for the Sand/Coir + Additives, so it is difficult to draw conclusions regarding treatment performance for this parameter among the BSM categories.

Physical and Chemical Properties

A number of BSM physical and chemical criteria are specified in the SWMMWW to ensure that BSMs perform well as filters and growth media. These criteria (specifically, organic matter [OM] content, saturated hydraulic conductivity [Ksat], and cation exchange capacity [CEC]) were compared with the results from the five studies. On average, the OM criterion was not met by any of the BSM categories, even the 60/40 Mix, which contains more organic material than any of the other BSM categories. The Ksat criterion was, on average, only met by the Loamy Sands BSM. Finally, the CEC criterion, which is included in the specification to help ensure that custom media blends can bind cations (specifically metals), is the lowest in the Sand/Coir + Additives BSMs, even though those media were far superior at removing metals when compared with the other BSM categories. The Sand/Coir + Additives mixes were furthest from meeting any of the three aforementioned criteria, yet they were consistently the best performers in terms of water quality treatment.

Three of the five studies conducted synthetic precipitation leaching protocol (SPLP) analyses to identify media components that may be contributing to pollutant export. Compost exhibited the highest SPLP values of any of the media components. Of the aggregates tested, relatively high levels of leachable copper was found in C-33 sands, but sands with lower copper concentrations were identified in other studies (volcanic sand and washed sand). Compost leached an order of magnitude more nitrogen than coconut coir or shredded bark. Copper was 5 to 8 times higher in the compost, and ortho-phosphate was 3 to 13 times higher in the compost when compared with the other organic media. The additives tended to leach very little copper and nutrients with

a few exceptions. Biochar leached high nutrient concentrations, activated alumina leached nitrate at 0.44 mg/L, and the wood ash leached 0.52 mg/L of ortho-phosphate.

CONCLUSIONS

- The most commonly exported pollutants from BSMs were copper, nitrogen, and phosphorus.
- All BSMs performed well for TPH-oil, fecal coliform, and zinc removal.
- Of the 19 BSMs evaluated in this report, the 60/40 Mix was, on average, the worst performing in terms of target pollutant flushing and target pollutant reduction, and the compost fraction appeared to be the source of the poor performance.
- Conversely, on average, the best performing BSMs were those that contained Sand/Coir + Additives.
- The volcanic sand and washed sand ("Alt" sands) leached less copper than C-33 sand.
- Flushing results indicate that, by one water year, the majority of BSMs have completed their equilibration/flushing period. However, the BSMs with compost tend to export relatively high levels of total phosphorus and ortho-phosphorus for at least 3 water years and nitrate + nitrite and dissolved copper for at least 2 water years.
- A high degree of dissolved pollutant removal is achievable at infiltration rates that exceed the current 2-12 in/hr requirement. However, suspended sediment removal to meet basic treatment criteria suffers at high flow rates.
- The Sand/Compost + Additives BSM performed marginally better than the 60/40 Mix but with no statistical significance. This indicates that efforts to alter the 60/40 Mix by reducing the percentage of compost and/or adding other components does not significantly improve the performance of BSMs that include compost.
- SPLP analyses were useful in determining the source of leachable target pollutants in the tested BSMs, with high SPLP leachate concentrations of target pollutants associated with high levels of pollutant leaching from the BSMs.
- The site suitability criteria to use native soil for basic treatment in Chapter 3 of Volume III of the 2014 SWMMWW (Ecology 2014) are identical to the custom BSM criteria in Chapter 5 of Volume V of the 2014 SWMMWW (Ecology 2014). The default 60/40 Mix and the alternative BSMs evaluated in this study, especially the best performers, exceed the maximum infiltration rate (Ksat) criterion and do not meet the criteria for minimum cation exchange capacity (CEC) and organic matter (OM) content.

RECOMMENDATIONS

- Loamy Sands performed better than the 60/40 Mix. However, the hydraulic performance of Loamy Sands is unpredictable, so their use is not recommended.
- Adding a polishing layer and reducing the compost content by a factor of 4 helped reduce pollutant export when compared with the 60/40 Mix. Therefore, this approach may be appropriate if alternate BSMs are not available or desirable. However, additional studies on long-term performance and constructability would be required to develop a specification for a polishing layer.
- Care should be taken to avoid water short-circuiting when bioretention systems are built with vertical walls—specifically, when using low infiltration rate BSMs.
- The current maximum allowable initial infiltration rate of $\leq$ 12 in/hr is appropriate for sizing, but custom mixes that have a Ksat as high as 100 in/hr should be included in further studies if it can be shown that the mix will meet basic and enhanced treatment goals, and will grow plants.
- More detailed plant growth studies should be conducted on the most promising BSMs tested thus far in the region.
- Evaluate plants to use in a "low OM content media" and develop a specific plant palette for low OM content media.
- Additional testing is required to determine how well copper remains bound to dissolved organic carbon after BSM effluent discharged from underdrains mixes with receiving waters.
- Research on alternate sources for the organic component of the BSM (such as shredded bark) should be conducted to find a potential substitute for compost (pollutant export issues) and coconut coir (a renewable resource but shipped from overseas and relatively expensive).
- SPLP testing on a large number of aggregates, organics, and additives from various sources should be conducted to more accurately determine the range of leachable pollutants associated with these BSM components.
- There is limited data on the effectiveness of BSM at removing organic pollutants from stormwater. Future studies should include the analysis of phthalates, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and other organic pollutants.
- Further toxicological studies should be performed on the current BSM specification and on alternate BSMs.

- Evaluate and develop custom BSM mix criteria that allow for specification of high performing BSM custom mixes.
- Develop recommendations for the continued use of the default 60/40 Mix with an underdrain based on receiving water sensitivity.
- Evaluate the in-stream impact of using the default 60/40 Mix with an underdrain throughout urbanized, wadable, stream watersheds based on Minimum Requirement 5 in the 2014 SWMMWW.

1. INTRODUCTION

Bioretention is one of the most common techniques used by municipalities when implementing Green Stormwater Infrastructure (GSI) and has been identified as a preferred site practice in the United States Green Building Council's Leadership in Energy and Environmental Design (LEED) certification process (Davis et al. 2009). Starting January 2017, the use of GSI will be required for jurisdictions in western Washington State pursuant to Municipal Stormwater Permit requirements (Ecology 2013). Consequently, in the State of Washington over the next 5 years, the use of bioretention in both the public and private sector will increase dramatically. Due to this trend away from traditional stormwater controls (e.g., wet ponds and vaults) and toward the use of GSI, it is imperative that we specify typical designs which will maximize system effectiveness for runoff treatment and runoff volume control/reduction.

The current Washington State Department of Ecology (Ecology) specification for bioretention soil mix (BSM) in western Washington (Ecology 2012b) is a mixture of 60 percent sand and 40 percent compost (hereafter referred to as the 60/40 Mix). Prior to 2005, there were no definitive guidelines on BSM composition, and either topsoils conforming roughly to a loamy sand classification or native soil mixed with sand were employed. In 2005, the region's first Low Impact Development Guidance Manual was produced (Hinman and Wulkan 2005). One of the objectives of that manual was to issue guidance on a BSM that would produce more predictable hydraulic performance than what was being achieved at the time. The authors recommended 60 to 65 percent loamy sand mixed with 35 to 40 percent compost, or 30 percent loamy sand, 30 percent coarse sand, and 40 percent compost. The few peer-reviewed studies at the time indicated that bioretention systems were excellent at pollutant removal (Davis et al. 2001; Davis et al. 2003). Consequently, the focus on optimizing for consistent hydraulic performance while not fully testing water quality treatment effectiveness appeared justified.

In 2013, the City of Redmond completed a study that showed significant pollutant export from a bioretention system that was constructed with the 60/40 Mix for the 185th Avenue Extension Project (Herrera 2014a). Specifically, measured effluent concentrations from the system were typically higher than influent concentrations for all of the following parameters: total suspended solids (TSS), total phosphorus, soluble reactive phosphorus, total copper, dissolved copper, total lead, dissolved lead, total Kjeldahl nitrogen, and nitrate + nitrite nitrogen. For many of these parameters, the export appeared to exhibit a "flushing" pattern such that effluent concentrations tended to decrease over time relative to maximum values that were measured immediately following construction of the system. The only parameters that were not exported from the system were dissolved zinc, total zinc, motor oil, and fecal coliform. Consequently, instead of acting as a pollutant sink, the system was acting as a source for a majority of the pollutants measured. Follow-up testing indicated the specific source of the pollutants was the compost and, secondarily, the sand used to construct the BSM.

Simultaneous with the 2013 Redmond 185th Avenue Northeast Study, Washington State University (WSU) was conducting replicated studies on various BSMs at the WSU-Puyallup Low Impact Development Research Facility (WSU 2014). WSU was monitoring systems designed with 60 percent sand and 40 percent compost, 80 percent sand and 20 percent compost, and BSMs containing water treatment residuals and shredded bark. Results from the WSU studies also indicated export of nutrients and copper from the BSMs monitored, although at lower magnitudes than those observed in Redmond.

The Redmond 185th Avenue Northeast and WSU study results surprised many in the region, as it had been assumed that bioretention was one of the best options for pollutant removal from stormwater (particularly for metals). Pending further research, Ecology issued interim guidance in March 2014 that recommended bioretention systems with underdrains not be used where there would be a direct discharge to surface waters due to concerns over potential acute and chronic toxicity for aquatic life. That same guidance also recommended such systems not be used in areas where shallow groundwater is used for drinking water due to human health concerns. At the same time, Ecology issued a series of grants to fund additional research into bioretention system performance including: $345,000 for the City of Redmond to study six full-scale bioretention systems with various experimental BSMs (Herrera 2015b); $278,000 for the City of Tacoma to study the effectiveness of water treatment residuals for optimizing phosphorus removal in bioretention systems; and $288,000 for Kitsap County to conduct column experiments with the goal of identifying a BSM that would not export pollutants while still supporting plant growth and pollutant removal functions (Herrera 2015a).

Simultaneous with the effort by Ecology to gather more information through grant-funded studies, research at WSU continued with two additional studies: one looking at the effect of compost age on pollutant leaching (WSU aged-compost study) (Mullane 2015), and the other (funded by the Washington State Department of Transportation [WSDOT]) looking at leaching from BSMs containing composts from two sources not previously characterized but commonly used by WSDOT.

Collectively, the aforementioned studies, in conjunction with monitoring of two bioretention systems in Tacoma, Washington, that was conducted pursuant to Phase I Municipal Stormwater Permit requirements (Tacoma 2015), comprise the single largest research effort on a stormwater treatment technology ever conducted in the Puget Sound region. The objective of this report is to synthesize the results from previous studies, discuss common findings, and put forth recommendations for improving the current Ecology specification for BSM. The specific studies included in this synthesis are identified in Table 1; data from five of the eight aforementioned studies were obtained for this synthesis report.

Table 1. Summary Information for Reviewed Studies.					
Study	**Grant Manager/ Lead Entity**	**Date**	**No. of BSMs Tested**	**Field/Lab**	**Citation**
Tacoma Salishan Study	City of Tacoma	2010–2013	1	Field	Tacoma 2015
WSU Mesocosm Study	Washington State University	2011–2013	4	Field	WSU 2014
Redmond 185th Avenue NE Study	City of Redmond	2012–2013	1	Field	Herrera 2014a
Redmond Six Swales Study	City of Redmond	2014–2015	5	Field	Herrera 2014b
Kitsap Column Study	Kitsap County	2014–2015	8	Lab	Herrera 2014b

BSM = bioretention soil mix.

A summary of each study is provided in the *Results* section of this document. The summaries outline the studies' associated experimental designs and key findings. Results from each study are compiled and analyzed together in the *Results Summary* section. The subsequent *Discussion* section provides context regarding the overarching need for the studies and presents common findings from each study for the primary BSM components. Finally, the *Recommendations and Conclusions* section of this report presents recommendations for updating the Ecology specification and notes areas where further study is required.

2. RESULTS

This section summarizes the results from five studies (Table 1) on bioretention performance conducted over the past 5 years in the Puget Sound region. Summaries for each of the five studies are provided in the following subsections. Each study followed an Ecology-approved Quality Assurance Project Plan (QAPP), and all field studies were designed according to the Technology Assessment Protocol Ecology (TAPE), a rigorous field assessment methodology used to assess emerging stormwater treatment technologies (Ecology 2011b). Four studies were field studies of lined or, in the case of Tacoma Salishan, unlined bioretention systems. The fifth study was conducted in the laboratory using an apparatus for rapidly testing BSMs in columns. All of the studies included at least one treatment using the 60/40 Mix, three of the studies also used alternative BSMs. In total, 19 different BSMs were tested across the five studies. Given the range of BSMs tested, the resultant dataset provides valuable insight into the influence of compost on bioretention system performance.

This report provides a summary of the best available science for the Puget Sound region; however, the five studies were conducted at different scales and used various measurement and experimental approaches. Accordingly, careful attention should be given to how those differences influence study findings. As additional studies are implemented in the region, their results should be added to this synthesis in order to generate a more robust set of data.

2.1. TACOMA SALISHAN STUDY

The City of Tacoma conducted hydrologic and water quality monitoring at two bioretention systems installed in the Salishan residential housing development near the intersection of East 46th Street and R Street and East 44th Street parallel to T-Street Gulch (Tacoma 2015). The sites were monitored from January 2010 through June 2013. The study was required under Section S8.F of the 2007 and 2012 Phase I Municipal Stormwater Permits. The purpose of the study was to conduct full-scale field monitoring to evaluate the effectiveness and operation and maintenance requirements of stormwater treatment and hydrologic management best management practices (BMPs) applied within the city. Monitoring results from this study were intended to provide a performance feedback loop to Ecology and the City of Tacoma to confirm how well BMPs treat certain pollutants.

2.1.1. Study System

The bioretention systems studied were constructed to meet Ecology standards for bioretention in the 2005 SWMMWW (Ecology 2005). Specifically, the systems were sized to infiltrate 99 percent of the annual runoff volume through an 18-inch-deep BSM using the Western Washington Hydrologic Model, Version 3 (WWHM3). The systems have four primary

components: a vegetated planting strip, a 60/40 Mix BSM, a gravel drain layer, and a perforated underdrain pipe. The systems were built without a liner. During operation, stormwater runoff from the surrounding drainage basin enters the planting strip via the inlet pipe; runoff is retained in the planting strip for a sufficient period of time to allow infiltration to the underlying BSM layer. Absorption, filtration, retention, and evapotranspiration processes within the BSM provide water quality treatment and serve to attenuate stormwater runoff rates and volumes. Under saturated conditions, stormwater infiltrates from the BSM down to the gravel drain layer. The gravel drain layer provides additional storage for attenuating stormwater runoff flow rates and volumes. Flow through the gravel drain layer that does not infiltrate into the subgrade soil is collected in the perforated underdrain pipe, which subsequently discharges to a bypass structure and then to the stormwater conveyance system for the Salishan neighborhood.

The R Street bioretention system is approximately 80 feet long and runs approximately west to east near the intersection of East 46th Street and R Street. The 44th Street bioretention system is approximately 155.5 feet long and runs approximately north to south, just south of East 44th Street and parallel to T-Street Gulch.

The BSM for both the East 46th Street and R Street bioretention systems consist of the Ecology specified 60/40 Mix. The compost was sourced from Cedar Grove, Inc. There are no records of the source of the sand, and the gradation analysis was completed after the sand was mixed with the compost and the BSM was installed, so it is difficult to determine if the sand gradation met the Ecology specification. The East 46th Street BSM met the cation exchange capacity (CEC) specification of less than or equal to 5 millequivalents per 100 grams (≥ 5 meq/100g), while the R Street BSM did not meet the CEC criterion. Conversely, the R Street BSM met the organic matter (OM) content criterion (5 to 8 percent), while the East 46th Street BSM was, on average, less than 1 percent and did not meet the OM criterion.

2.1.2. Sampling Procedures

Monitoring was implemented using an Ecology approved QAPP that met TAPE standards for the study design. Automated sampling was used to characterize influent and effluent water quality and to evaluate the performance of the study system. Automated monitoring equipment was also installed to continuously measure influent, effluent, and bypass flows. The automated equipment collected flow-weighted composite samples of the system's influent and effluent during a total of 27 separate storm events. Water quality monitoring was initiated 12 months after the bioretention systems were installed and went online and continued for 30 months from the collection of the first sample. The collected flow-weighted composite samples were analyzed for the following water quality parameters:

- TSS
- Particle size distribution
- Total phosphorus
- Ortho-phosphate
- Total and dissolved copper, zinc, lead, cadmium, and mercury

- Hardness
- Semi-volatile organic compounds – phthalates
- Polycyclic aromatic hydrocarbons
- Pentachlorophenol
- Chlorinated pesticides
- Chlorinated herbicides

In addition to water quality monitoring, full-scale field infiltration testing was conducted during each monitoring year.

Gathered data were analyzed in the following ways:

- Computation of treatment efficiencies in pollutant concentration
- Statistical comparisons of influent and effluent concentrations

2.1.3. Hydrologic Performance

As described above, the bioretention systems were sized using WWHM3 (which predicted treatment of 99 percent of influent flows). Storm events that exceeded the WWHM3 water quality BMP design flowrate were predicted to bypass treatment, which is 0.0949 cubic foot per second for the R Street bioretention system and 0.688 cubic foot per second for the 44th Street Bioretention system. For both systems, the WWHM3 water quality BMP design flowrates were exceeded at times. However, it appears that the bioretention systems are effective at treating storm events greater than the WWHM3 water quality BMP design flowrate. Effluent bypasses at both systems were infrequent or not at all.

Infiltration testing was conducted in 2011, 2012, and 2013. The bioretention systems were functioning hydraulically in Year 3 in a capacity similar to Year 1. The infiltration rates at the 44th Street bioretention system ranged from 1.4 to 5.0 inches per hour (in/hr) and averaged 2.8 in/hr. The infiltration rates at the R Street bioretention system were about 10 times higher, ranging from 15 to 70 in/hr and averaging 39 in/hr. Relative to Ecology's and the City of Tacoma's recommended infiltration rates for these types of BMPs, the 44th Street bioretention system rates are in good agreement with design recommendations, whereas the R Street bioretention system is transmitting water at higher rates than are recommended (approximately four times higher than recommended short-term rates).

Attenuation of stormwater runoff flowrates and volumes was evident. Almost one-third of the stormwater runoff events discharging to the bioretention systems resulted in no effluent flow (27 to 32 percent). On average, there was a 50 percent reduction in peak flow rates when comparing influent and effluent flow rates. Total flow volumes were reduced by approximately 30 percent at the 44th Street bioretention system and by approximately 44 percent at the R Street bioretention system.

2.1.4. Water Quality Performance

Except for total phosphorus and ortho-phosphate, treatment efficiencies were generally good for solids, metals, and polycyclic aromatic hydrocarbons (PAHs) when influent concentrations were at detectable levels. Results showed:

- Solids: treatment efficiencies ranged from 63 to 98 percent.
- Metals: treatment efficiencies ranged from 81 to 97 percent for total lead and total zinc and 64 to 69 percent for dissolved zinc.
- PAHs: treatment efficiencies ranged from 3 to 91 percent for most PAHs.

The systems also appeared effective at treating influent concentrations of Bis(2-ethylhexyl) phthalate. However, treatment efficiencies may have been affected by the significant number of influent samples collected with concentrations that were below or near the analytical detection limits and one outlier (one effluent sample from the 44th Street bioretention system had a concentration of 57.9 µg/L while all other samples had concentrations that were less than 0.55 µg/L, and most were below the detection limit).

The study systems exported (i.e., effluent concentrations were higher than influent concentrations) total phosphorus and ortho-phosphate; thus, treatment efficiencies ranged from -5 to -3,362 percent. See Table 2 for summary statistics.

2.1.5. Findings

Both bioretention systems in this study were built with the same BSM specification; despite this, there were differences in CEC and OM content, as mentioned above). However, the infiltration rates varied widely between the two, averaging 2.8 and 39 in/hr at the 44th Street and R Street bioretention systems, respectively. Despite the order of magnitude difference in infiltration rates, water quality treatment between the two bioretention systems was similar for the majority of parameters. For example, mean effluent TSS concentrations were 2.2 and 1.2 milligrams per liter (mg/L) and mean effluent dissolved copper concentrations were 3.8 and 5.3 micrograms per liter (µg/L), at the 44th Street and R Street bioretention systems, respectively. Despite these similarities, total phosphorus export was an order of magnitude greater at the 44th Street bioretention system (mean effluent concentration = 0.998 mg/L) relative to the R Street bioretention system (mean effluent concentration = 0.073 mg/L). In this case, slower infiltration rates seemed to result in reduced phosphorus removal performance. Both systems acted as phosphorus sources, while the R Street bioretention system exported small amounts of dissolved copper and the 44th Street bioretention system did not.

Table 2. Influent, Effluent, and Percent Reductions from the 2013 Tacoma Salishan Study.

Parameter	Units	R Street Bioretention System			44th Street Bioretention system		
		Mean In	Mean Out	Concentration Based Treatment Efficiency	Mean In	Mean Out	Concentration Based Treatment Efficiency
Total Suspended Solids	mg/L	*15.7*	*2.2*	*86%*	*37.7*	*1.2*	*97%*
Total Phosphorus	mg/L	**0.054**	**0.073**	**-34%**	**0.114**	**0.998**	**-779%**
Ortho-phosphate	mg/L	**0.018**	**0.052**	**-190%**	**0.017**	**0.581**	**-3,362%**
Hardness	mg $CaCO_3$/L	**17.8**	**21.3**	**—**	**22.8**	**42.1**	**—**
Total Cadmium	µg/L	0.08	0.09	-15%	0.12	0.08	32%
Total Copper	µg/L	4.6	4.8	-5%	*14.2*	*3.9*	*72%*
Total Lead	µg/L	*1.1*	*0.2*	*81%*	*2.9*	*0.1*	*95%*
Total Mercury	µg/L	NC 0.017	NC 0.021	-23%	NC 0.028	NC 0.010	33%
Total Zinc	µg/L	*29.2*	*3.5*	*88%*	*39.2*	*3.7*	*92%*
Dissolved Cadmium	µg/L	0.042	0.048	-15%	NC 0.034	0.065	-80%
Dissolved Copper	µg/L	**2.48**	**3.84**	**-55%**	*6.82*	*5.25*	*41%*
Dissolved Lead	µg/L	0.07	0.07	NC	*0.45*	*0.05*	*86%*
Dissolved Mercury	µg/L	NC 0.02	NC 0.02	-26%	NC 0.02	NC 0.02	4%
Dissolved Zinc	µg/L	*15.76*	*5.35*	*66%*	*14.65*	*5.32*	*64%*
Phenanthrene (LPAH)	µg/L	*0.011*	*NC 0.003*	*77%*	*0.011*	*NC 0.002*	*79%*
Pyrene (HPAH)	µg/L	*0.009*	*NC 0.002*	*74%*	*0.014*	*NC 0.009*	*37%*
Bis(2-ethylhexyl) phthalate	µg/L	NC 0.42	NC 0.35	17%	**0.72**	**NC 3.06**	**-326%**

NC = not calculable because more than 50 percent of the data were at or below the reporting limit

Bold values in **red** indicate a significant increase; *italicized* values in *blue* indicate a significant decrease; values in black indicate no significant difference between inlet and the outlet (Mann-Whitney test p value < 0.05).

2.2. WSU Mesocosm Study

The Washington State University (WSU) Research and Extension Center in Puyallup, Washington, constructed an LID research facility (completed 2011) to study various performance characteristics of bioretention and permeable pavement systems. Part of the research facility is dedicated to examining the hydraulic and water quality treatment performance of various BSMs in large enclosed tanks, or mesocosms.

2.2.1. Study System

For the WSU (2014) study, the following five BSMs were installed in 20 mesocosms, with each BSM replicated four times:

- 60 percent mineral aggregate and 40 percent compost by volume (60/40).
- 80 percent mineral aggregate and 20 percent compost by volume (80/20).
- 60 percent mineral aggregate, 15 percent compost, 15 percent shredded cedar bark, and 10 percent water treatment residuals (aluminum and iron hydroxides) by volume (60sd/15comp/15sb/10wtr).
- 60 percent mineral aggregate, 30 percent compost, and 10 percent water treatment residuals (aluminum and iron hydroxides) by volume (60sd/30comp/10wtr)
- 60 percent mineral aggregate, 15 percent biosolids, 15 percent shredded cedar bark, and 10 percent water treatment residuals (aluminum and iron hydroxides) by volume (60sd/15bs/15sb/10wtr).

Each mesocosm was constructed with a 60 inch diameter by 52 inch deep media tank to hold the BSM during testing. The bottom of each media tank was filled with coarse sand to a depth of 12 inches; and 24 inches of the media was placed in 6 inch lifts over the aggregate layer and hand packed before water was introduced to the system. A slotted underdrain pipe within the aggregate layer serves as the drain for the media tank. Flow enters each tank through a manifold constructed of plastic piping perforated with drilled holes, which distributes water across the surface of the tank.

Stormwater is collected from a 72,084 square feet (ft^2) impervious drainage area on the WSU Puyallup campus. Runoff from approximately 25 percent of that area, or 18,021 ft^2, is routed to a 3,000-gallon cistern for storage and delivery to the mesocosms. Weir boxes constructed at the water surface elevation inside the cistern distribute flows to each mesocosm.

2.2.2. Sampling Procedures

There were three phases to the mesocosm sampling: Baseline sampling, Phase 1 monitoring, and Phase 2 monitoring. Baseline sampling characterized the physical and chemical properties of the various BSMs prior to stormwater sampling activities to quantify their physical and chemical characteristics. Phase 1 monitoring involved quantifying the treatment performance of each BSMs using stormwater generated during natural storms. Phase 2 monitoring quantified treatment performance of the BSMs using natural stormwater mixed with chemicals in the cistern to increase concentrations of contaminants in the stormwater.

One of the weir boxes in the mixing and distribution tank directs flow to a separate Influent Monitoring Station. Influent flows and chemistry for all the mesocosms were generalized based on representative data collected at the station. Effluent discharge rates were measured at the point of discharge from the slotted underdrain and control structure for each mesocosm through a Hydrological Services TB1-L tipping bucket flow gauge.

Flow weighted composite samples were collected during five storm events annually to characterize influent and effluent pollutant concentrations for each mesocosm. (Note: the four mesocosms with biosolids were not sampled due to lack of funding.) Influent and effluent samples were collected using Isco Model 6700 series automated samplers.

Due to a lack of funds the mesocosms were exposed to 1 full water year running through the media before sampling began. A total of 10 storms, or sampling events, are reported here from October 2012 to February 2014. Two of those sampling events were during Phase 1 of the research (natural stormwater with low concentrations of contaminants) and the remainder were during Phase 2 (increased stormwater concentrations).

Saturated hydraulic conductivity tests (Ksat) were conducted annually in each mesocosm using a falling head procedure. The media was saturated with three pore volumes. With the underdrain closed, each mesocosm was filled to 12 inches above the media surface. The underdrain was opened and time was recorded for the water level to reach the 6 inches and 0 inch mark (water no longer visible at soil surface).

2.2.3. Hydraulic Performance

In general, Ksat rates tended to increase and become more variable over time. Ksat rates for the 80/20 treatment were highly variable the first year, ranging from approximately 5 to 25 in/hr. As anticipated, Ksat rates for the 60sd/30comp/10wtr treatment were generally lower than the other treatments due to the addition of fine–textured, water treatment residuals (WTR). The addition of shredded bark to the 60sd/30comp/10wtr treatment increased Ksat rates by providing infiltration pathways through the media. Overall, the biosolids treatment had the lowest Ksat, likely due to the fine texture of the biosolids.

Ksat rates increased for all treatments in Year 2. The increase was likely due to plant establishment and increasing root penetration into the media column opening infiltration pathways. By Year 3, Ksat rates had increased again, with the 60/40 treatment approaching 50 in/hr. The biosolids treatment was removed, and no Ksat measurements were performed in Year 3.

2.2.4. Water Quality Treatment Performance

The water quality data presented herein (Table 3) represents the second water year of operation for the mesocosms. Due to lack of funding, no samples were collected for most of the treatments during the first water year.

TSS capture was similar in all treatments. For all treatments, very low mean influent concentrations (4.05 mg/L) resulted in a slight increase in effluent concentration; however, the concentrations remained low (approximately 5 to 7 mg/L).

Nitrate performance was variable. Mean influent concentration of 0.361 mg/L resulted in no statistical reduction in effluent concentration for the 80/20 media and a slight, but not statistically significant, increase for the 60sd/30comp/10wtr effluent concentrations. The 60sd/15comp/15sb/10wtr treatment had statistically significant lower effluent concentrations, resulting in a 39 percent mean reduction.

All treatments exported ortho-phosphate at statistically significant levels. The mean influent concentration was 0.0095 mg/L, and the effluent concentrations ranged from 0.19 to 0.33 mg/L and mean reduction (export) of up to -3,538 percent.

All treatments exported dissolved copper, although at low effluent concentrations. Influent concentration was low at 2.7 µg/L, and effluent concentrations ranged from 5.64 to 8.46 µg/L. Total zinc performance was good, however. Effluent concentrations ranged from 5.5 to 7.125 µg/L, with an influent concentration of 79 µg/L. Mean percent reductions ranged from 79 to 97 percent.

2.2.5. Findings

No treatment was exceptionally better for reducing flushing or pollutant capture. However, the 60sd/15comp/15sb/10wtr reduced nitrate-nitrite concentrations, flushed lower concentrations of ortho-phosphate, and was the slightly better performer.

Interestingly, lower compost content in the media did not reduce export of nutrients or copper. For example, ortho-phosphate effluent concentrations for 80/20 and 60/40 treatments were 0.26 mg/L and 0.24 mg/L, respectively, and nitrate + nitrite effluent concentrations were 0.35 mg/L and 0.165 mg/L, respectively.

Table 3. Influent, Effluent, and Percent Reductions from the WSU Mesocosm Study.

Parameter	Units	80/20			60/15/15/10			60/40			60/30/10		
		Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In[a]	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction
pH	std. units	*7.05*	*6.83*	*3*	*7.05*	*6.65*	*6*	6.93	6.85	1	*7.05*	*6.75*	*4*
Total Suspended Solids	mg/L	4.1	5.3	-9	4.1	7.1	-58	4.1	5.3	-21	4.1	5.6	-18
Hardness	mg/L as CaCO	**14.9**	**36.1**	**-178**	**14.9**	**38.9**	**-190**	**12.8**	**46.1**	**-35**	**14.9**	**40.1**	**-200**
Chemical Oxygen Demand	mg/L	**12.83**	**27.04**	**-91**	**12.83**	**29.92**	**-106**	**12.83**	**25.05**	**-80**	**12.83**	**35.09**	**-148**
Dissolved Organic Carbon	mg/L	1.5	2.5	-67	1.5	3.2	-114	1.5	3.2	-112	1.5	3.3	-123
Total Kjeldahl Nitrogen	mg/L	**0.49**	**1.03**	**-92**	**0.49**	**0.91**	**-63**	**0.49**	**0.85**	**-56**	**0.49**	**1.33**	**-130**
Nitrate + Nitrite	mg/L	0.361	0.352	0	*0.361*	*0.193*	*39*	0.361	0.165	26	0.361	0.410	-19
Ammonia	mg/L	**0.021**	**0.036**	**-95**	**0.021**	**0.042**	**-133**	**0.021**	**0.031**	**-61**	**0.021**	**0.043**	**-133**
Total Phosphorus	mg/L	**0.049**	**0.366**	**-630**	**0.049**	**0.276**	**-475**	**0.056**	**0.333**	**-259**	**0.049**	**0.480**	**-875**
Ortho-Phosphate	mg/L	**0.010**	**0.261**	**-2,861**	**0.010**	**0.193**	**-2,047**	**0.017**	**0.248**	**-1,272**	**0.010**	**0.327**	**-3,538**
Total Cadmium	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Dissolved Cadmium	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Total Chromium	µg/L	**0.5**	**1.5**	**-203**	**0.5**	**1.8**	**-260**	**0.5**	**1.0**	**-103**	**0.5**	**2.1**	**-323**
Dissolved Chromium	µg/L	**0.5**	**0.6**	**-25**	**0.5**	**0.7**	**-35**	**0.5**	**0.6**	**-28**	**0.5**	**0.8**	**-58**
Total Copper	µg/L	**3.5**	**8.7**	**-138**	**3.5**	**9.8**	**-170**	**4.9**	**10.2**	**-26**	**3.5**	**12.2**	**-210**
Dissolved Copper	µg/L	**2.7**	**5.6**	**-128**	**2.7**	**6.9**	**-174**	**2.9**	**7.7**	**-33**	**2.7**	**8.5**	**-212**
Total Lead	µg/L	0.8	1.2	-71	0.8	1.0	-43	0.8	0.5	38	0.8	1.6	-121
Dissolved Lead	µg/L	**0.1**	**0.2**	**-63**	**0.1**	**0.2**	**-50**	0.1	0.1	-38	**0.1**	**0.2**	**-75**
Total Zinc	µg/L	*79.0*	*5.9*	*91*	*79.0*	*5.5*	*92*	*97.3*	*5.4*	*47*	*79.0*	*7.1*	*89*
Dissolved Zinc	µg/L	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
TPH – Diesel	mg/L	*NC*	*NC*	*NC*	NC	NC	NC	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
TPH – Motor Oil	mg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
PAH	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Fecal Coliform	CFU/100 ml	*166*	*21*	*69*	*NC*	*NC*	*NC*	*166*	*12*	*81*	*166*	*25*	*58*

[a] Influent concentrations for the 60/40 differ from the other media because additional testing was conducted on the 60/40 cells alone.

NC = not calculable because more than 50 percent of the data were at or below the reporting limit

CFU/100 mL = colony forming units per 100 milliliters

TPH = total petroleum hydrocarbons

Bold values in **red** indicate a significant increase; *italicized* values in *blue* indicate a significant decrease; values in black indicate no significant difference between inlet and the outlet (Wilcoxon Signed Rank test α = 0.05).

The results from the WSU Mecocosm Study corroborate other regional studies cited in this synthesis, indicating that bioretention systems using a BSM that meets the 60/40 specification from the SWMMWW will likely act as a source of nutrients and copper for a minimum of 2 years.

2.3. Redmond 185th Avenue Northeast Study

The City of Redmond conducted hydrologic and water quality monitoring at a bioretention system (referred to as bioretention swales in Redmond) installed at the southeast corner of 185th Avenue Northeast and Northeast Union Hill Road from February 2012 through September 2013 (Herrera 2014a). The 185th Avenue Northeast bioretention system (study system) is above an unconfined, municipal drinking water aquifer. To study potential impacts to the aquifer from infiltrating treated road runoff, the study system was lined with an impermeable geomembrane and incorporated an underdrain system, which does not allow stormwater to infiltrate and, thereby, avoids potential contamination of groundwater. At the same time, these design features allow influent and effluent water from the study system to be captured and characterized to quantify the level of treatment that occurs within the study system for specific pollutants of concern. Monitoring results from this study system were intended to inform broader management decisions by the City of Redmond about the use of infiltrating LID systems as a viable stormwater treatment option, given the need to protect its drinking water supply.

2.3.1. Study System

The study system was designed and constructed to meet Ecology standards for bioretention in the 2005 SWMMWW (Ecology 2005). Specifically, the swales were designed to infiltrate 99 percent of the annual runoff volume through an 18-inch-deep BSM, according to WWHM3. As with all capital improvement projects (CIPs) in Redmond, strict construction inspection controls were used to ensure the proper materials were provided and installed. The 60/40 Mix was applied at depths ranging from 36 inches at each side slope of the swale to 18 inches in the center. The BSM was underlain by a 6-inch sand blanket, then 3 inches of pea gravel over 11 inches of WSDOT Road and Highway Manual specification for backfill for under drains. The backfill contained an 8-inch perforated (not slotted) pipe, which served as the only egress for infiltrated surface runoff that entered the system. A variety of perennial grasses and shrubs were planted in the treatment system. Initially, a 2-inch mulch layer was placed above the BSM. Early observations indicated that the mulch layer was impeding infiltration, and the mulch was removed and not replaced prior to the beginning of the monitoring period for the study.

2.3.2. Sampling Procedures

Monitoring was implemented using an Ecology approved QAPP that met TAPE standards for study design. This was the first time that full-scale (i.e., built to design standards for contributing area) TAPE monitoring of bioretention treatment effectiveness occurred in Washington. A combination of automated sampling and grab sampling was used to characterize influent and

effluent water qualities, evaluating the performance of the study system. Automated monitoring equipment was installed to continuously measure influent, effluent, and bypass flows. The automated equipment collected flow-weighted composite samples of the system's influent and effluent during a total of 20 separate storm events. Water quality monitoring was initiated 3 months after the bioretention swale was installed and went online and continued for 20 months from the collection of the first sample. The collected flow-weighted composite samples were analyzed for the following water quality parameters:

- TSS
- Suspended sediment concentration
- Total phosphorus
- Soluble reactive phosphorus
- Total Kjeldahl nitrogen
- Nitrate + nitrite
- Total and dissolved copper, zinc, lead, cadmium, and mercury
- Chloride
- Hardness

In addition, field personnel collected grab samples during 20 storm events. Samples from two of those events were lost by the laboratory, so results for only 18 samples were included in the study. During the course of the study, the grab samples were collected for events with and without corresponding flow-weighted composite samples. Grab samples were collected for:

- Fecal coliform
- TPH-oil

In addition, synthetic precipitation leaching protocol (SPLP) analysis was conducted on each media component to try and isolate the source of various pollutants. Finally, full-scale field infiltration testing was conducted.

Data gathered by both the automated equipment and the grab samples were subsequently analyzed in the following ways:

- Computation of pollutant removal efficiencies with bootstrap confidence intervals
- Statistical comparisons of influent and effluent concentrations during both the first year (Year 1) and second year (Year 2) of monitoring

2.3.3. Hydrologic Performance

Flow control requirements for the study were vested with a proposed development in 1999. The vested requirement dictates that the site should generate a peak discharge of no more than 0.15 cubic foot per second per acre during a 10-year storm event. The bioretention swales were sized using WWHM3 to meet this requirement (which predicted treatment of 99 percent of

influent flows). Monitoring data showed that stormwater bypassed the treatment system during 5 of the 207 monitored events during the monitoring period. Although bypass volumes were not calculated, an measured bypass frequency of only 2.4 percent and modeling predictions form WWHM3 indicating the swale would treat 99 percent of flows, suggest that the systems may have been oversized relative to today's water quality treatment standards (91 percent of the average annual runoff volume).

Infiltration testing conducted on March 21, 2012, 3 months after the completion of construction, indicated that saturated infiltration rates were 1.5 in/hr. A second infiltration test conducted 18 months later, indicated that this value increased to 2.9 in/hr. The approximate two-fold increase in infiltration rate could be the result of increased plant establishment and associated macropore flow, increased infiltration due to bioturbation, fines, flushing from the system, or the decreased effect of the clogging mulch layer, which was removed in January 2012.

Interestingly, though the system was lined, the data indicated that the study system reduced influent volumes by 69 percent in the dry season and 78 percent in the wet season. Mechanisms for water loss in the system include evapotranspiration and leaks in the liner (one of which was confirmed during the monitoring period). In addition, because influent flows were scaled up from one representative inlet to estimate inflow from the three actual inlets, there could have been extrapolation error that contributed to the discrepancy between influent and effluent flow.

2.3.4. Water Quality Performance

The study system was effective at treating influent concentrations of total zinc, dissolved zinc, TPH-oil, and fecal coliform bacteria. During the second year of operation, the average percent reductions for these parameters were 89, 43, 88, and 77, respectively (Table 4). The system also appeared effective at treating influent concentrations of pentachlorophenol and Bis(2-ethylhexyl) phthalate (removals estimated from three grab samples).

Despite these reductions, the study system exported (i.e., effluent concentrations were higher than influent concentrations) many other constituents. For example, during the first year of study (Year 1), significant pollutant export was observed for all measured nutrients, chloride, hardness, total copper, dissolved copper, and total lead (Table 4). During the second year of study (Year 2), there continued to be significant export of total phosphorus, orthophosphate, and nitrate + nitrite. Effluent concentrations for Kjeldahl nitrogen, hardness, chloride, and dissolved copper were also generally higher than influent concentrations during the second year, although the observed differences were not statistically significant (Table 4). In addition, one grab sample indicated a large export of methylene chloride. The results indicate that the study system itself was a source for many pollutants during the first 2 years of operation.

Table 4. Influent, Effluent, and Percent Reductions from the Redmond 2013 185th Avenue Northeast Study.

Parameter	Units	Year 1			Year 2			All Years		
		Mean IN	Mean OUT	Mean % Reduction	Mean IN	Mean OUT	Mean % Reduction	Mean IN	Mean OUT	Mean % Reduction
Total Suspended Solids	mg/L	77	74	-61	*194*	*21*	*85*	*135*	*47*	*14*
Suspended Solids Conc.	mg/L	72	79	-65	*185*	*25*	*82*	*129*	*52*	*10*
Total Phosphorus	mg/L	**0.16**	**4.14**	**-4,029**	**0.30**	**1.40**	**-820**	**0.23**	**2.77**	**-2,419**
Orthophosphate	mg/L	**0.025**	**2.893**	**-57,854**	**0.003**	**1.187**	**-46,527**	**0.014**	**2.040**	**-53,089**
Total Kjeldahl Nitrogen	mg/L	**1.27**	**14.82**	**-1,163**	5.75	7.15	-60	**3.51**	**10.98**	**-595**
Nitrate+Nitrite	mg/L	**0.75**	**53.78**	**-31,971**	**0.27**	**0.55**	**-198**	**0.51**	**27.17**	**-16,134**
Hardness	mg $CaCO_3$/L	**25**	**141**	**-527**	49	52	-74	**37**	**97**	**-304**
Chloride	mg/L	**3**	**20**	**-643**	29	20	-166	**16**	**20**	**-407**
Total Cadmium	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC
Total Copper	µg/L	**16**	**43**	**-336**	29	17	25	23	30	-155
Total Lead	µg/L	**5**	**10**	**-277**	*9*	*2*	*72*	7	6	-102
Total Mercury	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC
Total Zinc	µg/L	*143*	*51*	*54*	*162*	*13*	*89*	*152*	*32*	*72*
Dissolved Cadmium	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC
Dissolved Copper	µg/L	**5**	**19**	**-990**	6	11	-291	**5**	**15**	**-608**
Dissolved Lead	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC
Dissolved Mercury	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC
Dissolved Zinc	µg/L	*46*	*17*	*34*	*22*	*8*	*43*	*34*	*12*	*39*
TPH – Diesel	mg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC
TPH – Oil	mg/L	*1.11*	*0.41*	*49*	*1.74*	*0.12*	*88*	*1.43*	*0.26*	*68*
Fecal Coliform	CFU/100 mL	*3,010*	*371*	*64*	*2,808*	*236*	*77*	*2,904*	*300*	*71*

NC = not calculable because more than 50 percent of the data were at or below the reporting limit

CFU/100 mL = colony forming units per 100 milliliters

TPH = total petroleum hydrocarbons

Bold values in **red** indicate a significant increase; *italicized* values in *blue* indicate a significant decrease; values in black indicate no significant difference between inlet and the outlet (Wilcoxon Signed Rank test α = 0.05).

SPLP extractions indicated that the compost in the BSM was the greatest source of nutrients, zinc, and copper. Compared with the compost, the sand in the mix was a less significant source for zinc and copper and did not appear to contribute to the observed nutrient export.

2.3.5. Study Systems

The swales were designed to infiltrate 91 percent of the annual runoff volume through an 18-inch-deep BSM using WWHM3. As with all CIP projects in Redmond, strict construction inspection controls were used to ensure the proper materials were provided and installed. Four of the swales are located at the City's MOC on Northeast 76th Street in Redmond, Washington. Those four swales (referred to as D1-60/40, D2-RBSM, D3-LSMV, and D4-LSW) are co-located in a block design with a shared inlet (MOC-IN). The two remaining bioretention swales are located on 185th Avenue Northeast, 200 feet north of the intersection with Northeast 68th Street. One swale is located on the west side of the road (referred to as 185-RBSMs), and the other is immediately across the street on the east side of the road (referred to as 185-Coir). Table 5 provides information of the BSM used in each swale.

Table 5. Bioretention Soil Mixes for MOC and 185th Bioretention Swales.

Bioretention Swale Name	Bioretention Soil Mix
D1-60/40	60% sand, 40% compost (60/40 Mix)
D2-RBSM	60% sand, 15% compost, 15% biochar; 10% shredded bark
D3-LSMV	Loamy sand mix (source 1)
D4-LSW	Loamy sand mix (source 2)
185-RBSMs	60% sand, 15% compost, 15% biochar; 10% shredded bark
185-Coir	80% sand, 20% coconut coir

2.3.6. Sampling Procedures

Monitoring was implemented using an Ecology approved QAPP that met TAPE standards for study design. A combination of automated sampling and grab sampling was used to characterize influent and effluent water qualities and to evaluate the performance of the study systems. Automated monitoring equipment was installed to continuously measure influent, effluent, and bypass flows. The automated equipment collected flow-weighted composite samples of the system's influent and effluent during 17 to 20 events, depending on the swale. Water quality monitoring was initiated immediately after the bioretention swales were installed and continued for 13 months from the collection of the first sample. The collected flow-weighted composite samples were analyzed for the following water quality parameters:

- pH
- TSS
- Total Kjeldahl nitrogen
- Nitrite + nitrate nitrogen

- Particle size distribution (influent only)
- Copper, total and dissolved
- Lead, total and dissolved
- Zinc, total and dissolved
- Total phosphorus
- Orthophosphate
- Hardness
- Dissolved organic carbon
- Major cations: calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K)
- Major anions: sulfate (SO_4), chloride (Cl)
- Alkalinity
- Sulfide

In addition, field personnel collected grab samples during 13 to 16 storm events, depending on the swale. Grab samples were collected for:

- Fecal coliform
- TPH-oil

During the course of the study, grab samples were collected for events with and without corresponding flow-weighted composite samples.

Data gathered by both the automated equipment and the grab samples were subsequently analyzed in the following ways:

- Computation of pollutant removal efficiencies with bootstrap confidence intervals
- Statistical comparisons of influent and effluent concentrations
- Flushing analysis of all six swales
- Comparison of effluent concentrations to applicable standards

In addition, SPLP analysis was conducted on each media component to try and isolate the source of various pollutants. Finally, infiltration testing was conducted on each BSM.

2.3.7. Hydrologic Performance

During the monitoring period, 117 individual events were identified at the MOC and there was zero bypass recorded. At 185-Coir 103, individual events were identified; two of those produced bypass flow. At 185-RBSMs, 111 individual events were identified; 10 of those produced bypass flow. Bypass volumes were not recorded, but the bypass frequency analysis above indicates that the standard design of bioretention in western Washington is results in swales much larger than potentially needed (visual observations using time-lapse photography indicated that ponding

depth never exceeded 1 inch for only a portion of each swale, even the loamy sand swales with very low Ksat). The bioretention swales on 185th Avenue Northeast were also likely oversized because the infiltration rate was assumed to be 2 in/hr when, in fact, it was much higher.

Controlled infiltration testing was conducted on May 20 through 23, 2014, at the MOC. Infiltration testing was not conducted at 185th Avenue Northeast at the time because the media installed were identical to the media installed in D2-RBSM at the MOC. On May 26, 2014, new sand and coconut coir media were installed at 185-Coir; that media was infiltration tested on May 29, 2015, 1 year later. The media was replaced because the precast vault was leaking so much water that no flow was observed discharging from the underdrain. The City required the contractor to excavate the cell, reseal the concrete cell, and replace the gravel and BSM. Redmond switched to sand and coir based on the preliminary data that the sand/compost/biochar mix was not performing better than 60/40 Mix.

The sand and coir mix had the highest infiltration rate (61 in/hr) when compared with the other media, and the 60/40 Mix had the second highest infiltration rate at 11.8 in/hr. Reducing the compost content and adding biochar and shredded bark to the mix (i.e., creating the RBSM mix) apparently reduced the infiltration rate by about 50 percent; infiltration rates at D2-RBSM were 6.0 in/hr. The loamy sands had the lowest infiltration rates, which were between 1.3 and 5.1 in/hr, based on lab permeability testing.

2.3.8. Water Quality Performance

For most parameters, the 185-Coir swale flushed its pollutants more quickly (by 20 percent of the water year [20%WY]) than the other swales and stabilized at effluent concentrations that were well below those of the other swales. Nutrient export was greatest from the swales containing compost, with the loamy-sand swales exporting equivalent nitrate + nitrite but less total phosphorus. Again, after an initial flush, the 185-Coir swale effluent had the lowest nutrient content of all the swales. Copper export was greatest from the swales containing compost. The loamy sand swales exported copper at a slightly lower level, while the 185-Coir swale reduced copper concentrations (though not significantly) despite the fact that concentrations were relatively low at the influent (mean = 4.1 µg/L) (Table 6). All six swales performed very well at reducing concentrations of total and dissolved zinc, TPH-oil, and fecal coliform (Table 6).

SPLP extractions indicated that the compost fraction was the largest contributor to copper and nutrient export. The biochar also seemed to be a source of nutrients. These SPLP results were reflected in the field data, which showed the systems that contained compost exported the highest levels of copper among the six swales, while the systems with compost and biochar exported the highest levels of nutrients.

One of the primary objectives of this study was to determine if export from the study systems would result in exceedances of groundwater or surface water quality criteria. (The state of Washington does not have stormwater quality standards. For reference purposes, stormwater runoff pollution concentrations are compared to groundwater and surface water quality

standards.) No groundwater quality standards (WAC 173-100) were exceeded in any of the effluent samples. However, surface water quality standards (WAC 173-201a) for dissolved copper were frequently exceeded at all the swales except 185-Coir.

2.3.9. Findings

The results from the Six Swales Study corroborate other recent studies in the Puget Sound region indicating that bioretention systems using Washington's default BSM (60/40 Mix) act as a pollutant-generating source of nutrients and copper.

For systems installed with underdrains that discharge to sensitive receiving waters (specifically, small streams and phosphorous-sensitive lakes), there is a potential for increasing downstream nutrient and copper impacts. For such applications, future bioretention projects should use sand with low metal and nutrient concentrations and should find organic alternatives to compost, such as coconut coir. Follow-up studies at both the bench scale and field scale are currently being conducted with the goal of formulating a BSM that does not export pollutants but still functions to support plants and reduce influent pollutant concentrations.

2.4. Kitsap Column Study

Kitsap County implemented a study to explore new media components and improve BSM performance for the capture and retention of nitrogen, phosphorus, and copper. The study had four main objectives:

1. Select new individual BSM components that show promise for improved water quality treatment performance.

2. Analyze media blends developed from components identified in objective 1 for the ability to capture and retain nitrogen, phosphorus, copper, and other stormwater pollutants of concern when exposed to flushing and dosing regimens in columns. (The ability of the media blends to germinate vegetation was also assessed.)

3. Develop recommendations for updating current BSM media guidelines for improved capture and retention of nitrogen, phosphorus, and copper based on leaching, pollutant retention, hydraulic considerations, cost, and sustainability criteria.

4. Identify unresolved water quality and hydraulic performance issues from the study that may warrant future evaluation.

Table 6. Chemistry Summary Table, Redmond Six Swales Study.

Parameter	Units	MOC-IN	D1-60/40		D2-RBSM		D3-LSMV		D4-LSW		185-COIR			185-RBSMs		
		Mean In	Mean Out	Mean % Reduction	Mean Out	Mean % Reduction	Mean Out	Mean % Reduction	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction
Alkalinity	$mgCaCO_3/L$	15.9	**39.9**	**-163%**	**37.4**	**-154%**	**23.0**	**-53%**	**21.6**	**-43%**	6.4	**14.6**	**-128%**	9.3	**46.2**	**-415%**
Chloride	mg/L	3.4	**3.6**	**-9%**	**3.7**	**-17%**	**3.6**	**-12%**	**3.5**	**-13%**	0.9	1.1	-50%	1.1	**2.6**	**-170%**
Dissolved Copper	mg/L	0.0056	**0.0086**	**-74%**	**0.0067**	**-33%**	0.0054	-6%	**0.0064**	**-16%**	0.0041	0.0028	-9%	0.0041	**0.0078**	**-111%**
Dissolved Lead	mg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Dissolved Organic Carbon	mg/L	7.28	8.52	-19%	7.84	-15%	*6.46*	*6%*	7.05	-2%	3.25	3.24	-15%	3.08	**7.41**	**-174%**
Dissolved Zinc	mg/L	0.0426	*0.0058*	*86%*	*0.00425*	*89%*	NC	NC	*0.004925*	*88%*	0.0148	NC	NC	0.0175	*0.0039*	*76%*
Hardness	$mgCaCO_3/L$	15.3	**30.3**	**-117%**	**32.4**	**-137%**	**22.6**	**-65%**	**22.2**	**-61%**	7.5	**16.4**	**-138%**	13.8	**43.1**	**-316%**
Nitrate + Nitrite	mg/L	0.138	**0.501**	**-546%**	**0.545**	**-1,028%**	**0.446**	**-343%**	**0.383**	**-257%**	0.112	**0.145**	**-61%**	0.117	**0.865**	**-765%**
Ortho-phosphate	mg/L	0.294	**0.275**	**-105%**	**0.362**	**-262%**	*0.073*	*53%*	*0.086*	*48%*	0.020	**0.040941**	**-968%**	0.009	**0.321**	**-7,296%**
pH	pH units	6.9	6.9	0%	**7.1**	-3%	**7.0**	-1%	6.9	0%	6.8	**7.0**	-4%	6.8	**7.3**	-7%
Total Phosphorus	mg/L	0.485	**0.459**	**-52%**	**0.539**	**-98%**	*0.204*	*26%*	*0.220*	*24%*	0.106	0.219353	-347%	0.219	**0.533**	**-285%**
SSL-Coarse > 75 um	mg/L	3.2	2.1	-51%	2.8	-51%	2.9	-60%	3.1	-55%	17.4	*2.2*	*58%*	74.3	*1.4*	*94%*
SSL-Fine < 75 um	mg/L	16.0	*8.8*	*-5%*	18.6	-258%	18.2	-210%	20.2	-238%	13.3	37.8	-660%	48.8	34.5	-117%
Sulfate	mg/L	1.18	1.15	-14%	**1.44**	**-31%**	**1.50**	**-50%**	1.22	-33%	1.32	1.33	-25%	1.55	1.44	-6%
Sulfide	mg/L	0.17	0.13	-1%	0.19	-74%	0.15	-2%	0.15	-9%	0.15	0.14	-7%	0.16	0.17	-43%
Total Calcium	mg/L	5.00	**8.99**	**-93%**	**7.88**	**-70%**	5.16	-10%	5.12	-9%	2.62	**3.69**	**-46%**	4.39	**11.57**	**-206%**
Total Copper	mg/L	0.0095	**0.0115**	**-45%**	0.0110	-44%	0.0100	-28%	0.0113	-36%	0.0101	0.0127	-64%	0.0188	0.0151	-12%
Total Kjeldahl Nitrogen	mg/L	1.63	1.20	-15%	0.98	5%	*0.69*	*26%*	*0.70*	*24%*	0.90	*1.08*	*-18%*	1.56	1.07	10%
Total Lead	mg/L	0.0016	NC	NC	NC	NC	NC	NC	NC	NC	0.0036	NC	NC	0.0044	*0.0013*	*32%*
Total Magnesium	mg/L	0.70	**1.90**	**-311%**	**3.10**	**-673%**	**2.37**	**-550%**	**2.28**	**-508%**	0.25	**1.75**	**-1,231%**	0.82	**3.46**	**-1,983%**
Total Potassium	mg/L	2.12	**7.83**	**-330%**	**6.59**	**-242%**	**2.44**	**-18%**	**2.75**	**-35%**	0.60	**1.86**	**-333%**	0.92	**8.00**	**-1,253%**
Total Sodium	mg/L	3.29	**3.76**	**-23%**	**4.70**	**-57%**	**4.55**	**-53%**	**4.24**	**-41%**	1.04	**2.33**	**-116%**	1.89	**2.53**	**-47%**
Total Suspended Solids	mg/L	22.3	*10.4*	*8%*	18.0	-75%	19.5	-85%	21.6	-104%	29.9	42.3	-203%	101.2	*32.6*	*39%*
Total Zinc	mg/L	0.0678	*0.0141*	*78%*	*0.0109*	*84%*	*0.0121*	*81%*	*0.0142*	*79%*	0.0391	*0.0158*	*45%*	0.0957	*0.0149*	*77%*
Fecal Coliform	CFU/100 mL	10,721	6,641	-9%	5,603	-46%	*5,626*	*-1%*	*6,008*	*-14%*	929	*430*	*31%*	4,162	*1,591*	*-27%*
TPH – Diesel	mg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
TPH – Motor Oil	mg/L	0.24	*0.12*	*39%*	*0.12*	*41%*	*0.16*	*17%*	*0.13*	*37%*	0.45	NC	NC	0.67	*0.14*	*64%*

$mgCaCo_3/L$ = milligrams of calcium carbonate per liter

NC = not calculable because more than 50 percent of the data were at or below the reporting limit.

CFU/100 mL = colony forming units per 100 milliliters.

TPH = total petroleum hydrocarbons.

LCL95 = lower 95 percent confidence limit on the mean (calculated with a bootstrap approach).

UCL95 = upper 95 percent confidence limit on the mean (calculated with a bootstrap approach).

Bold values in red indicate a significant increase between inlet and outlet; *italicized* values in *blue* indicate a significant decrease; values in black indicate no significant difference between inlet and the outlet (Wilcoxon Signed Rank test α = 0.0.

2.4.1. Study System

There were four key tasks to achieve the above objectives in the Kitsap Column Study:

1. Conduct a rapid survey of potential BSM components based on pollutant capture capability, cost, availability, and sustainability. Select individual media components from survey and project partner input.

2. Conduct synthetic precipitation leaching protocol (SPLP Method 1312) to determine nitrogen, phosphorus, and copper leaching potential. Select the media components that minimize leaching potential, provide adequate hydraulic conductivity, and support plants.

3. Combine components at various ratios, place in column arrays, flush the media blends with deionized water, and assess the effluent for nitrogen, phosphorus, copper, and other stormwater pollutants of concern. Hydraulic conductivity of the media blends was assessed during the flushing experiments.

4. Dose the best performing media columns with natural stormwater spiked (if necessary) with reagent grade chemicals to attain pre-determined concentrations. Assess the effluent for nitrogen, phosphorus, copper, and other stormwater pollutants of concern.

2.4.1.1. Select Media Components

A rapid survey of the scientific literature was performed to identify candidate media components in each of the following categories: bulk aggregates (e.g., sands) and bulk organic materials (e.g., compost) that comprise the majority of the media blends, and mineral and organic additives that provide specific pollutant capture and/or hydraulic characteristics, and comprise less of the overall volume.

SPLP extractions were performed on the 26 prospective media components identified from the survey results. The extractions were subsequently analyzed for total nitrogen, nitrate + nitrite, total phosphorus, ortho-phosphate, and total and dissolved copper. Media components were ranked from lowest to highest; lower ranks indicated lower leaching potential. The individual rankings for each parameter were also summed to provide an overall rank of leaching potential. The rankings were then used to select media components included for further testing as part of media blends. The components selected represented materials with the lowest or near lowest rankings for leaching potential; however, availability and cost also influenced selection.

Media components selected for the media blends for the column tests include:

- Bulk aggregate: C-33 sand (sand), volcanic sand (vs), and washed sand (ws). For the purposes of this synthesis paper, the volcanic sand and washed sand were grouped and termed "Alt Sand."

- Bulk organic: iron- coated wood chips (fe) and coconut coir pith (cp).
- Mineral additives: diatomaceous earth (de) and activated alumina.
- Organic additive: 1230AW granular activated charcoal (gac), high-carbon wood ash (ash) and activated bone char.

Based on best professional judgment, Herrera combined selected media components in a series of media treatments designed to minimize pollutant flushing and maximize pollutant capture performance. Composition of each media treatment is summarized in Table 7.

Table 7. Composition of Media Treatments Used in Flushing and Dosing Experiments, Kitsap Column Study.

Media Treatment Name	Bulk Aggregate	Bulk Organic	Mineral Additive	Organic Additive
60sd/40comp[a]	60% C-33 sand	40% compost[b]	NA	NA
70vs//20fe/10de	70% volcanic sand	20% iron-coated wood chips	10% diatomaceous earth	NA
70vs/20fe/10ash	70% volcanic sand	20% iron-coated wood chips	NA	10% high carbon wood ash
70vs/20cp/10de	70% volcanic sand	20% coconut coir pith	10% diatomaceous earth	NA
70vs/20cp/10gac	70% volcanic sand	20% coconut coir pith	NA	10% granulated activated charcoal[c]
70ws/20cp/10ash	70% washed sand	20% coconut coir pith	NA	10% high carbon fly ash
70vs/20cp/10ash	70% volcanic sand	20% coconut coir pith	NA	10% high carbon wood ash
90vs/10comp/p-layer[d]	90% volcanic sand	10% compost[e]	See footnote "d"	See footnote "d"

a Media treatment used default BSM specifications from the 2012 SWMMWW (Ecology 2012b) to serve as a control.

b Cedar Grove compost

c 1230AW (acid wash) coconut granular activated charcoal

d Media treatment included a polishing layer consisting of volcanic sand, activated alumina, and bone char in place of the Type 26 drainage aggregate used in the other treatments.

e Land Recovery Incorporated (LRI) compost.

ash = high-carbon fly ash
cp = coconut coir pith
de = diatomaceous earth
fe = iron-fused wood chips
gac = granular activated charcoal
p-layer = polishing layer
NA = not applicable
sd = C-33 sand
vs = volcanic sand
ws = washed sand

2.4.1.2. Column Flushing and Dosing Experimental Rig

Twenty-four columns for flushing and dosing experiments were constructed at the Seattle University Engineering Laboratory. The columns were built using polyvinyl chloride (PVC) with an 8-inch diameter and a height of 36 inches. Each column includes a 1-inch slotted underdrain placed at the bottom of the column. Media components meeting SPLP, cost, and sustainability criteria were combined into media blends and placed in the columns for subsequent flushing and dosing experiments. Each of the eight media treatments identified in Table 7 were replicated three times in the 24-column array using a random block design, per the project QAPP. The media depth was 18 inches with a 12-inch aggregate bedding layer placed under the media to provide a final filter before discharge through the underdrain pipe. Calibrated peristaltic pumps were installed to deliver water to the columns during the experiments.

2.4.2. Sampling Procedures

2.4.2.1. Flushing Experiments

Flushing experiments were performed to evaluate potential pollutant leaching from the media treatments. Each of the 24 columns was flushed 19 times with deionized water over a 1-month period (once per day excluding weekends). Approximately 13.4 liters of deionized water were applied to each column for the first 11 flushes; 26.8 liters were applied for the last 8 flushes. The total volume applied to each column approximates the volume that would be delivered to a bioretention system given typical sizing criteria and average annual precipitation in Seattle over one water year (October 1 through September 30).

Samples were collected on four occasions corresponding to the first, sixth, twelfth, and nineteenth flushing events. Sample collection occurred over a 2-day period; 12 of the 24 columns were sampled the first day and the remaining 12 the second day. A sample was also collected from an influent monitoring port each day for a total of 26 samples per sampling event (12 effluent samples plus 1 influent sample the first day; and 12 effluent samples plus 1 influent sample the second day).

2.4.2.2. Dosing Experiments

Dosing experiments were performed to evaluate the pollutant capture potential of the media treatments. Each of the 24 columns was dosed on five occasions with natural stormwater or natural stormwater augmented with reagent grade chemicals to attain target concentration ranges identified in the project QAPP. Approximately 13.4 liters of stormwater were applied to each column for the first three dosing events. This is equivalent to 1.32 inches of precipitation for a typically sized bioretention system. Approximately 26.8 liters of stormwater were applied to each column for the last two dosing events. This is equivalent to 2.43 inches of precipitation for

a typically sized bioretention system. The natural stormwater used in the experiments was obtained from a catch basin that collects runoff from the City of Redmond MOC on Northeast 76th Street in Redmond, Washington. Chemicals added to attain target concentrations are as follows: Sil-Co-Sil 106 to introduce TSS; potassium phosphate to introduce phosphorus; copper sulfate to introduce copper; and zinc chloride to introduce zinc. See additional details in the subsections below.

2.4.2.3. Hydraulic Conductivity

Two methods were used to evaluate Ksat. Falling head Ksat tests were performed for every column at the beginning of the flushing and at the end of the dosing experiments. In addition, constant head permeability tests were performed by Shannon and Wilson using American Society for Testing and Materials (ASTM) D2434. The additional testing was performed to provide Ksat test values comparable to previous media analyses.

2.4.3. Hydraulic Performance

Ksat rates for all the treatments tested were very high (ranging from 32 to 161 in/hr). For an individual measurement, the column falling head tests results ranged from a high rate of 195 in/hr for the 60sd/40comp control to a low of 43.06 in/hr for the 70ws/20cp/10ash treatment. Mean rates ranged from a high of 161.20 in/hr for the 60sd/40comp control to a low of 56.48 in/hr for the 70ws/20cp/10ash treatment.

For an individual measurement, Ksat rates from the ASTM D2434 tests ranged from a high rate of 196.00 in/hr for the 90vs/10comp/p-layer treatment to a low of 4.00 in/hr for the 70vs/20cp/10de treatment. Mean rates ranged from a high of 148.00 in/hr for the 90vs/10comp/p-layer treatment to a low of 32.00 in/hr for the 70ws/20cp/10ash treatment. The ASTM constant head test was not performed on the 60sd/40comp control.

2.4.4. Water Quality Treatment Performance

2.4.4.1. Flushing Experiments

The 60sd/40comp control performed poorly (other than for TSS) compared to the other treatments in the flushing experiments. Nitrate + nitrite, total phosphorus, ortho-phosphate, and dissolved copper were exported from the 60sd/40comp in all flushing experiments, sometimes at dramatically higher concentrations. For example, the median nitrate + nitrite effluent concentration (1.27 mg/L) for the 60sd/40comp control was approximately two orders of magnitude higher than the treatments not containing compost (e.g., 0.03 mg/L for the 70vs/20cp/10de ash treatment).

All the treatments generally exhibited some initial flushing of nitrate + nitrite, total phosphorus, ortho-phosphate, and dissolved copper. However, concentrations were initially lower and

declined to lower effluent concentrations relative to those for the 60sd/40comp control. Flushing of ortho-phosphate from the 60sd/40comp control actually increased substantially before decreasing.

The treatment containing 10 percent compost with a polishing layer (70vs/10comp/p-layer) also flushed elevated levels of nitrogen and phosphorus compared to treatments not containing compost. However, concentrations were lower than the 60sd/40comp control.

2.4.4.2. Dosing Experiments

The 90vs/10comp/p-layer treatment was the top performer for TSS capture (median effluent concentration ranging from 1.9 to 9.6 mg/L and 92 to 96 percent removal), indicating the polishing layer (consisting of a finer sand mix) may provide a higher performance filter for mineral and organic particulates than the Type 26 material used in the other treatments. The 70ws/20cp/10ash was the next best performer for TSS (4.1 to 23.9 mg/L and 53 to 93 percent removal). See Table 8 for summary dosing results.

In general, percent removal for nitrate + nitrite varied across experiments and treatments from export to 90 percent plus removal. Three treatments achieve consistently high percent reductions (60 to 99 percent) across all influent concentration levels: 70vs/20cp/10gac, 70vs/20cp/10ash and 70ws/20cp/10ash. The 60sd/40comp control consistently exported nitrate + nitrite.

Total phosphorus median percent removal for all treatments except the 60sd/40comp control generally fell in a range of 20 to 70 percent. The median effluent concentration for the 60sd/40comp control was significantly higher than all other treatments, and the media exported total phosphorus in all but one experiment. All other treatment median effluent concentrations were not significantly different.

Ortho-phosphate median percent removal for all treatments except the 60sd/40comp and the 90vs/10comp/p-layer generally fell in a range of 10 to 80 percent. The median effluent concentration for the 60sd/40comp control was significantly higher than all other treatments, and the media exported ortho-phosphate in all experiments. Other treatments, including 70vs/20fe/10de, 70vs/20fe/10de and 90vs/10comp/p-layer, also exported ortho-phosphate in some experiments, including those with low and higher influent concentrations.

Dissolved copper median percent removal for all treatments except the 60sd/40comp, 70vs/20fe/10de, and 70vs/20fe/10ash treatments generally fell in a range of 10 to 80 percent. The 60sd/40comp, 70vs/20fe/10de, and 70vs/20fe/10ash treatments consistently exported dissolved copper in all but the high-dose experiments. The median effluent concentrations were high (approximately 10-40 µg/L) for the 70vs/20fe/10de and 70vs/20fe/10ash treatments.

2.4.5. Findings

Based on the study results, several conclusions were made. The 60sd/40comp control exported statistically higher concentrations of nitrate + nitrite, total phosphorus, ortho-phosphate, and dissolved copper compared to the non-compost treatments during the flushing and dosing phases. Export concentrations were often one to two orders of magnitude higher. These results are consistent with previous studies (Herrera 2014a; Herrera 2015b; WSU 2014) that have been performed on the 60/40 Mix BSM and indicate the compost fraction is the predominant source of these pollutants.

All the treatments generally exhibited some initial flushing of total phosphorus, ortho-phosphate, and dissolved copper. However, concentrations were initially much lower and rapidly declined relative to those for the 60sd/40comp control. Flushing of total phosphorus and ortho-phosphate from the 60sd/40comp control actually increased substantially before decreasing.

The treatment containing 10 percent compost with a polishing layer (70vs/10comp/p-layer) also flushed elevated levels of nitrogen and phosphorus compared to treatments not containing compost. However, concentrations were lower than the 60sd/40comp control.

Pollutant capture performance in the dosing experiments for the 70vs/10comp/p-layer treatment was also better than the 60sd/40comp control, but significantly poorer than the better performers not containing compost. The 70vs/10comp/p-layer treatment was the best performer for TSS capture, likely due the finer texture of the polishing layer compared to the Type 26 drainage layer used in all other treatments.

The treatments containing iron-coated woodchips leached dissolved copper during the dosing experiments; this leaching pattern was not observed during the flushing experiments. The addition of the woodchips to the media blends did not substantially improve treatment performance for phosphorus as originally intended.

In general, treatments containing the coconut coir pith and either granular activated carbon or high carbon wood ash were the best performers with regard to pollutant flushing and pollutant capture. It is not clear which additive, granular activated carbon or high carbon wood ash, provides the most benefit in these blends.

Ksat rates for all the treatments tested were extremely high (ranging from 32 to 161 in/hr). Performance for TSS and particulate-bound pollutants may be improved with media blends having lower Ksat rates; however, optimizing treatment performance based on this aspect of media design was outside the study scope.

Table 8. Dosing Experiment Concentration Summary Statistics, Kitsap Column Study.

Parameter	Units	60/40			90vs/10comp/p-layer			70vs/20cp/10de			70vs/20cp/10gac			70ws/20cp/10ash			70vs/20cp/10ash			70vs/20fe/10ash			70vs/20fe/10de		
		Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction	Mean In	Mean Out	Mean % Reduction
Alkalinity	mg $CaCO_3$/L	32.8	37.0	-24	**29.7**	**58.7**	**-114**	*32.8*	*13.5*	*51*	*29.7*	*9.7*	*65*	*29.7*	*16.7*	*39*	*29.7*	*14.8*	*46*	32.8	24.4	14	*32.8*	*19.0*	*35*
Chloride	mg/L	5.0	4.5	7	5.2	4.3	12	*5.0*	*4.1*	*15*	*5.2*	*2.1*	*47*	*5.2*	*3.8*	*22*	*5.2*	*4.0*	*19*	5.0	5.0	-1	5.0	5.1	-6
Dissolved Cadmium	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Dissolved Copper	µg/L	**8.4**	**10.7**	**-27**	*8.2*	*5.5*	*34*	*8.4*	*5.4*	*36*	*8.2*	*3.4*	*59*	*8.2*	*1.8*	*78*	*8.2*	*4.8*	*42*	**8.4**	**20.6**	**-142**	**8.4**	**25.6**	**-202**
Dissolved Lead	µg/L	*0.5*	*0.3*	*31*	*0.5*	*0.3*	*37*	*0.5*	*0.2*	*56*	*0.5*	*0.2*	*56*	*0.5*	*0.2*	*60*	*0.5*	*0.3*	*41*	0.5	0.6	-25	0.5	0.6	-24
Dissolved Organic Carbon	mg/L	**9.20**	**20.97**	**-131**	*10.70*	*8.04*	*5*	**9.20**	**13.15**	**-39**	10.70	8.52	15	*10.70*	*5.80*	*41*	11.15	9.50	2	**9.20**	**49.64**	**-451**	**9.20**	**56.49**	**-512**
Dissolved Potassium	µg/L	**3,145**	**9,837**	**-205**	3,175	3,257	-2	*3,145*	*1,390*	*55*	*3,175*	*1,705*	*45*	*3,175*	*1,103*	*65*	*3,175*	*1,812*	*41*	**3,145**	**5,743**	**-78**	**3,145**	**4,840**	**-52**
Dissolved Sodium	µg/L	4,835	2,683	29	4,960	3,965	4	4,835	3,487	11	4,960	2,215	27	4,960	2,678	24	4,960	2,470	27	4,835	3,412	17	4,835	3,418	17
Dissolved Zinc	µg/L	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
Hardness	mg/L	**32.8**	**77.2**	**-155**	**33.8**	**86.4**	**-207**	*32.8*	*21.4*	*27*	*33.8*	*14*	*48*	*33.8*	*24.1*	*18*	*35.2*	*21.6*	*31*	32.8	36.8	-20	32.8	36.4	-18
Nitrate + Nitrite	mg-N/L	**1.12**	**12.51**	**-1,924**	**1.22**	**1.47**	**-54**	*1.12*	*0.86*	*14*	*1.22*	*0.03*	*94*	*1.22*	*0.19*	*80*	*1.27*	*0.29*	*73*	*1.12*	*0.56*	*43*	*1.12*	*0.67*	*42*
Ortho-phosphate	mg-P/L	**0.099**	**0.957**	**-962**	0.323	0.115	16	*0.099*	*0.110*	*-43*	*0.323*	*0.051*	*72*	*0.323*	*0.023*	*83*	*0.266*	*0.071*	*63*	0.099	0.126	-50	0.099	0.134	-40
Sulfate	mg/L	**4.6**	**7.1**	**-65**	**5.9**	**28.2**	**-417**	4.6	5.0	-12	*5.9*	*3.1*	*43*	*5.9*	*3.8*	*33*	5.9	5.0	12	**4.6**	**27.4**	**-444**	**4.6**	**28**	**-506**
Total Cadmium	µg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Total Calcium	µg/L	**10,502**	**20,412**	**-115**	**10,664**	**22,753**	**-164**	*10,502*	*5,356*	*43*	*10,664*	*3,144*	*63*	*10,664*	*5,947*	*35*	*11,130*	*5,382*	*45*	10,502	9,722	0	10,502	9,683	1
Total Copper	µg/L	*122.8*	*14.4*	*35*	*128.8*	*9.5*	*67*	*122.8*	*9.8*	*57*	*128.8*	*12.7*	*46*	*128.8*	*7.2*	*72*	*97.0*	*9.7*	*60*	122.8	25.4	-22	122.8	31.8	-53
Total Kjeldahl Nitrogen	mg-N/L	**1.22**	**3.09**	**-162**	*1.16*	*1.05*	*7*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	1.22	1.37	-19	1.22	1.51	-31
Total Lead	µg/L	*2.9*	*0.8*	*71*	*3.0*	*0.4*	*86*	*2.9*	*0.7*	*75*	*3.0*	*1.1*	*65*	*3.0*	*0.7*	*76*	*3.0*	*0.7*	*76*	*3.0*	*1.1*	*63*	*3.0*	*1.1*	*61*
Total Magnesium	µg/L	**1,662**	**6,427**	**-297**	**1,702**	**7,196**	**-358**	**1,662**	**1,969**	**-27**	1,702	1,490	-2	**1,702**	**2,238**	**-42**	**1,759**	**1,969**	**-21**	**1,662**	**3,039**	**-90**	**1,662**	**2,984**	**-87**
Total Phosphorus	mg-P/L	**0.769**	**1.212**	**-111**	*0.773*	*0.379*	*46*	*0.769*	*0.355*	*51*	*0.773*	*0.434*	*37*	*0.773*	*0.314*	*58*	*0.721*	*0.390*	*48*	*0.769*	*0.470*	*30*	*0.769*	*0.516*	*17*
Total Suspended Solids	mg/L	*53.1*	*16.1*	*67*	*83.0*	*4.4*	*94*	*53.1*	*34.1*	*24*	*83.0*	*46.9*	*15*	*83.0*	*18.4*	*64*	*74.3*	*20.3*	*64*	*53.1*	*18.6*	*65*	*53.1*	*28.8*	*45*
Total Zinc	µg/L	*198.4*	*6.9*	*92*	*NC*	*NC*	*NC*	*198.4*	*5.7*	*93*	*206*	*9.6*	*88*	*206*	*6.6*	*92*	*167.9*	*6.5*	*92*	*198.4*	*6*	*93*	*198.4*	*6.4*	*93*

mgCaCo3/L = milligrams of calcium carbonate per liter

NC = not calculable because more than 50 percent of the data were at or below the reporting limit.

Bold values in **red** indicate a significant increase; *italicized* values in *blue* indicate a significant decrease; values in black indicate no significant difference between inlet and the outlet (Wilcoxon Signed Rank test α = 0.05).

2.5. Results Summary

In the five studies summarized above, 19 separate BSMs were tested in either the lab or the field (Table 9) and over 70 parameters were analyzed.

Table 9. Bioretention Soil Mixes Tested in the Five Studies.

Site/Media Name	BSM Constituents	BSM Category
Tacoma Salishan Study		
R street	60% sand/40% compost	60/40 Mix
44th Street	60% sand/40% compost	60/40 Mix
WSU Mesocosm Study		
60/40	60% sand/40% compost	60/40 Mix
80/20[a]	60% sand/40% compost	60/40 Mix
60sd/15comp/15sb/10wtr	60% sand/15% compost/10% shredded bark/15% WTR	Sand/Compost + Additives
60sd/30comp/10wtr	60% sand/30% compost/10% WTR	Sand/Compost + Additives
Redmond 185th Avenue Northeast Study		
60/40	60% sand/40% compost	60/40 Mix
Redmond Six Swales Study		
D1-60/40	60%sand/40% compost	60/40 Mix
D2-RBSM	60% sand/15% compost/15% biochar/10% shredded bark	Sand/Compost + Additives
D3-LSMV	50% sand/50% loamy sand (Maple Valley)	Loamy Sands
D4-LSW	50% sand/50% loamy sand (Woodinville)	Loamy Sands
185-RBSMs	60% sand/15% compost/15% biochar/10% shredded bark	Sand/Compost + Additives
185-Coir[b]	80% sand/20% coconut coir	Sand/Coir + Additives
Kitsap Column Study		
60/40	60% sand/40% compost	60/40 Mix
90vs/10comp/p-layer[c]	90% sand/10% compost with polishing layer	Sand/Compost + Additives
70vs/20cp/10de	70% sand/20% coconut coir/10% diatomaceous earth	Sand/Coir + Additives
70vs/20cp/10gac	70% sand/20% coconut coir/10% granular activated carbon	Sand/Coir + Additives
70ws/20cp/10ash	70% sand/20% coconut coir/10% wood ash	Sand/Coir + Additives
70vs/20cp/10ash	70% sand/20% coconut coir/10% wood ash	Sand/Coir + Additives

[a] Although the 80/20 mix was technically not a 60/40 Mix, it was categorized as such because it performed similarly to the 60/40 Mix and did not contain any additives.

[b] Although this BSM did not contain additives, it performed similarly to the Sand/Coir + Additive mixes so they were grouped.

[c] p-layer = 12-inch drainage layer consisting of volcanic sand, activated alumina, and bone char

vs = volcanic sand; ws = washed sand.
All other sands were C-33 builders sand per the bioretention specification from the SWMMWW (Ecology 2012b).

WTR = water treatment residuals

This section presents results from all five studies, focusing on the following aspects of system performance:

- Infiltration
- Treatment as a function of influent, time, and infiltration rate
- Physical and chemical properties of media components

To streamline the data and explore trends among BSMs with different components, the 19 BSMs were grouped into four categories:

1. 60/40 Mix (n = 7)
2. Sand/Compost + Additives (n = 5)
3. Loamy Sands (n = 2)
4. Sand/Coir + Additives (n = 5)

Additives for the BSMs included one or more of the following: activated alumina, biochar, diatomaceous earth, granular activated carbon, high carbon wood ash, shredded bark, and water treatment residuals. The specific BSMs assigned to each category are shown in Table 9. The Sand/Coir + Additives category includes the BSM used in the Redmond Six Swales Study, which contained no additives, as well as the four coir-based BSMs in the Kitsap Column Study, which each contained a different additive. The results from the five coir-based BSMs were considered similar enough that grouping was warranted.

2.5.1. Infiltration

Each of the five studies assessed infiltration rates using one or more of three methods. Field infiltration was conducted in the field over a relatively large area of the bioretention system using various adaptations of the Pilot Infiltration Test (Ecology 2012a). Column falling head tests were conducted in columns with various diameters and generally involved holding 12 inches of head over the media and then opening the underdrain and timing drawdown. Finally, permeability testing was conducted in a lab and followed ASTM 2434 modified in accordance with Appendix V-B of the 2012 SWMMWW (Ecology 2012b).

Table 10 presents the infiltration results from the five studies. As is apparent, the results vary, depending upon which infiltration method was used. The laboratory permeability testing and column falling head testing reported higher infiltration rates than those from field infiltration testing. This discrepancy could be caused by increased compaction of BSMs in the field due to environmental conditions and foot traffic. Alternatively, potential wall effects (i.e., water short-circuiting down the column wall instead of moving through the media) may be artificially inflating infiltration rates in the lab. Regardless, the infiltration rates for the 60/40 Mix range

Table 10. Results from Infiltration Rate Testing for the Five Studies.											
	Tacoma Salishan	WSU Mesocosm	Redmond 185th	Redmond Six Swales			Kitsap Columns				
BSM Category	Field Infiltration (in/hr)	Column Falling Head (in/hr)	Field Infiltration (in/hr)	Field Infiltration (in/hr)	Column Falling Head (in/hr)	Permeability (ASTM 2434) (in/hr)	Column Falling Head (in/hr)	Permeability (ASTM 2434) (in/hr)	Field Infiltration Average (in/hr)	Column Falling Head Average (in/hr)	Permeability Average (in/hr)
60/40 Mix	20.9	41.7	2.9	11.8	49	11.9	84.0	210[a]	84.0	11.9	112.6
Sand/Compost + Additives		34.7		6	26.5	6	58.2	148	58.2	6.0	76.6
Loamy Sands						3.2					3.2
Sand/Coir + Additives				61		61	91.9	85.5	91.9	61.0	85.5

[a] Permeability value extrapolated based on falling head test relationship.

Blank cells in dicate the parameter was not measured.

from a minimum of 3 in/hr to as high as 200 in/hr (across all methods and studies), which are much higher than the Ecology specification of 2 to 12 in/hr. When additives are used to augment the 60/40 Mix, there is a decrease in infiltration rates; rates range from 6 to 148 in/hr, depending upon the test and method (Table 10). This may be due to the fact that many of the additives used (e.g., biochar, WTR) are either fine-grained or have a high water holding capacity. The Loamy Sands exhibited the lowest infiltration rates among the BSMs tested (3.2 in/hr), while the Sand/Coir + Additives exhibited the highest infiltration rates in every test except the permeability test. The effect that infiltration rates may have on effluent concentrations is discussed below.

2.5.2. Water Quality Treatment

This section reduces and summarizes the water quality results for a subset of the most important parameters. Specifically, results for the following parameters are presented herein in graphical and tabular format:

- TSS
- Total phosphorus
- Ortho-phosphate
- Nitrate + nitrite
- Dissolved copper
- Dissolved zinc
- TPH – oil
- Fecal coliform

Graphical results of effluent concentrations for all measured parameters are in Appendix A, and are presented as temporal plots and boxplots. Because the focus of the temporal plots is to characterize pollutant flushing through time, the Kitsap Column Study dosing data were not included, but the flushing data from the same study were. Many of the measured parameters in the five studies show a strong temporal flushing pattern that varied depending upon the BSMs tested.

TSS flushing from the BSMs was essentially complete by one water year (100%WY), and effluent values for all BSM categories converged on a value of less than 10 mg/L (Figure 1). At this equilibrated effluent concentration, all the BSMs would perform as basic treatment BMPs after 1 year. Figure 1 indicates that the Sand/Coir + Additives flush significantly more TSS than the other BSMs, the 60/40 Mixes perform the best, and the Sand/Compost + Additives and Loamy

Sands fall somewhere in between. These results can also be seen in Table 11, which shows the best performing BSM was the Sand/Compost + Additives from the Kitsap Column Study. That media consisted of 90 percent sand, 10 percent compost, and a polishing layer of sand, activated alumina, and bone char (Table 9). It was the only BSM of the 19 in this study that used a sand as the drainage layer instead of the more common gravelly sand (Type 26, which was used for all other BSMs except the Redmond 185th Avenue Northeast Study) or pea gravel (which was used for the Redmond 185th Avenue Northeast Study). In addition, the one study that used a perforated pipe and pea gravel (Redmond 185th Avenue Northeast Study) instead of a slotted pipe and Type 26 exported the highest initial effluent concentrations (120 mg/L) of all the studies (Figure 1). The implications of these findings are presented in the *Recommendations* section.

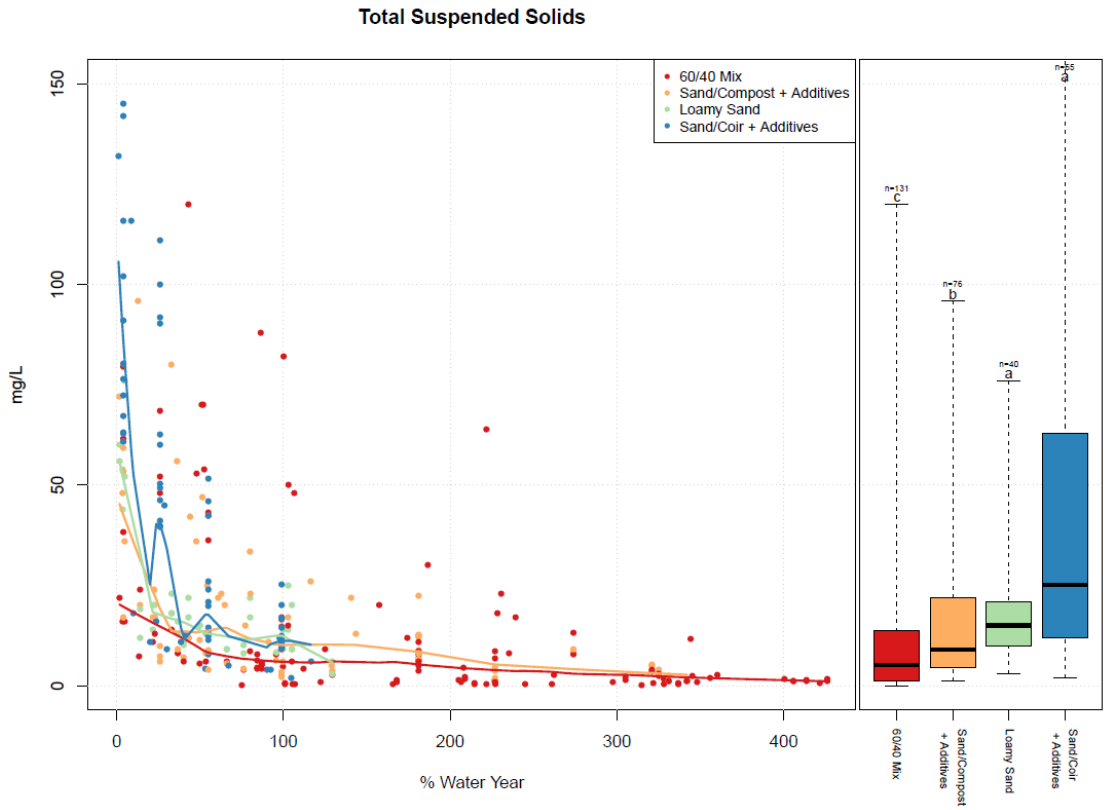

Figure 1. Total Suspended Solids Effluent Concentration Results for Each BSM Category.

Total phosphorus flushing appeared to take longer (perhaps up to 3 water years [300%WY]) and to equilibrate at a higher effluent concentration in the 60/40 Mix than in the other BSM categories (Figure 2). Including additives in the 60/40 Mix seemed to help with total phosphorus performance, but the difference was not significant (Figure 2). The Sand/Coir + Additives BSM started with an initial high concentration flush of total phosphorus, which was likely associated with the high flush of solids from the same BSMs. However, after 50 percent of the water year (50%WY) the Sand/Coir + Additives BSM equilibrated to an effluent concentration level that was the lowest among the four BSM categories. The Loamy Sands had the lowest initial effluent concentrations and after 50%WY equilibrated to a low level just above the concentrations measured from the Sand/Coir + Additives mixes (Figure 2). Table 11 indicates that the best

performers for total phosphorus removal were the Loamy Sands, the Sand/Coir + Additives, and the Sand/Compost + Additives from the Kitsap Column Study. Again, this last BSM contained a polishing layer which resulted in a high level of solids retention. The total phosphorus performance of this BSM can be attributed to the reduction in solids export.

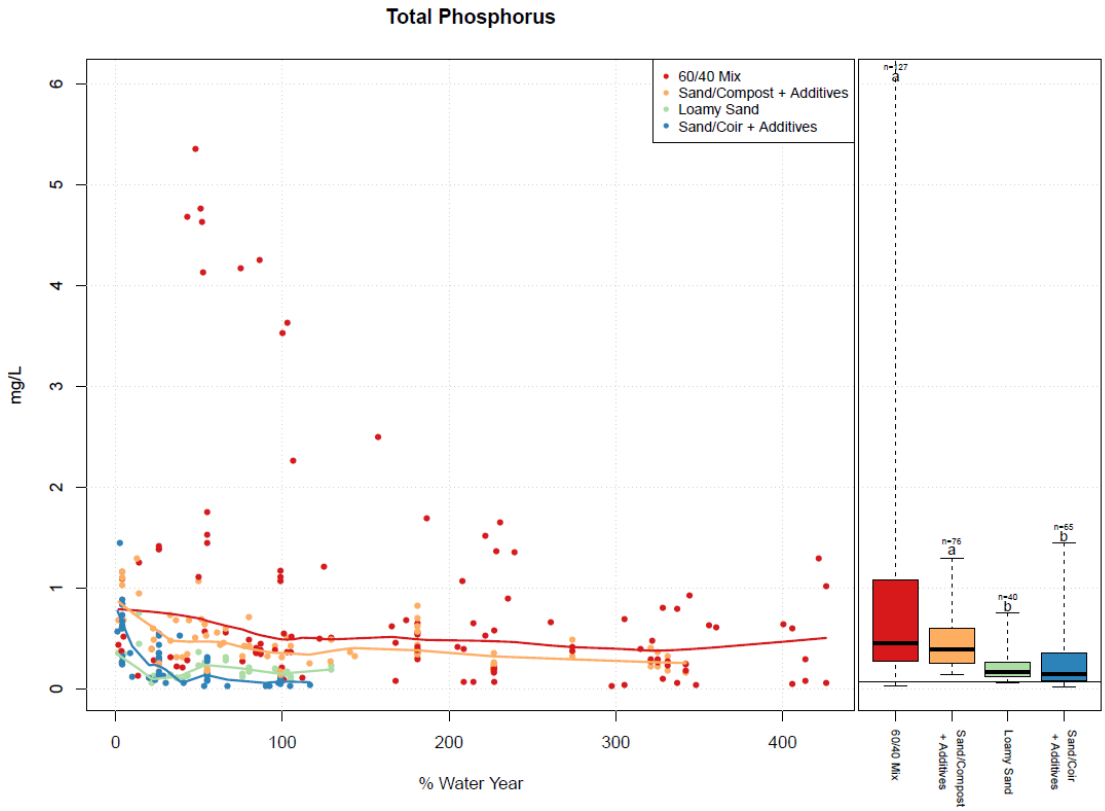

Figure 2. Total Phosphorus Effluent Concentration Results for Each BSM Category.

Both the 60/40 Mix and the Sand/Compost + Additives exported significantly more ortho-phosphate than the Loamy Sands and the Sand/Coir + Additives (Figure 3). The Sand/Compost + Additives and the Sand/Coir + Additives exhibited a slight flush which was complete by 25 percent of the water year (25%WY). The 60/40 Mix exhibited a flush lasting about 300%WY and equilibrated at a higher concentration than the other BSMs (~0.5 mg/L) (Figure 3). Table 11 indicates that the addition of a polishing layer to a 90/10 mix (Kitsap Column Study Sand/Compost + Additives) results in vastly improved ortho-phosphate removal, likely due to sorption of ortho-phosphate to the activated alumina in the polishing layer. However, the effluent concentrations still do not reach the low levels achieved by the Loamy Sands and the Sand/Coir + Additives BSMs.

The nitrate + nitrite flushing pattern for the 60/40 Mix exhibited a few high values that equilibrated to ~0.4 mg/L by 200%WY (Figure 4). After 200%WY the Sand/Compost + Additives and the Loamy Sands performed similarly to the 60/40 Mix. The Sand/Coir + Additives flushed very little nitrate + nitrite and equilibrated to ~0.1 mg/L by 25%WY (Figure 4). Table 11 indicates that the 60/40 Mixes generally performed poorly at nitrate + nitrite removal and tended to export nitrate + nitrite.

Table 11. Summary of Influent, Effluent, and Percent Removal for Each Study by BSM Category.

Parameter	Units	Tacoma Salishan Study			WSU Mesocosm Study			Redmond 185th Avenue NE Study			Redmond Six Swales Study			Kitsap Column Study		
		Mean Influent	Mean Effluent	Median % Removal	Mean Influent	Mean Effluent	Median % Removal	Mean Influent	Mean Effluent	Median % Removal	Mean Influent	Mean Effluent	Median % Removal	Mean Influent	Mean Effluent	Median % Removal
60/40																
Total Suspended Solids	mg/L	26.7	1.7	94	4.4	5.3	-12	*135.1*	*42.0*	*76*	*22.3*	*10.4*	*63*	*53.1*	*16.1*	*71*
Total Phosphorus	mg/L	0.087	0.638	-637	**0.054**	**0.344**	**-516**	**0.227**	**2.768**	**-1,171**	**0.485**	**0.459**	**-25**	**0.769**	**1.212**	**-133**
Ortho-Phosphorus	mg/L	0.018	0.360	-1,897	**0.014**	**0.252**	**-1,550**	**0.014**	**2.040**	**-39,708**	**0.294**	**0.275**	**-114**	**0.099**	**0.957**	**-758**
Nitrate + Nitrite	mg/L	0.059	0.177	-198	0.361	0.259	10	**0.507**	**27.165**	**-335**	**0.138**	**0.501**	**-244**	**1.123**	**12.506**	**-813**
Dissolved Copper	µg/L	4.7	4.0	14	**2.8**	**7.0**	**-137**	**5.1**	**14.9**	**-327**	**5.6**	**8.6**	**-79**	**8.4**	**10.7**	**-26**
Dissolved Zinc	µg/L	15.5	5.4	65	NC	NC	NC	*34.2*	*12.5*	*49*	*42.6*	*6.7*	*84*	*142.2*	*4.3*	*85*
TPH – Motor Oil	mg/L	–	–	–	NC	NC	NC	1.43	0.27	73	0.25	0.12	48	–	–	–
Fecal Coliform	CFU/100 ml	–	–	–	*166*	*17*	*96*	*3,065*	*317*	*89*	10,214	5,937	0	–	–	–
Sand/Compost + Additives																
Total Suspended Solids	mg/L	–	–	–	**4.1**	**6.4**	**-28**	–	–	–	*60.6*	*24.9*	*50*	*83.0*	*4.4*	*95*
Total Phosphorus	mg/L	–	–	–	**0.049**	**0.378**	**-631**	–	–	–	**0.364**	**0.536**	**-109**	*0.773*	*0.379*	*44*
Ortho-Phosphorus	mg/L	–	–	–	**0.010**	**0.260**	**-2,500**	–	–	–	**0.161**	**0.343**	**-809**	0.323	0.115	10
Nitrate + Nitrite	mg/L	–	–	–	0.361	0.302	8	–	–	–	**0.129**	**0.697**	**-412**	**1.221**	**1.475**	**-30**
Dissolved Copper	µg/L	–	–	–	**2.7**	**7.7**	**-190**	–	–	–	**4.9**	**7.3**	**-61**	*8.2*	*5.5*	*48*
Dissolved Zinc	µg/L	–	–	–	NC	NC	NC	–	–	–	*30.4*	*5.7*	*75*	*133.8*	*4.1*	*86*
TPH – Motor Oil	mg/L	–	–	–	NC	NC	NC	–	–	–	0.43	0.12	59	–	–	–
Fecal Coliform	CFU/100 ml	–	–	–	NC	NC	NC	–	–	–	*8,132*	*3,393*	*12*	–	–	–
Loamy Sands																
Total Suspended Solids	mg/L	–	–	–	–	–	–	–	–	–	22.2	20.5	23	–	–	–
Total Phosphorus	mg/L	–	–	–	–	–	–	–	–	–	*0.490*	*0.212*	*43*	–	–	–
Ortho-Phosphorus	mg/L	–	–	–	–	–	–	–	–	–	*0.298*	*0.080*	*48*	–	–	–
Nitrate + Nitrite	mg/L	–	–	–	–	–	–	–	–	–	**0.139**	**0.415**	**-195**	–	–	–
Dissolved Copper	µg/L	–	–	–	–	–	–	–	–	–	**5.6**	**5.9**	**-10**	–	–	–
Dissolved Zinc	µg/L	–	–	–	–	–	–	–	–	–	*42.6*	*5.8*	*87*	–	–	–
TPH – Motor Oil	mg/L	–	–	–	–	–	–	–	–	–	0.25	0.14	32	–	–	–
Fecal Coliform	CFU/100 ml	–	–	–	–	–	–	–	–	–	*10,214*	*5,196*	*55*	–	–	–
Sand/Coir + Additives																
Total Suspended Solids	mg/L	–	–	–	–	–	–	–	–	–	31.3	42.3	60	*73.4*	*30.1*	*53*
Total Phosphorus	mg/L	–	–	–	–	–	–	–	–	–	0.111	0.219	8	*0.760*	*0.373*	*47*
Ortho-Phosphorus	mg/L	–	–	–	–	–	–	–	–	–	**0.021**	**0.041**	**-330**	*0.253*	*0.064*	*69*
Nitrate + Nitrite	mg/L	–	–	–	–	–	–	–	–	–	0.109	0.145	-10	*1.207*	*0.345*	*79*
Dissolved Copper	µg/L	–	–	–	–	–	–	–	–	–	4.0	2.9	25	*8.3*	*3.8*	*53*
Dissolved Zinc	µg/L	–	–	–	–	–	–	–	–	–	*14.6*	*5.0*	*56*	*128.4*	*4.1*	*86*
TPH – Motor Oil	mg/L	–	–	–	–	–	–	–	–	–	0.46	0.11	61	–	–	–
Fecal Coliform	CFU/100 ml	–	–	–	–	–	–	–	–	–	1,090	376	50	–	–	–

Bold values in **red** indicate a significant increase; italicized values in *blue* indicate a significant decrease; values in black indicate no significant difference between inlet and the outlet (Wilcoxon Signed Rank test α = 0.05).
Dash indicates no samples in category.
Tacoma Salishan Study data were not paired, so Wilcoxon test was not run on results.
CFU/100 mL = colony forming units per 100 milliliters.
NC = not calculable because more than 50 percent of the data were at or below the reporting limit.
TPH = total petroleum hydrocarbons.

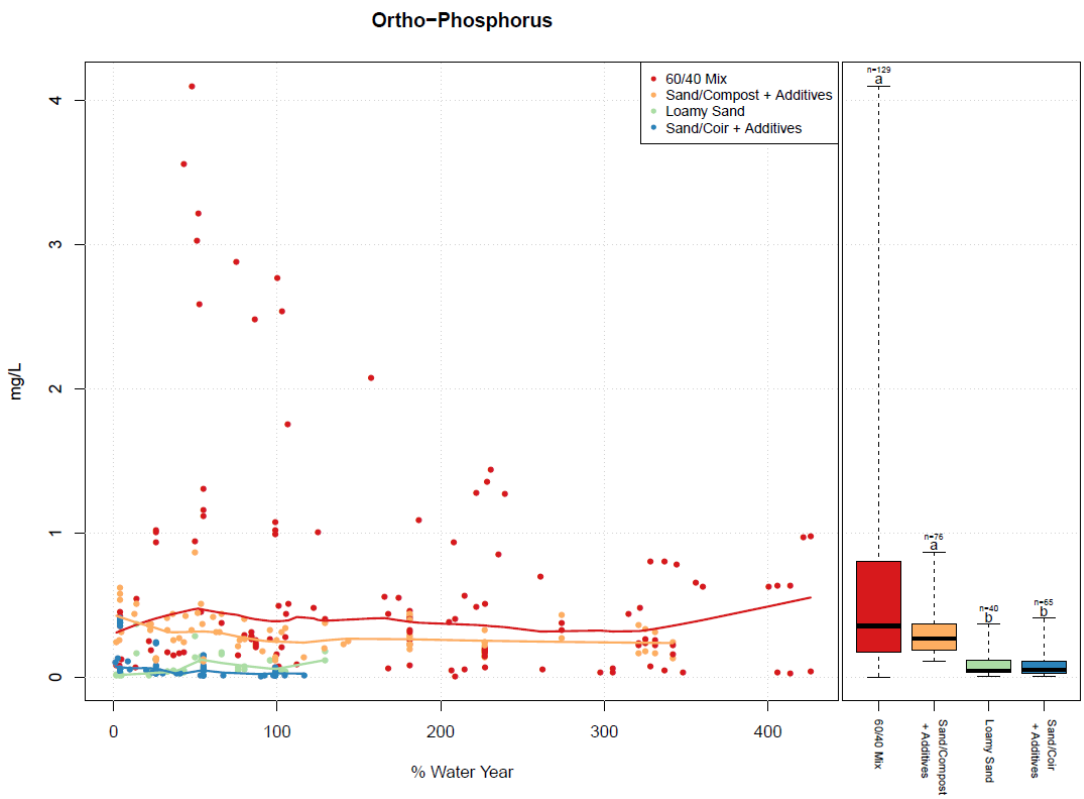

Figure 3. Ortho-Phosphate Effluent Concentration Results for Each BSM Category.

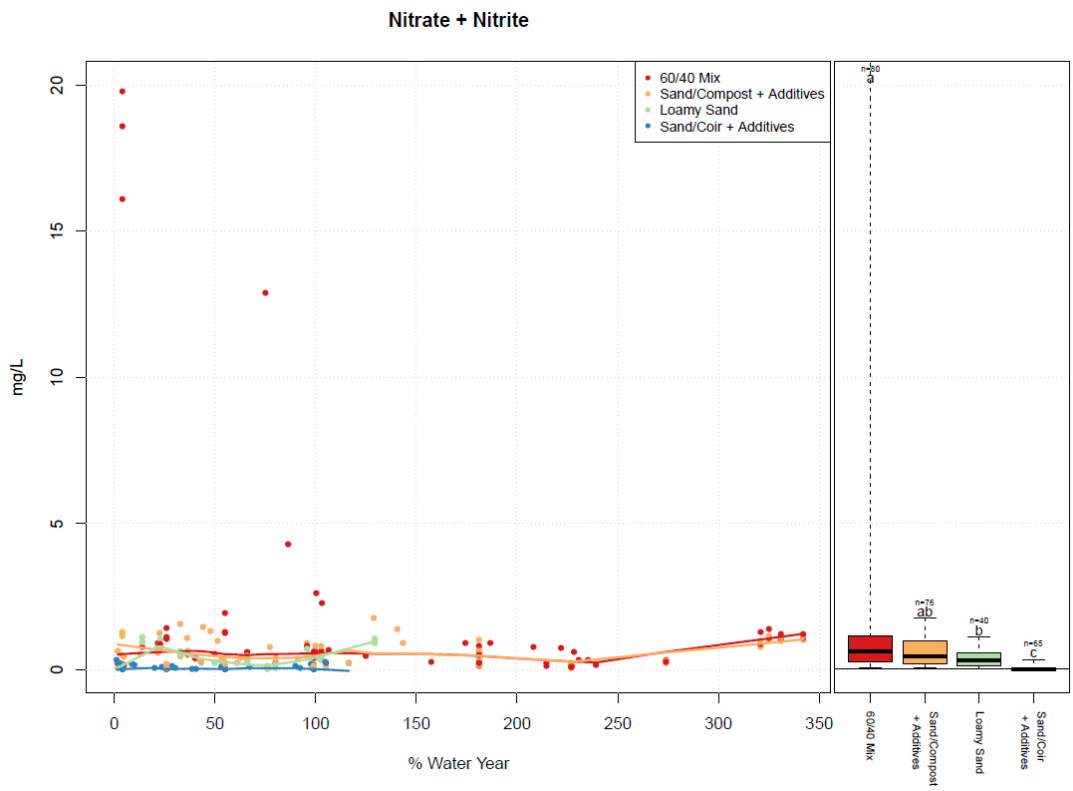

Figure 4. Nitrate + Nitrite Effluent Concentration Results for Each BSM Category.

The exception was the Tacoma Salishan Study, which exhibited export, but effluent concentrations were low compared with the other studies (mean = 0.177 mg/L). This may have been due to the fact that no samples were collected during the first year of the study, so a large portion of the nitrate + nitrite may have flushed out by the time the first sample was collected. Overall, Table 11 indicates that the best performing BSM for nitrate + nitrite removal was the Sand/Coir + Additives.

The 60/40 Mix exported the highest initial concentrations of dissolved copper and then the effluent equilibrated after 2 water years (200%WY) to approximately 5 µg/L. (However, due to considerable variability in the data, the results may not indicate equilibration at all). The Sand/Compost + Additives and Loamy Sands BSMs performed slightly better but were still outperformed by the Sand/Coir + Additives (Figure 5; Table 11). The Sand/Coir + Additives performed significantly better than the other BSM categories, beginning with a low level flush and then equilibrating to an effluent concentration of approximately 1 µg/L (Figure 5). Table 11 indicates the best performing BSM for dissolved copper reduction was the Sand/Coir + Additives, based on effluent concentrations and percent removal. However, it also appears that the Sand/Compost + Additive from the Kitsap Column Study (a mix consisting of 90 percent sand, 10 percent compost, and a polishing layer of sand, activated alumina, and bone char) achieved a high percent removal (48 percent) of dissolved copper.

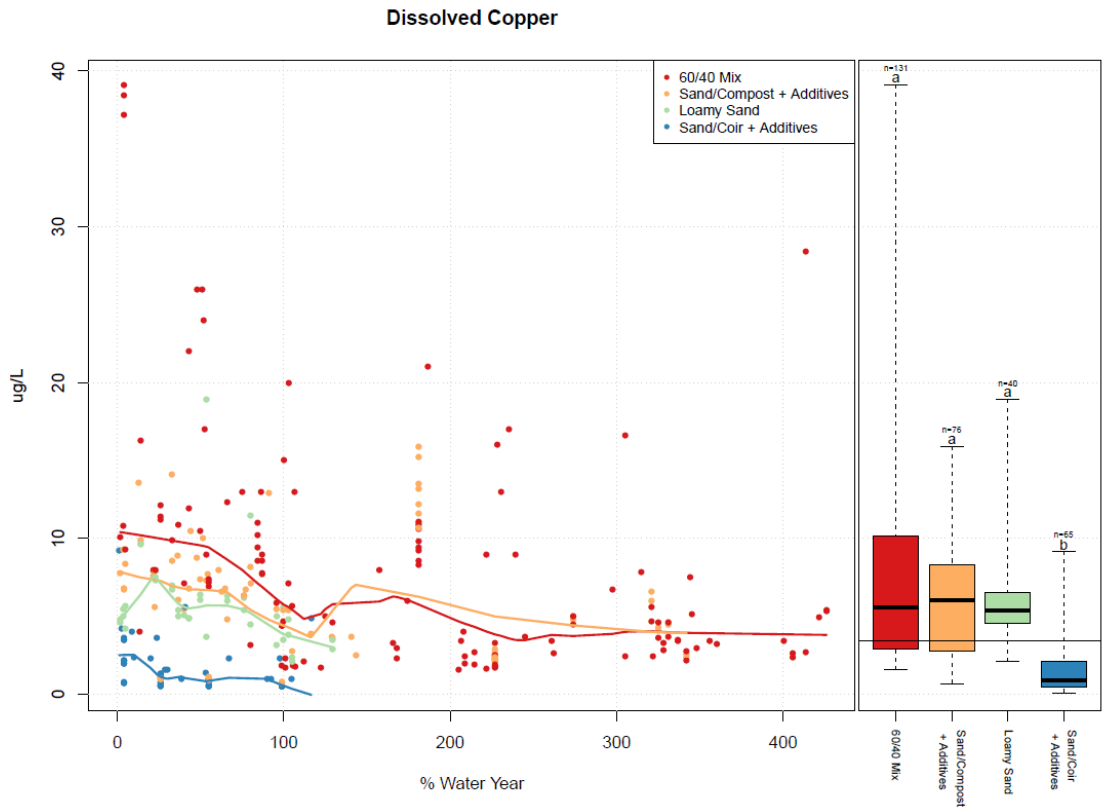

Figure 5. Dissolved Copper Effluent Concentration Results for Each BSM Category.

Each BSM tended to reduce influent concentrations of dissolved zinc (Table 11). In addition, there was a slight flushing pattern observed from the 60/40 Mix, the Sand/Compost + Additives, and the Loamy Sands (Figure 6). No flushing pattern was observed from the Sand/Coir + Additives, and the effluent concentration remained consistently low (~4 µg/L) (Figure 6). The 60/40 Mix showed the greatest variability but also some of the lowest effluent concentrations of all the mixes (Figure 6). In general, minimal amounts of dissolved zinc flushed from the BSMs, and all 19 BSMs did very well at removing dissolved zinc from influent waters.

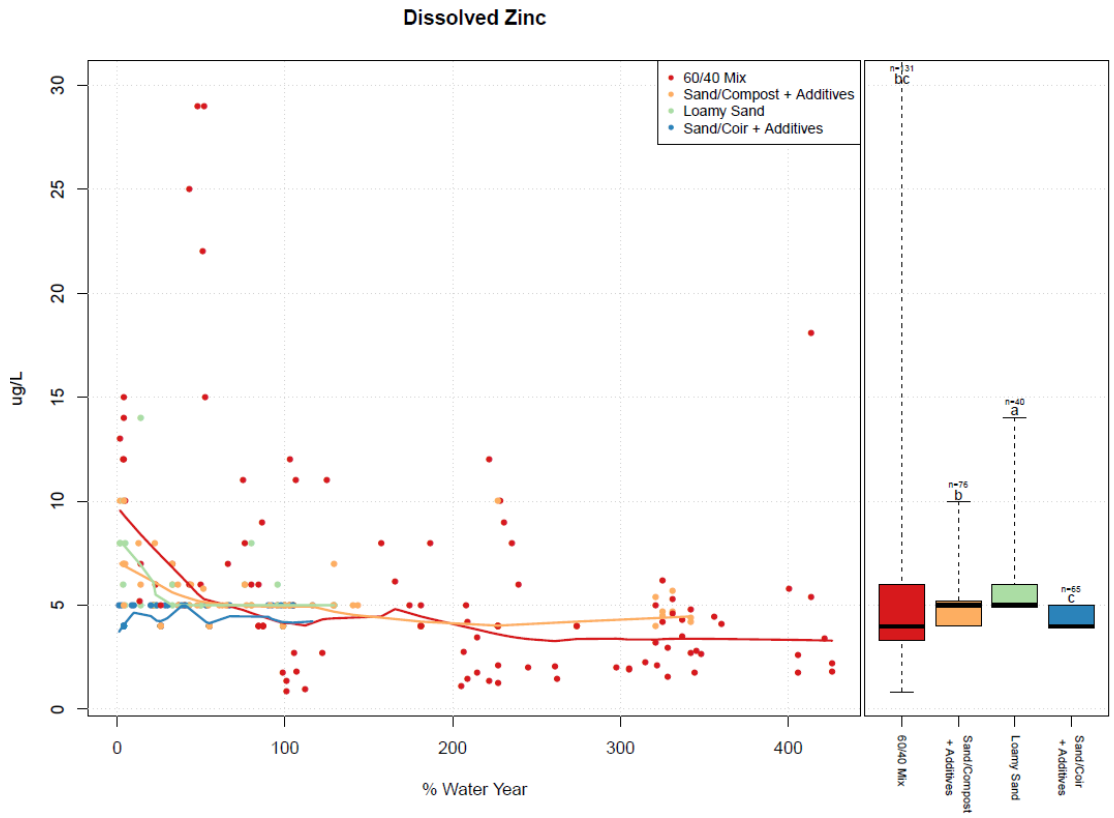

Figure 6. Dissolved Zinc Effluent Concentration Results for Each BSM Category.

A fecal coliform bacteria flush by 100%WY was evident in each BSM category. Figure 7 indicates that the flush from the Sand/Coir + Additives was more rapid, but, because only one study analyzed fecal coliform bacteria for the Sand/Coir + Additives, this analysis cannot determine if that trend is site-specific or more pervasive. Table 11 indicates that the 60/40 Mixes monitored in the WSU Mesocosm Study exhibited the best fecal coliform bacteria reductions and lowest effluent concentrations, while the 60/40 Mix monitored in the Redmond Six Swales Study performed the worst, with a median removal of 0 percent. Fecal coliform bacteria removal across all 19 BSMs was generally good; however, due to the highly variable nature of study results, this synthesis report cannot state with certainty that one BSM category performs better than another.

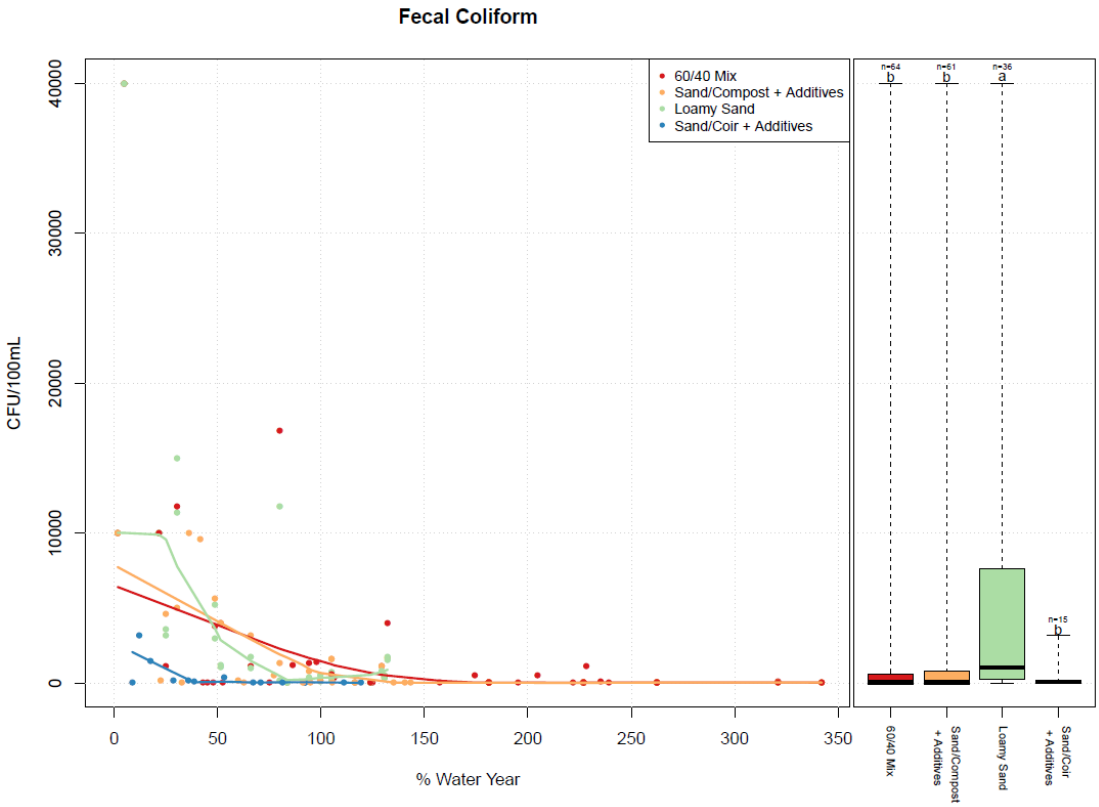

Figure 7. Fecal Coliform Effluent Concentration Results for Each BSM Category.

There was no strong flushing trend for TPH-oil in any of the BSM categories (Figure 8). The Loamy Sands and Sand/Coir + Additives BSMs exhibited the lowest effluent concentrations, but, as mentioned above for fecal coliform, the n-value was low so it is difficult to draw conclusions regarding TPH-oil treatment among the BSM categories. Table 11 shows influent and effluent concentrations and percent removal data for TPH-oil. Figures in the table show that TPH reductions were comparable across the studies. Testing with higher influent concentrations would be useful for determining differences among the BSM categories.

As indicated in the *Infiltration* section (Section 2.6.1), the BSM categories had highly variable saturated hydraulic conductivities. To assess if contact time with the BSM was a driving factor in water quality treatment performance, mean effluent concentrations for TSS, total phosphorus, ortho-phosphate, nitrate + nitrite, dissolved copper, dissolved zinc, TPH–oil, and fecal coliform for each of the 19 BSMs were regressed against infiltration rate and are presented in Figure 9. If reduced contact time with the BSM was a controlling factor in performance, then a positive relationship between effluent concentration and infiltration rate should be apparent. However, Figure 9 indicates that only TSS exhibited a positive significant relationship with infiltration rate, while there was a significant negative relationship for dissolved copper, fecal coliform, and ortho-phosphate. There is no obvious mechanism that would explain why decreased contact time would promote retention of those parameters, so it must be assumed that other mechanisms in the high flow rate BSMs (e.g., Sand/Coir + Additives) such as metals and nutrient sorption are driving this trend. Conversely, a high flow rate media must have greater void space

and, consequently, more numerous flow paths for fine TSS export, which may explain the TSS relationship observed in Figure 9.

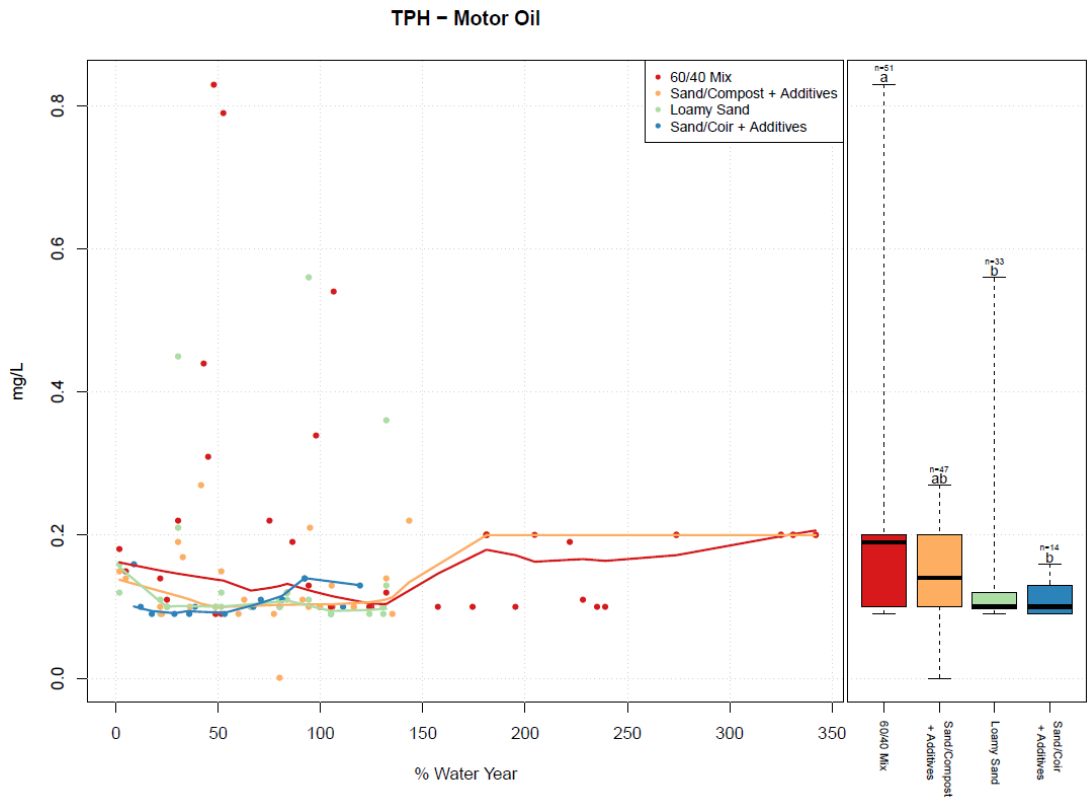

Figure 8. TPH-Oil Effluent Concentration Results for Each BSM Category.

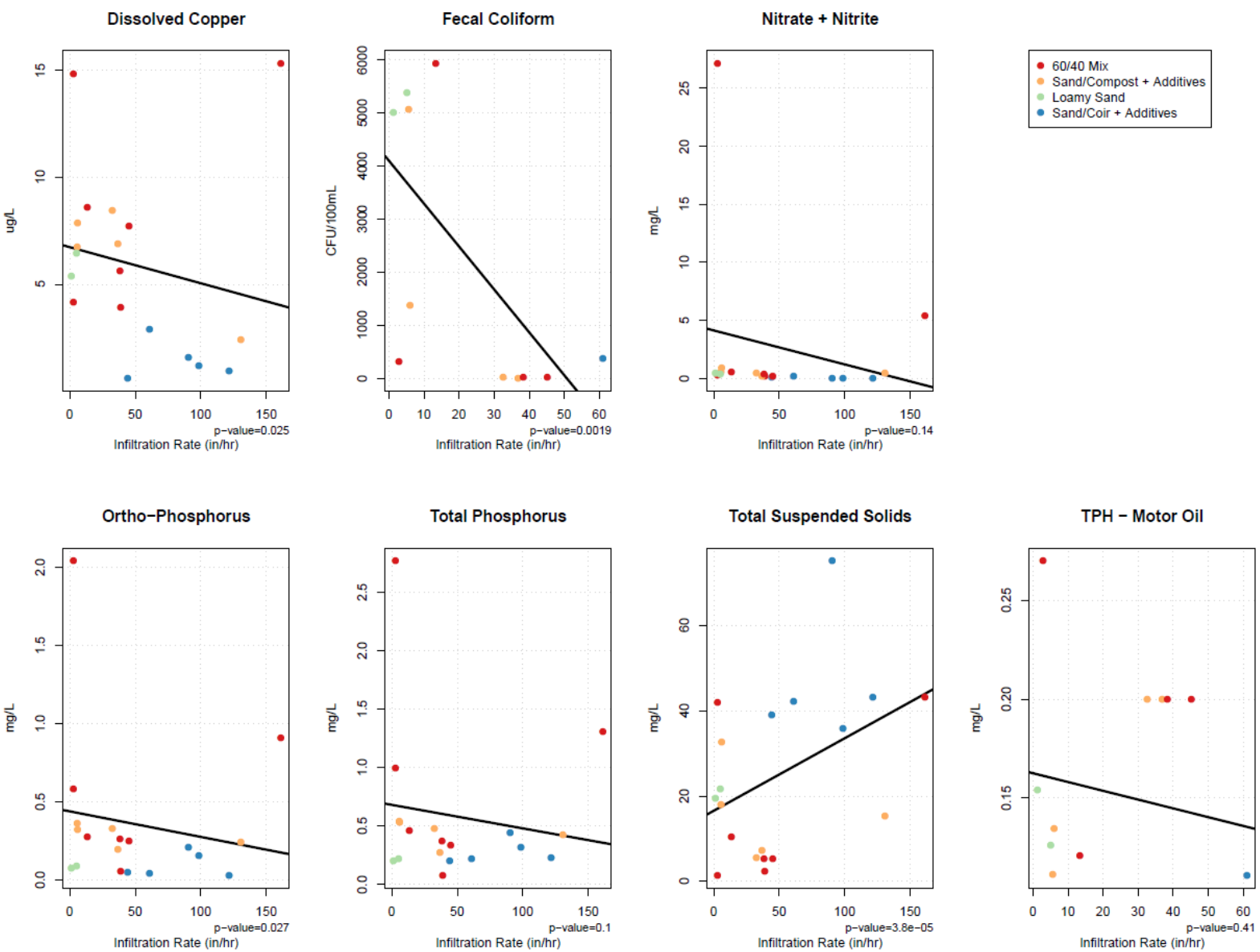

Figure 9. Infiltration Rate Versus Effluent Concentration for the 19 BSMs.

Table 12. Comparison of Ecology Design Criteria for Custom Bioretention Soil Mixes to Media Tested in the Five Studies.

Media Type	Tacoma Salishan			WSU Mesocosm			Redmond 185th			Redmond Six Swales			Kitsap Columns			Average		
	CEC (meq / 10 g)	OM Content (%)	Ksat (in/hr)	CEC (meq / 10 g)	OM Content (%)	Ksat (in/hr)	CEC (meq/ 10 g)	OM Content (%)	Ksat (in/hr)	CEC (meq /10 g)	OM Content (%)	Ksat (in/hr)	CEC (meq/ 10 g)	OM Content (%)	Ksat (in/hr)	CEC (meq/ 10 g)	OM Content (%)	Ksat (in/hr)
Ecology Criteria	≥ 5	5–8	< 12	≥ 5	5–8	< 12	≥ 5	5–8	< 12	≥ 5	5–8	< 12	≥ 5	5–8	< 12	≥ 5	5–8	< 12
60/40 Mix	5.8	**3.3**	**20.9**			**41.7**	10		2.9	7.38	5.1	**13.4**			**161**	7.7	**4.2**	**48**
Sand/Compost + Additives						**34.7**				**4.75**	**4.0**	5.8	**1.4**	**1.7**	**131**	**3.1**	**2.9**	**57**
Loamy Sands										6.16	**3.05**	3.2				6.2	**3.1**	3.2
Sand/Coir + Additives										**1.42**	**1.3**	**61**	**2.4**	**2.7**	**88.7**	**1.9**	**2.0**	**74.9**

Bold values in **red** indicate that the Ecology design criteria are not met.

Criteria also exist for pH and percent fines, but they were not included herein. pH was not measure in any of the studies, and the percent fines criteria is captured in the Ksat results.

Blank cells indicate the parameter was not measured.

CEC = cation exchange capacity

OM = organic matter

Ksat = Saturated Hydraulic Conductivity. Note: Ksat was determined by various methods, depending upon the study (see Table 10 for a more complete presentation).

2.5.3. Physical and Chemical Properties

Of the 19 BSMs evaluated in this synthesis report, only 7 were 60/40 Mixes; the remaining were all custom media mixes (Table 12). Ecology provides specifications for custom BSMs in the SWMMWW to ensure any alternatives to the 60/40 Mix will still meet target infiltration rate and treatment requirements. Among the five studies included in this analysis, numerous custom BSMs (primarily those containing sand and coir) exhibited a high level of treatment. Consequently, determining if those high performing mixes and the default 60/40 Mix meet the Ecology specification for custom BSMs is informative.

Table 12 presents the measured results for OM content, Ksat, and CED—three of the primary Ecology criteria that custom BSMs must meet and that are typically used by local governments in BSM specifications. In the table, values that do not meet those Ecology criteria are highlighted in red. As shown in Table 12, on average, the OM criterion is not met by any of the BSM categories, even the 60/40 Mix, which contains more organic material than any of the other BSM categories. The Ksat criterion is, on average, only met by the Loamy Sands BSM. Finally, the CEC criterion, which is included in specifications to help ensure that custom BSMs can bind cations (specifically metals), is the lowest in the Sand/Coir + Additives mixes, even though those BSMs were far superior at removing metals when compared with the other BSM categories. As shown, the Sand/Coir + Additives mixes were farthest from meeting any of the three criteria in Table 12, yet they were consistently the best performers in terms of water quality treatment (with the exception of TSS).

To determine which media components may be contributing to pollutant flushing from the various mixes, SPLP results from the Redmond 185th Avenue Northeast, Redmond Six Swales, and Kitsap Column studies (the other two studies did not measure SPLP) were averaged by media component type and are presented in Table 13. The colored bars in the table cells represent relative concentrations in comparison to other media components. As is indicated in Table 13, the SPLP n-values are low because few studies conducted SPLP analyses. Further SPLP testing should be conducted on media components to increase the power of this analysis. Regardless, the trends seen in Table 13 are worth noting.

Of the aggregates tested, it is apparent that leachable copper is found in some sands. However, sands with lower copper concentrations can be found, as they were for the Kitsap Column Study ("Alt Sands" in Table 13).

Table 13 indicates there are marked differences between the organic components tested. Compost exhibited the highest SPLP values out of any of the media components. For example, compost had an order of magnitude more nitrogen than coconut coir or shredded bark. In the compost, copper was 5 to 8 times higher and ortho-phosphate was 3 to 13 times higher than in the other organic components used in the BSMs.

The additives tended to leach very little copper and nutrients, with a few exceptions. Biochar leached high nutrient concentrations; activated alumina leached nitrate at 0.44 mg/L; and wood ash leached 0.52 mg/L of ortho-phosphate.

Table 13. Summary of Mean Synthetic Precipitation Leaching Protocol Results.

	Aggregate			Organic			Additive				
Parameter	Alt Sand	C33 Sand	Loamy Sand	Coir	Compost	Shredded Bark	Biochar	AA	DE	GAC	Wood Ash
Dissolved Copper	0.005	0.008	0.007	0.003	0.026	0.005	0.001	0.002	0.001	0.001	0.001
Nitrate+Nitrite	0.02	0.02	0.09	0.07	22.86	0.06	0.97	0.44	0.09	0.02	0.02
Ortho-Phosphate	0.08	0.05	0.15	0.38	6.45	2.05	3.35	0.00	0.03	0.16	0.52
Total Kjeldahl Nitrogen	1.00	1.00	1.00	1.35	47.00	3.20	1.00	1.00	1.00	1.00	1.00

Results are all in milligrams per liter.

Colored bars represent a relative comparison between media components for each water quality parameter

Alt Sand = washed sand and volcanic sand used in the Kitsap Column Study

AA = activated alumina

DE = diatomaceous earth

GAC = granular activated carbon

C-33 Sand and Compost n = 3

Loamy Sands, Coir, and Alt Sand n = 2

Additives and Shredded Bark n = 1

3. DISCUSSION

3.1. BACKGROUND

The impetus for this synthesis of regional research on bioretention performance was research conducted at WSU in 2011 and in Redmond in 2012, which indicated that underdrained bioretention systems were exporting nutrients and copper. Those results were contrary to much of the most-widely cited literature (Ahiablame et al. 2012; Davis et al. 2009; Davis et al. 2003; Dietz 2007; Geosyntec 2013; Hunt et al. 2006; Seelsaen et al. 2006). This report concludes that the results from the WSU Mesocosm Study and Redmond 185th Avenue Northeast Study have been corroborated by other studies. The 60/40 Mix consistently exports nitrogen and copper during a flushing phase that lasts for about one to two water years, while elevated levels of phosphorus may continue for at least 3 water years. Details of these findings are presented in the following subsections. Conclusions and recommendations for improving the current Ecology BSM specification are presented section 4. For context, the following paragraphs explain how the discrepancy between the published literature and results from regional studies came about.

One of the earliest and most cited studies on bioretention metals removal performance was conducted by Davis et al. (2003). The authors of that study used a combination of mesocosms and field studies to examine the performance of a loamy sand media and began testing after vegetation establishment. Influent copper concentrations for that study ranged from 66 to 140 µg/L. The authors found dissolved copper removals ranging from 82 to 93 percent. The study was subsequently cited in numerous influential literature reviews (Ahiablame et al. 2012; Davis et al. 2009; Dietz 2007) and has been used locally to highlight expected metals removal performance of bioretention systems in western Washington (Geosyntec 2013; Taylor Aquatic Science and Policy and Cardno TEC 2013). However, the loamy sand media evaluated was not representative of the 60/40 Mix used in the Puget Sound region because it does not contain compost. Influent dissolved copper concentrations used in the Davis et al. (2003) study were also substantially higher than those typically observed in the Puget Sound region, which generally range from 2.3 to 11 µg/L (Ecology 2011a). Furthermore, monitoring was delayed to allow vegetation establishment; therefore, an initial flushing of metals from newly installed systems may have been missed. Consequently, extrapolation of the Davis (2003) results to predict the performance of systems in western Washington may lead to spurious conclusions.

Another early full-scale bioretention field study was conducted by Hunt et al. (2006). The study authors found total phosphorus and nitrate export on a concentration basis, but, because the system was unlined and infiltrated between 46 to 93 percent of influent volume, mass removal values of total phosphorus and nitrate were high and no export (on a mass basis) was evident. Those findings, along with mass removals of copper, were reported in the abstract. The mass removal values from the Hunt et al. study were subsequently reported in Dietz (2007), Taylor

Aquatic Science and Policy and Cardno TEC (2013), and Ahiablame et al. (2012) with other studies reporting concentration percent removals, thus skewing the overall results in favor of removal.

In another example of how the literature is either misreported or not comparable to the studies summarized in this synthesis report, Seelsaen et al. (2006) found that compost was most effective at removing copper (90 to 93 percent removal) out of eight BSMs tested in a laboratory sorption study. However, initial solution concentrations of copper in the synthetic stormwater were 5 mg/L, or 500 times that of typical stormwater in western Washington. It is unclear if lower initial concentrations would have revealed a release of copper from the compost media.

What is evident from this brief survey of the literature is that studies from other locations, using different BSMs, different influent concentrations, and different methods, provide little useful information for predicting how bioretention systems will perform in western Washington. Therefore, the results from this report should be used as a reference for expected treatment performance of bioretention in western Washington.

3.2. Discussion by Media Component

The following sections discuss the results from the five studies analyzed in this synthesis report (Table 1) by media component: aggregate fraction, organic fraction, and additives. Table 14 provides a rating system (see Appendix B for scale explanation) to assess the cost and environmental impact of the various media components discussed in this report.

3.2.1. Aggregate

Because aggregate comprises the majority of a BSM, it plays a key role in determining infiltration rates. Both the default BSM specification and the custom BSM specification in Ecology's SWMMWW require 2 to 5 percent fines (defined as the mass percentage of material caught on the 200 sieve) for the aggregates used in a BSM. The purpose of this requirement is to meet the target initial infiltration rate of 2 to 12 in/hr, thus promoting water holding capacity, flow attenuation, and, assumedly, pollutant retention. As noted above (Figure 9) there is no strong relationship between pollutant retention and infiltration rate, so water holding capacity (to promote plant health), nutrient exchange (for plant growth), and flow attenuation (to reduce peaks flows in downstream receiving waters) remain as the sole justifications for the percent fines criterion.

The current infiltration rate criteria in the specifications for bioretention systems result in systems that are conservatively sized (roughly 15:1 drainage basin to bioretention cell surface area ratio). This sizing has many advantages, not the least of which is that it will take many years for the BSM to clog under normal loading conditions. To now recommend that the initial infiltration rate be increased to 50 in/hr or greater based on the findings from this synthesis report may result in unintended operation and maintenance ramifications. Consequently,

Table 14. Component Cost and Sustainability Scoring Table.							
Media Component	**Cost (per cubic yard delivered to Seattle)/ Score (1-4)**		**Origin/Score (1-5)**		**Manufacturing Process/Score (1-5)**		**Final Score**
Aggregates							
Volcanic sand	$40.50 (> 300 CY)	3	Western WA (Mt. Saint Helens)	4	Byproduct with low energy input[a]	4	**11**
Washed sand[b]	$44.25 (100 CY)	3	Puget Sound (Black Diamond)	5	Single-use product with high input	3	**11**
C-33 sand	$18.60 (CY)	4	Puget Sound	5	Single-use product with high input	4	**13**
Loamy sand	$29.00 (CY)	3	Puget Sound	5	Byproduct with high energy input	3	**11**
Organics							
Compost	$24.00 (> 300 CY)	4	Puget Sound	5	Biological from renewable feedstock	5	**14**
Coconut coir pith	176.7 (CY)	1	Overseas (India, southeast Asia, South Pacific)	1	Byproduct with low energy input	4	**6**
Shredded Bark	$19.90	4	Puget Sound	5	Byproduct with high energy input	3	**12**
Additives							
AA	$1,750.00 (< 100 CY)	1	North America (eastern US and Canada)	2	Single-use product with high input	1	**4**
DE	$300.00 (> 300 CY)	1	North America (western US)	2	Byproduct with high energy input	3	**6**
WTR	NA	2	Puget Sound	5	Byproduct with low energy input	4	**11**
GAC (coconut-based)	$718.20 (< 100 CY)	1	North America (Nebraska)	2	Byproduct with high energy input	3	**6**
High carbon wood ash PD 100+ mesh	$400.00 (CY)	1	PNW (Oregon)	3	Byproduct with high energy input	3	**7**
GAC (bone char)	$718.20 (< 100 CY)	1	North America (Nebraska)	2	Byproduct with high energy input	3	**6**

[a] Excavated from Mt. Saint Helens deposits to prevent flooding in Chehalis River.

[b] Since the Kitsap Column Study ended, this source of sand has become unavailable.

AA = activated alumina

DE = diatomaceous earth

GAC = granular activated carbon

WTR = water treatment residuals

Herrera recommends that Ecology keep the 2 to 12 in/hr initial infiltration rate criteria for sizing purposes but consider accepting custom media mixes that infiltrate at a rate higher than 12 in/hr if they demonstrate good water quality treatment and plant growth performance, and are sized at 2 to 12 in/hr.

The SPLP results (Table 13) indicate that C-33 sands (builder's sands; the sands currently in the SWMMWW for bioretention) tend to have a higher copper content than other sands. The washed sand and the volcanic sand (Alt Sand) used in the Kitsap Column Study both exhibited lower leachable copper levels than C-33 sands. To prevent the use of sand with potentially high leachable copper content (the Kitsap Column Study found sands with copper SPLPs as high as 14 µg/L), Herrera recommends that a SPLP criterion be incorporated into the specifications for the aggregate fraction in both the default BSM and custom BSMs.

An aggregate's physical and chemical properties are primary factors in selecting the best media for bioretention. However, the costs and environmental impact (from manufacturing and transportation) of the media must also be considered. Of the four aggregates tested among the five studies, the C-33 sands received the highest score, primarily because they are locally sourced and inexpensive. This factor must be weighed against the fact that, on average, C-33 sands exported more copper than other aggregates. Herrera recommends that designers perform SPLP analyses on C-33 aggregates to try and locate a source with lower copper concentrations.

3.2.2. Organic

There were only three primary organic components to the 19 BSMs in this study: compost, coconut coir, and the loam fraction of the loamy sand. Table 9 illustrates that 12 of the BSMs contained compost, 5 contained coconut coir, and 2 contained loamy sand. In addition, shredded bark was used in small quantities (10 percent) in three of the BSMs (Table 9).

The organic fraction of the BSM is the most vital for plant establishment and health. It not only provides soil structure and water holding capacity, it is also the primary source of nutrients within the BSM. However, the SPLP analyses (Table 13) indicate that the compost leached between 4 and 380 times the amount of nutrients or copper when compared with the other organic components. As indicated in the *Results Summary* section, the BSMs containing the 60/40 Mix also leached the most nutrients and copper in column and full-scale tests. Given these considerations, Herrera recommends that an SPLP criterion for copper be incorporated into the specifications for the organic fraction in both the default BSM and custom BSMs. Similar to the criterion proposed above for the aggregate fraction, this would serve to screen out organic components that may contribute to copper export.

It is further recommended that SPLP criteria for nutrients also be considered for specifications related to the organic fraction in both the default BSM and custom BSMs. In recommending

nutrient SPLP criteria for the organic fraction, the threshold selected should not be so low that it would contribute to plant mortality.

The Redmond Six Swales Study provides useful information regarding plant health and BSM nutrient leaching. The two Loamy Sand cells tested as part of that study exhibited mean nitrate + nitrite and ortho-phosphate SPLP concentrations of 0.09 and 0.15 mg/L, respectively. These concentrations are 254 and 43 times less than the mean SPLP concentrations for the same constituents in the tested composts. Yet both of the Loamy Sand cells supported healthy plant communities through the duration of the study. Figure 10 shows four bioretention cells from the Redmond Six Swales Study: one with the 60/40 Mix, one with Sand/Compost + Additives, and two with Loamy Sands. As indicated, the cells with Loamy Sands have robust plant communities that are difficult to differentiate from those in the cells with compost.

Figure 10. Photograph Depicting Differences in Vegetative Cover in Four Bioretention Cells Monitored as Part of the Redmond Six Swales Study.

Based on these observations, Herrera recommends Ecology use this information and additional nutrient data to develop SPLP criteria for nitrogen + nitrogen and the same for total phosphorus and to incorporate the criteria into the specifications for the organic fraction in both the default BSM and custom BSMs.

Research by Linbo et al. (2009) has indicated the copper acute water quality criterion may not be an accurate assessment of potential toxicity for fish because numerous other constituents bind

with copper and inhibit uptake by organisms. However, as indicated in this synthesis report, the current 60/40 Mix specification may result in a net export of copper, and the same systems also export large quantities of dissolved organic carbon, which binds with copper and reduces its toxic effects on fish and invertebrates (McIntyre et al. 2015). Nevertheless, the Six Swales Study, which used the biotic ligand model that accounts for copper interactions with dissolved organic carbon and other solutes, found that the effluent from a bioretention cell with the 60/40 Mix was more toxic than effluent from cells containing sand and coir; loamy sands; and sand, compost, and additives (Herrera 2015b). Based on these findings, Herrera recommends further toxicological studies on the 60/40 Mix and alternate BSMs currently being tested. Also, additional testing should be done to determine how well copper remains bound to dissolved organic carbon after the underdrain effluent water mixes with receiving waters.

Table 14 indicates that, of the three organic components tested in the five studies, compost is the most sustainable and cost-effective. However, compost is not an acceptable water quality treatment material for BSM applications where underdrains discharge to phosphorus-sensitive waters. Coconut coir is shipped from overseas and costs seven times more than compost; consequently, it has a much lower score than compost. However, coconut coir provides exceptional qualities and is the only material found to date that sorbs nitrate + nitrite and provides very high water holding capacity. Shredded bark scored below compost but above coconut coir and may be an alternative to compost and coir in bioretention, but no one has yet studied a media with shredded bark as the only organic source, it instead was used as an amendment. Herrera recommends further research on the use of shredded bark or other yet-to-be-tested organic materials as the sole organic fraction in bioretention.

3.2.3. Additives

The primary components of a BSM are a bulk aggregate, an organic fraction, and an optional additive for targeting specific pollutants. During the dosing phase of the Kitsap Column Study, three sand and coir BSMs, each containing a separate additive (wood ash [ash], diatomaceous earth [de], and granular activated carbon [gac]), were compared. Also, the Redmond Six Swales Study conducted field testing of a similar mix (sand and coir) with no additives (185-Coir).

The resultant effluent concentration from the three BSMs in the Kitsap Column Study (70vs/20cp/10ash, 70vs/20cp/10de, and 70/vs/20cp/10gac) and one BSM in the Redmond Six Swales Study (185-Coir) are compared in Figure 11. Due to variable influent concentrations and study scales, the comparison among the four BSMs is not ideal. However, useful information can still be derived from the comparison. Figure 11 indicates that granular activated carbon results in significantly better nitrate + nitrite and dissolved copper retention than the other media with additives. The 185-Coir BSM exhibited low effluent concentrations for each parameter in Figure 11, but, again, the influent concentrations were many times lower than for the other three BSMs with additives. Further research is required to quantify the benefits of additives for pollutant retention, but, based on the data presented herein, it appears that the addition of

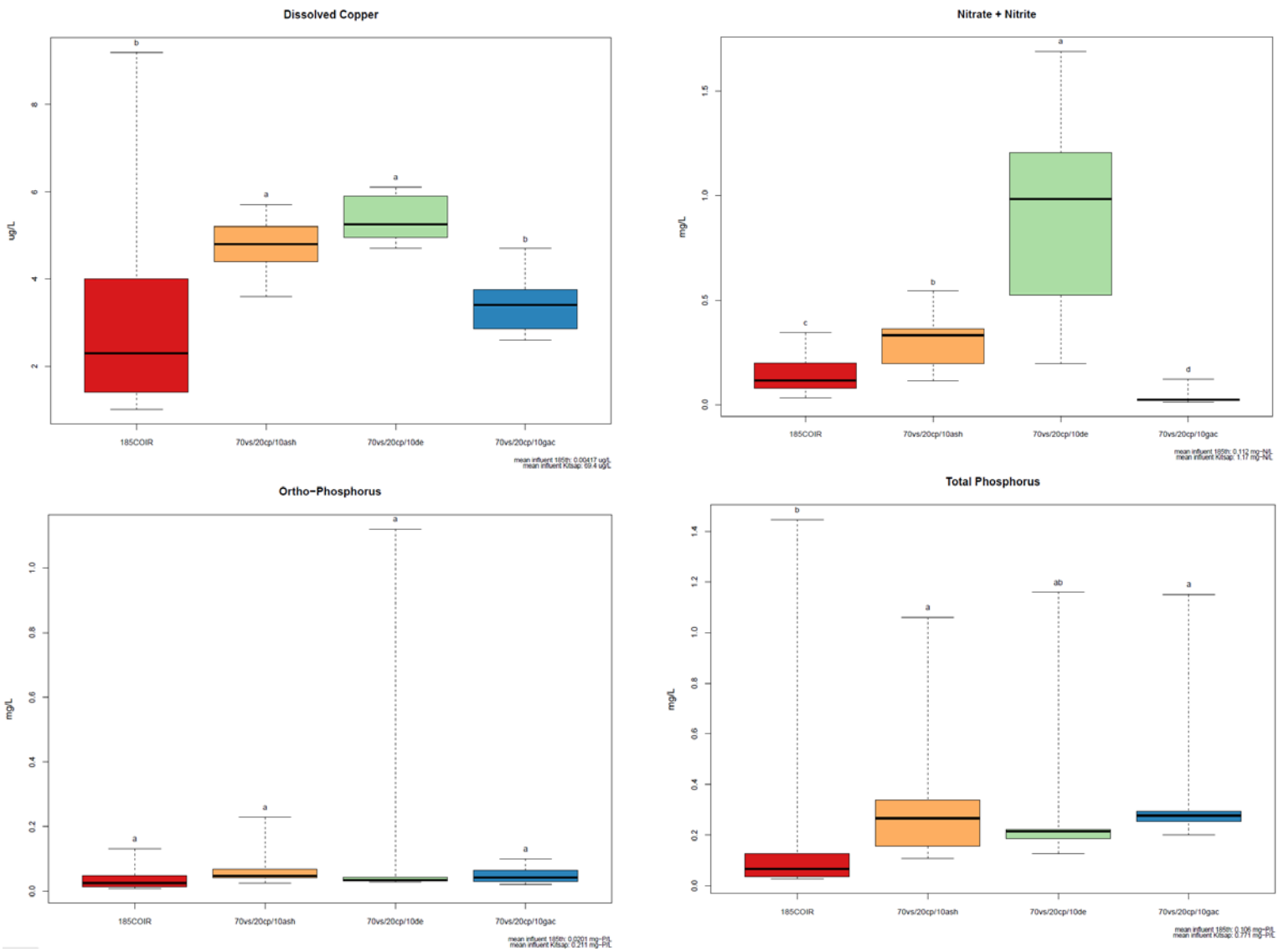

Figure 11. Boxplots Comparing Effluent Concentrations among Sand and Coir BSMs with Different Additives.

granular activated carbon promotes nitrate + nitrite and copper retention. Granular activated carbon is an expensive additive, so its cost must be weighed against its pollutant reduction benefit. Further research of BSM mixes without additives is warranted to ensure additives and their expense are justified to achieve pollutant removal targets.

Figures 1 through 8 present a temporal analysis of effluent concentrations from the BSM categories. It is apparent from these figures that including additives in the 60/40 Mix reduces flushing and improves performance but not by a statistically significant amount. Consequently, one can conclude that altering the 60/40 Mix with additives will not be a viable solution to the nutrient and copper export issues.

Table 14 indicates that one of the most cost-effective and sustainable additives is WTR, which is locally sourced and is the only additive tested that is a low-energy byproduct of another industrial process. However, based on the results from the WSU Mesocosm Study, this additive actually decreased system performance (Table 3). This result was inconsistent with at least one other study that indicate WTR can improve total phosphorus removal (Lucas and Greenway 2011). This inconsistency indicates further research on WTR is warranted.

Although limited to only 1 of the 19 BSMs assessed herein, the inclusion of a polishing layer that contains additives appeared to greatly improve performance of the sand and compost BSM. Future research on polishing layers may indicate a solution wherein the current 60/40 Mix specification could remain unchanged as long as it is underlain by a high performance polishing layer.

3.3. Plant Growth

Soil samples for all treatments except the 60/40 Mix were sent from the Kitsap Column Study to Soil Control Laboratory in California to assess the physical, chemical, and plant germination and growth characteristics of the media. The plant germination and growth tests used three types of plants (cucumber, barley and clover) in small pots and controlled indoor growing conditions. Table 15 shows the average percent germination and height for all three plant types (Herrera 2015a), arranged by germination, then height, from highest to lowest value.

Plants germinated in all of the BSMs sent to the laboratory. While no clear pattern emerged for specific treatments, the BSM containing compost performed best. The plant germination tests provide a first look at the media to confirm that there are no toxins inhibiting germination and that plants will grow during the 2-week test. However, more detailed studies on plant establishment and health with plants used in bioretention systems are recommended to confirm the capability of the tested BSMs to support healthy plants. Herrera also recommends evaluating plant species for inclusion in the bioretention plant palette that are aesthetically pleasing and can thrive in media that meet the recommended SPLP criteria for organic BSM components.

Table 15. Plant Germination and Height Results for Kitsap Column Study BSMs.		
Treatment	**Germination (%)**	**Height (inches)**
90vs/10comp/p-layer	94.4	3.2
70vs/20cp/10gac	91.1	2.6
70vs/20fe/10de	88.9	2.2
70ws/20cp/10ash	87.8	2.9
70vs/20fe/10ash	86.7	3.2
70vs/20cp/10de	85.5	3.3

Source: (Herrera 2015a)

Figure 10 provides full-scale field evidence indicating that plant growth in loamy sands is equivalent to growth in mixes that contain more nutrient-rich compost. This indicates that the high nutrient levels in mixes with compost are not required for a healthy plant community and that mixes with less nutrients may still provide vibrant and healthy bioretention systems. Again, further controlled plant growth studies are recommended to identify the media formulations that can support the desired bioretention plant palettes in western Washington.

3.4. Other Bioretention Soil Mix Criteria

Table 16 summarizes Ecology's current custom BSM criteria and notes where the BSMs discussed this synthesis report deviated from the criteria. Table 12 indicates that, on average, none of the BSM categories, including the default 60/40 Mix, met the OM content criterion of 5 to 8 percent. The data also indicate that OM content does not appear directly related to water quality treatment. The Redmond Six Swales Study results show that the Loamy Sands BSM had an OM of only 3.1 percent (Table 12), yet performed better than the 60/40 Mixes and was able to support plants (Figure 10). Based on that study, Herrera recommends that Ecology consider lowering the 5 to 8 percent OM criterion for custom BSMs. Herrera also recommends evaluating plant species to use in a "low OM content media" and potentially including a specific plant palette for low OM content media.

The BSMs with the highest performance in removing metals in the Redmond Six Swales study had the lowest CEC values. Consequently, it is apparent that the CEC criterion of ≥ 5 meq/10 g may be too high. Herrera recommends that this value be lowered to allow for the use of sand and coir mixes in Washington. Herrera also recommends conducting long-term performance and testing of CEC to determine the long-term implications of lowering the initial CEC criterion.

Finally, the custom BSM criteria for percent fines and Ksat both appear to be too restrictive. The studies in this synthesis have shown that BSM with fines less than 2 percent and Ksat above 12 in/hr can be effective filters for dissolved pollutants. Herrera recommends revisiting and amending both criteria.

Table 16. Custom Bioretention Soil Mix Criteria Comparison.					
Custom Mix Criteria	**Media Component Tested**	**Unit**	**Method**	**Current Criteria**	**Noted Variance**
Organic Matter	BSM	%	D2974	5–8	Healthy plant communities and good pollutant removal seen at OM % as low at 3 %
Cation Exchange Capacity	BSM	meq/100 g	EPA 9081	≥ 5	Good metals removal performance observed with CECs as low as 1 meq/100 g
pH	BSM	std. unit		5.5–7.0	Parameter not measured in studies from synthesis.
Percent Fines Passing 200 Sieve	Aggregate	%	TMECC 04.11-A	2–5	High flow rate media with less than 2% fines were shown to be effective at dissolved pollutant capture.
Initial Ksat	BSM	in/hr	D2434	< 12	Media with Ksats in excess of 12 in/hr have shown good treatment performance

OM = organic matter
CEC = cation exchange capacity
Ksat = saturated hydraulic conductivity
SPLP = synthetic precipitation leaching procedure

3.5. Other Findings

With the increased use of bioretention in urban settings with limited right-of-way space, the use of double-walled bioretention cells is becoming more common. Instead of having a trapezoidal cross-section with sloping walls consisting of BSM, the double-walled cells tend to have vertical concrete walls and a flat bottom to contain the BSM. Infiltration testing conducted as part of the Redmond Six Swales Study found that, when BSMs exhibit low infiltration rates (less than approximately 3 in/hr), water may find flow paths down the wall of the cell and bypass the BSM into the underdrain (Herrera 2014b). Care should be taken to use a high flow rate BSM in double-walled bioretention cells to prevent such short circuiting. Alternatively, a trapezoidal BSM profile could be designed within the confines of the concrete vertical walls to promote water flow paths through, and not around, the BSM.

4. CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the results of the study and the recommendations made in the discussion section. Because of the numerous conclusions and recommendations, this section is delineated by bullet points.

4.1. CONCLUSIONS

- The most commonly exported pollutants from BSMs were copper, nitrogen, and phosphorus.
- All BSMs performed well for TPH-oil, fecal coliform, and zinc removal.
- Of the 19 BSMs evaluated in this report, the 60/40 Mix was, on average, the worst performing in terms of target pollutant flushing and target pollutant reduction, and the compost fraction appeared to be the source of the poor performance.
- Conversely, on average, the best performing BSMs were those that contained Sand/Coir + Additives.
- The volcanic sand and washed sand ("Alt" sands) leached less copper than C-33 sand.
- Flushing results indicate that, by one water year, the majority of BSMs have completed their equilibration/flushing period. However, the BSMs with compost tend to export relatively high levels of total phosphorus and ortho-phosphorus for at least 3 water years and nitrate + nitrite and dissolved copper for at least 2 water years.
- A high degree of dissolved pollutant removal is achievable at infiltration rates that exceed the current 2-12 in/hr requirement. However, suspended sediment removal to meet basic treatment criteria suffers at high flow rates.
- The Sand/Compost + Additives BSM performed marginally better than the 60/40 Mix but with no statistical significance. This indicates that efforts to alter the 60/40 Mix by reducing the percentage of compost and/or adding other components does not significantly improve the performance of BSMs that include compost.
- SPLP analyses were useful in determining the source of leachable target pollutants in the tested BSMs, with high SPLP leachate concentrations of target pollutants associated with high levels of pollutant leaching from the BSMs.

- The site suitability criteria to use native soil for basic treatment in Chapter 3 of Volume III of the 2014 SWMMWW (Ecology 2014) are identical to the custom BSM criteria in Chapter 5 of Volume V of the 2014 SWMMWW (Ecology 2014). The default 60/40 Mix and the alternative BSMs evaluated in this study, especially the best performers, exceed the maximum infiltration rate (Ksat) criterion and do not meet the criteria for minimum cation exchange capacity (CEC) and organic matter (OM) content.

4.2. RECOMMENDATIONS

- Loamy Sands performed better than the 60/40 Mix. However, the hydraulic performance of Loamy Sands is unpredictable, so their use is not recommended.

- Adding a polishing layer and reducing the compost content by a factor of 4 helped reduce pollutant export when compared with the 60/40 Mix. Therefore, this approach may be appropriate if alternate BSMs are not available or desirable. However, additional studies on long-term performance and constructability would be required to develop a specification for a polishing layer.

- Care should be taken to avoid water short-circuiting when bioretention systems are built with vertical walls—specifically, when using low infiltration rate BSMs.

- The current maximum allowable initial infiltration rate of ≤ 12 in/hr is appropriate for sizing, but custom mixes that have a Ksat as high as 100 in/hr should be included in further studies if it can be shown that the mix will meet basic and enhanced treatment goals, and will grow plants.

- More detailed plant growth studies should be conducted on the most promising BSMs tested thus far in the region.

- Evaluate plants to use in a "low OM content media" and develop a specific plant palette for low OM content media.

- Additional testing is required to determine how well copper remains bound to dissolved organic carbon after BSM effluent discharged from underdrains mixes with receiving waters.

- Research on alternate sources for the organic component of the BSM (such as shredded bark) should be conducted to find a potential substitute for compost (pollutant export issues) and coconut coir (a renewable resource but shipped from overseas and relatively expensive).

- SPLP testing on a large number of aggregates, organics, and additives from various sources should be conducted to more accurately determine the range of leachable pollutants associated with these BSM components.

- There is limited data on the effectiveness of BSM at removing organic pollutants from stormwater. Future studies should include the analysis of phthalates, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and other organic pollutants.
- Further toxicological studies should be performed on the current BSM specification and on alternate BSMs.
- Evaluate and develop custom BSM mix criteria that allow for specification of high performing BSM custom mixes.
- Develop recommendations for the continued use of the default 60/40 Mix with an underdrain based on receiving water sensitivity.
- Evaluate the in-stream impact of using the default 60/40 Mix with an underdrain throughout urbanized, wadable, stream watersheds based on Minimum Requirement 5 in the 2014 SWMMWW.

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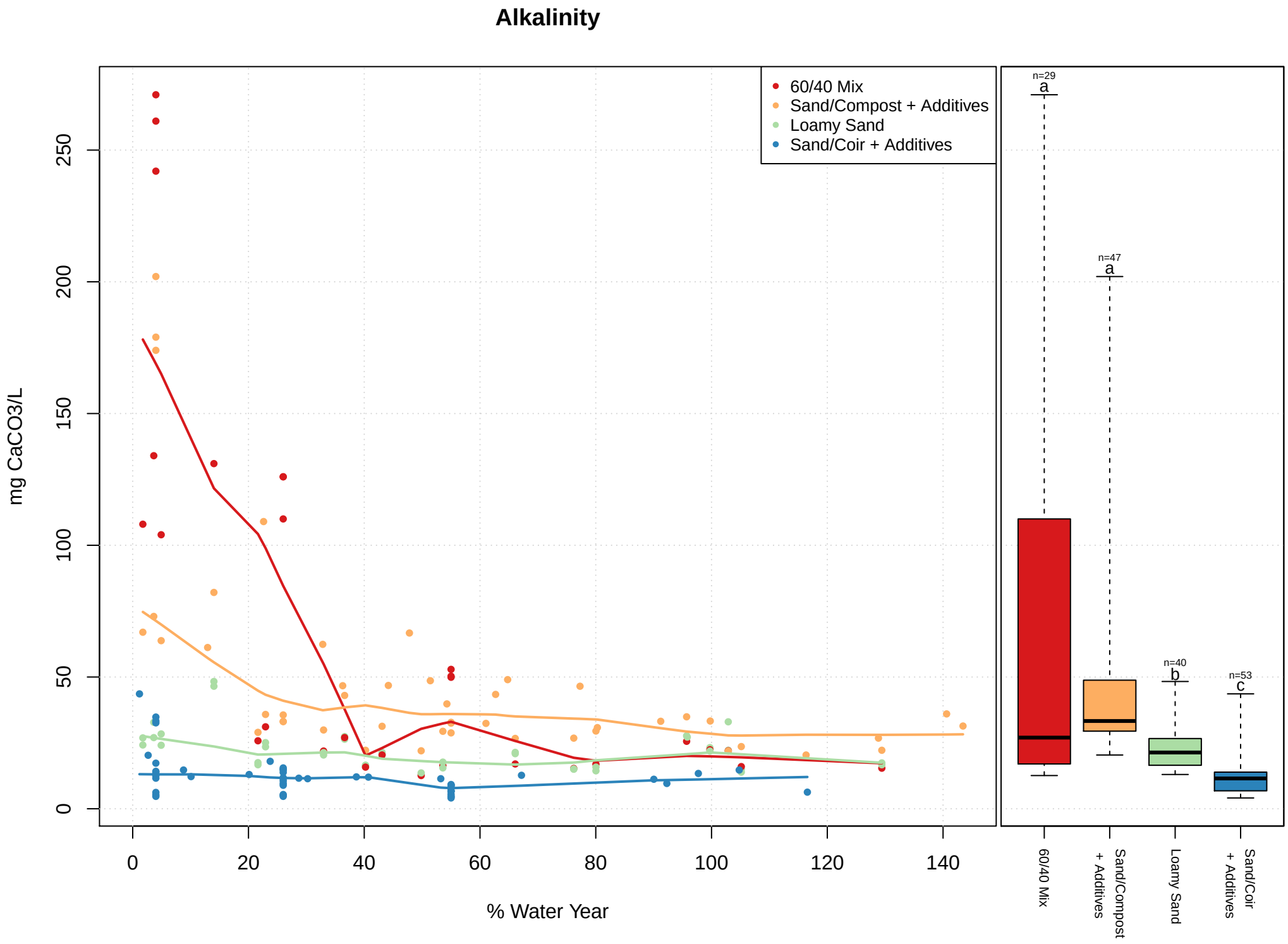
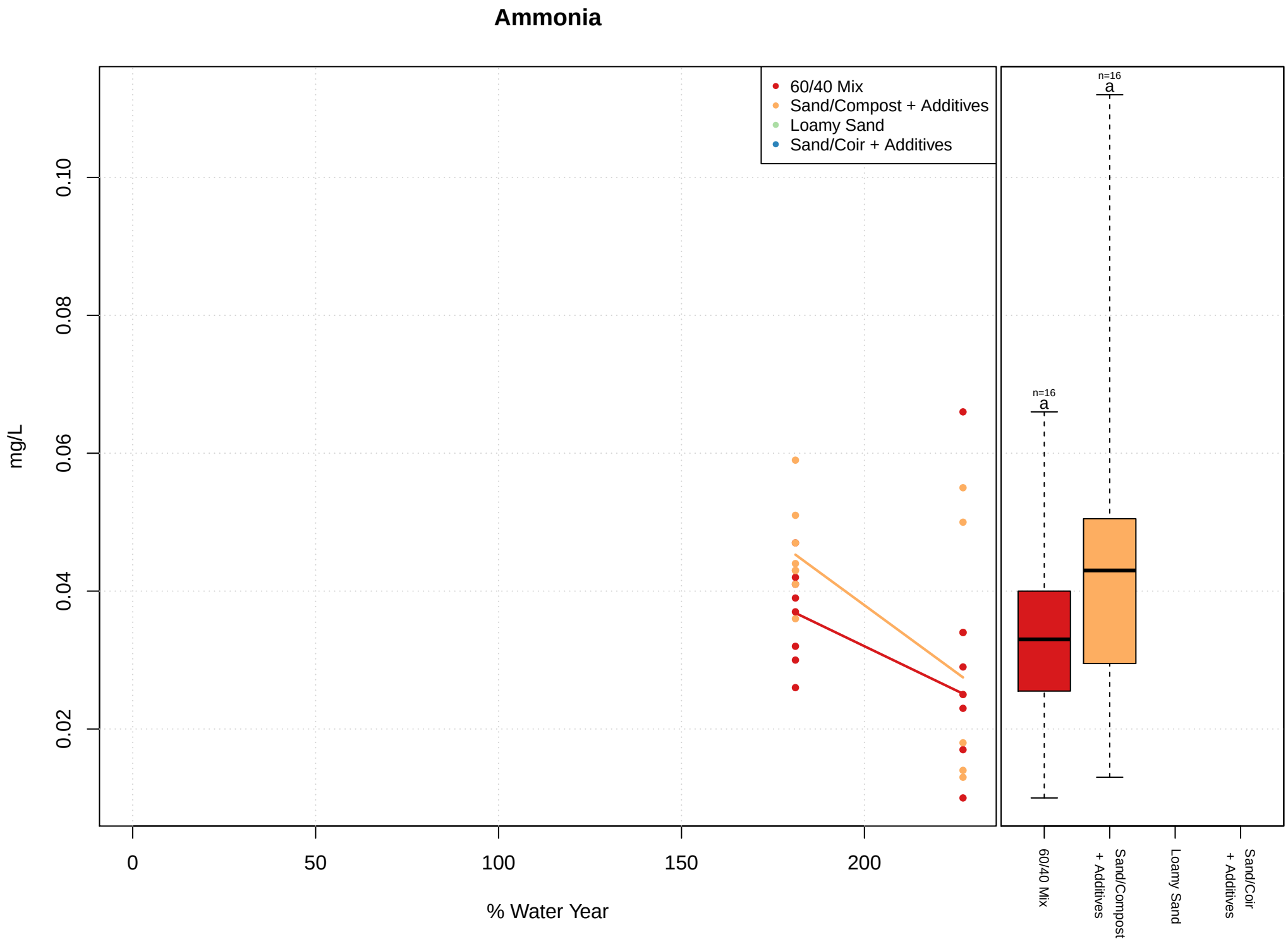
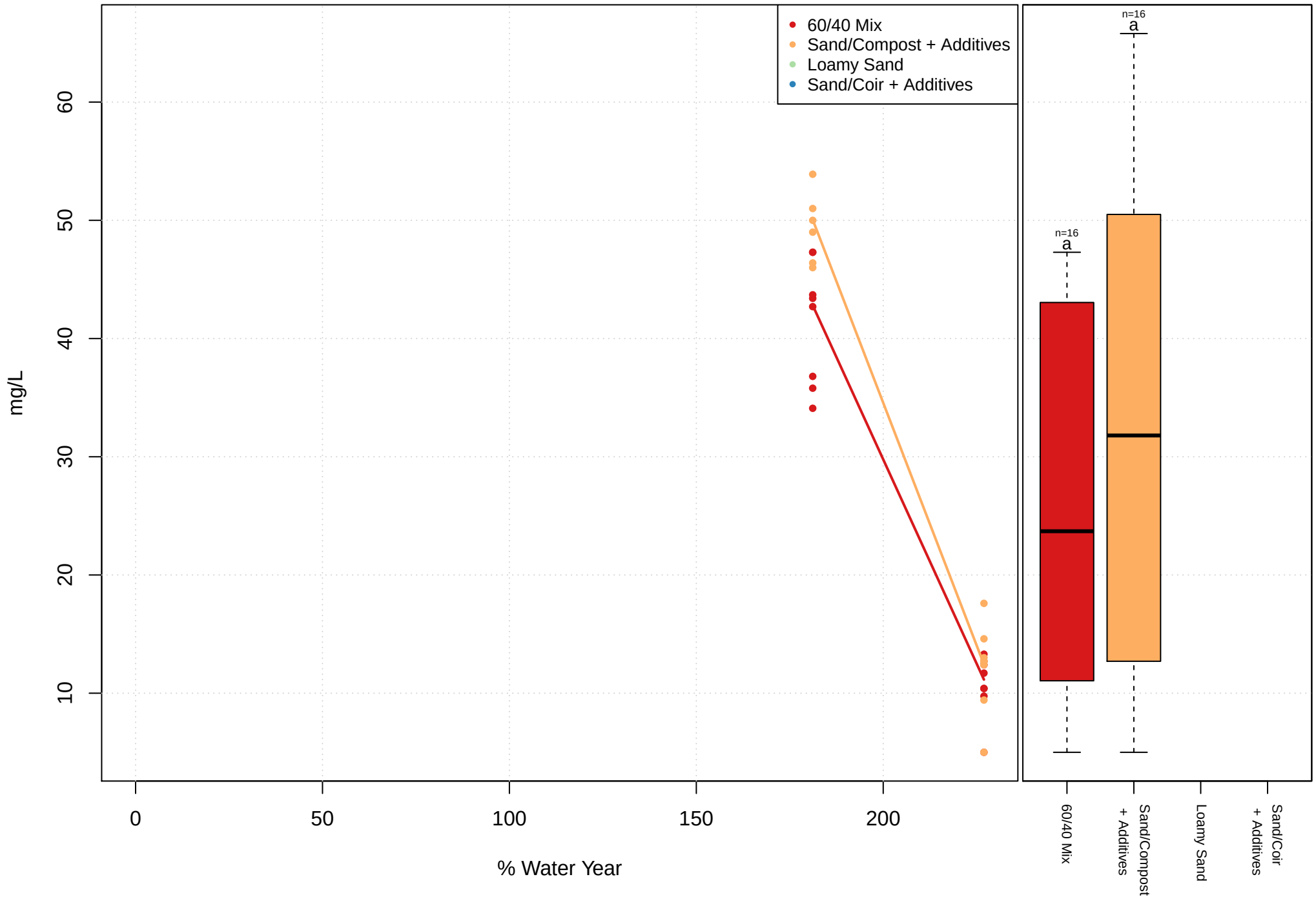
APPENDIX A

Effluent Concentration Figures for Each Measured Parameter

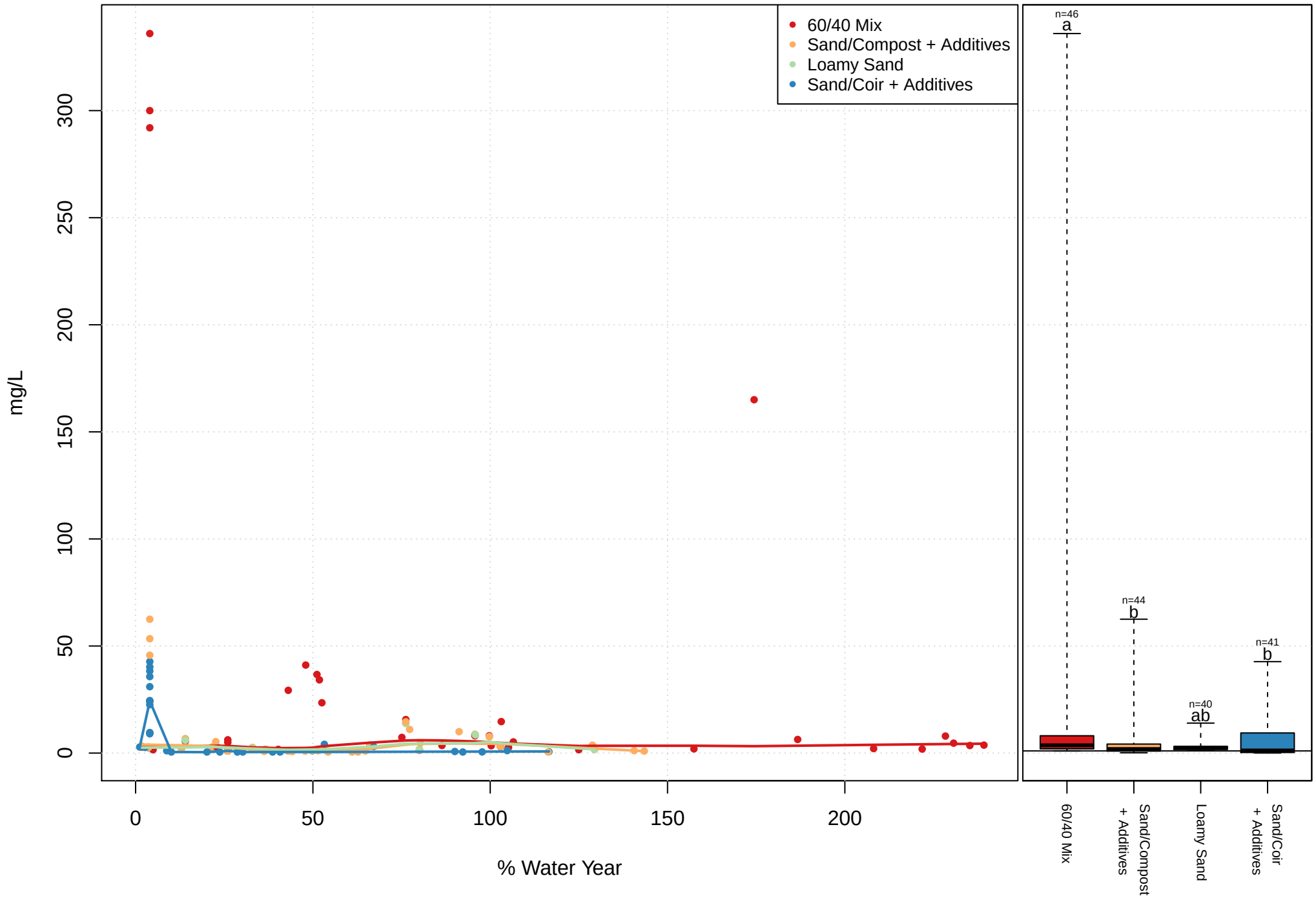

Alkalinity
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg CaCO3/L
0
50
100
150
200
250
0
20
40
60
80
100
120
140
% Water Year
n=29
a
n=47
a
n=40
b
n=53
c
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Ammonia
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0.02
0.04
0.06
0.08
0.10
0
50
100
150
200
% Water Year
n=16
a
n=16
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

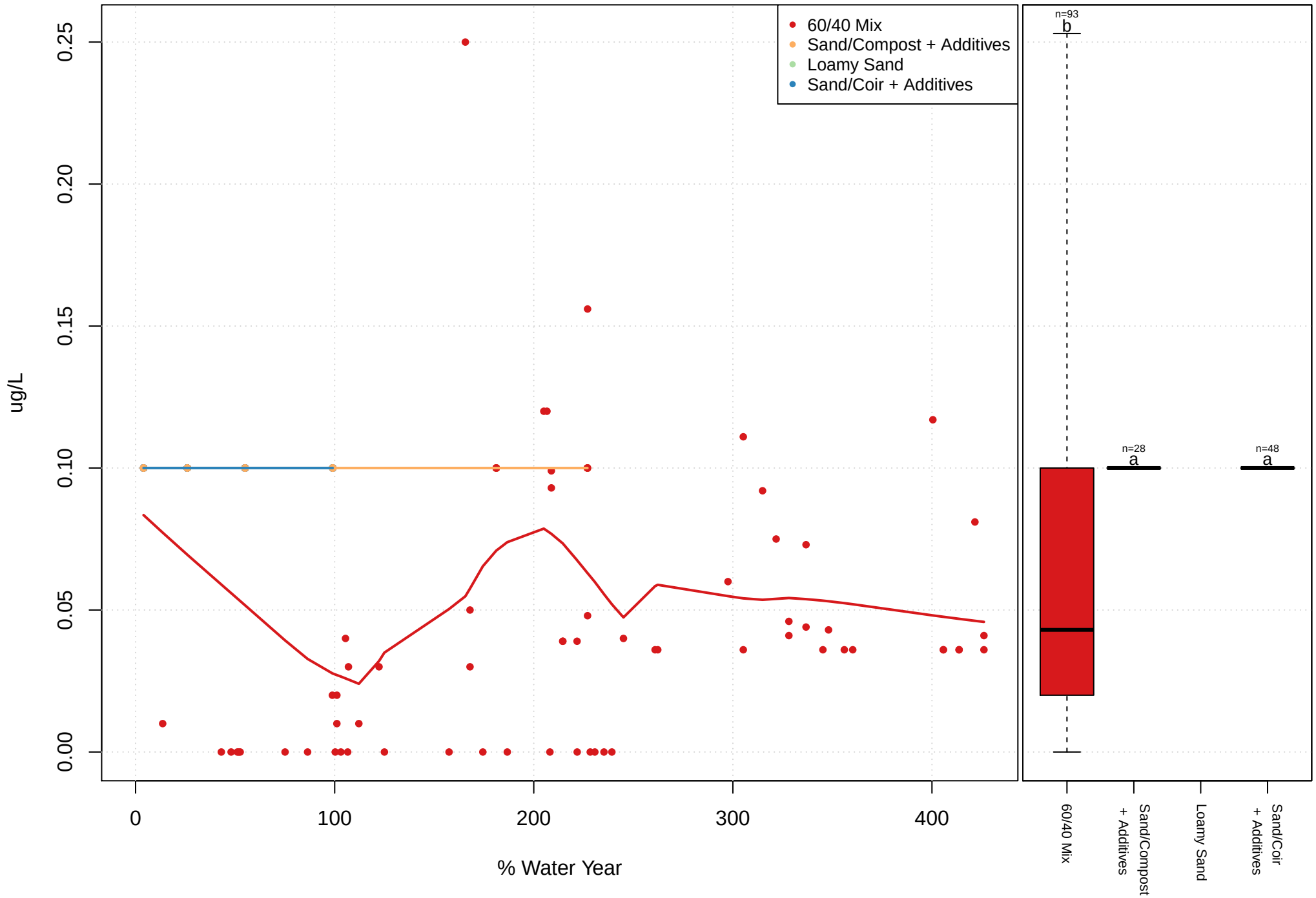
Chemical Oxygen Demand



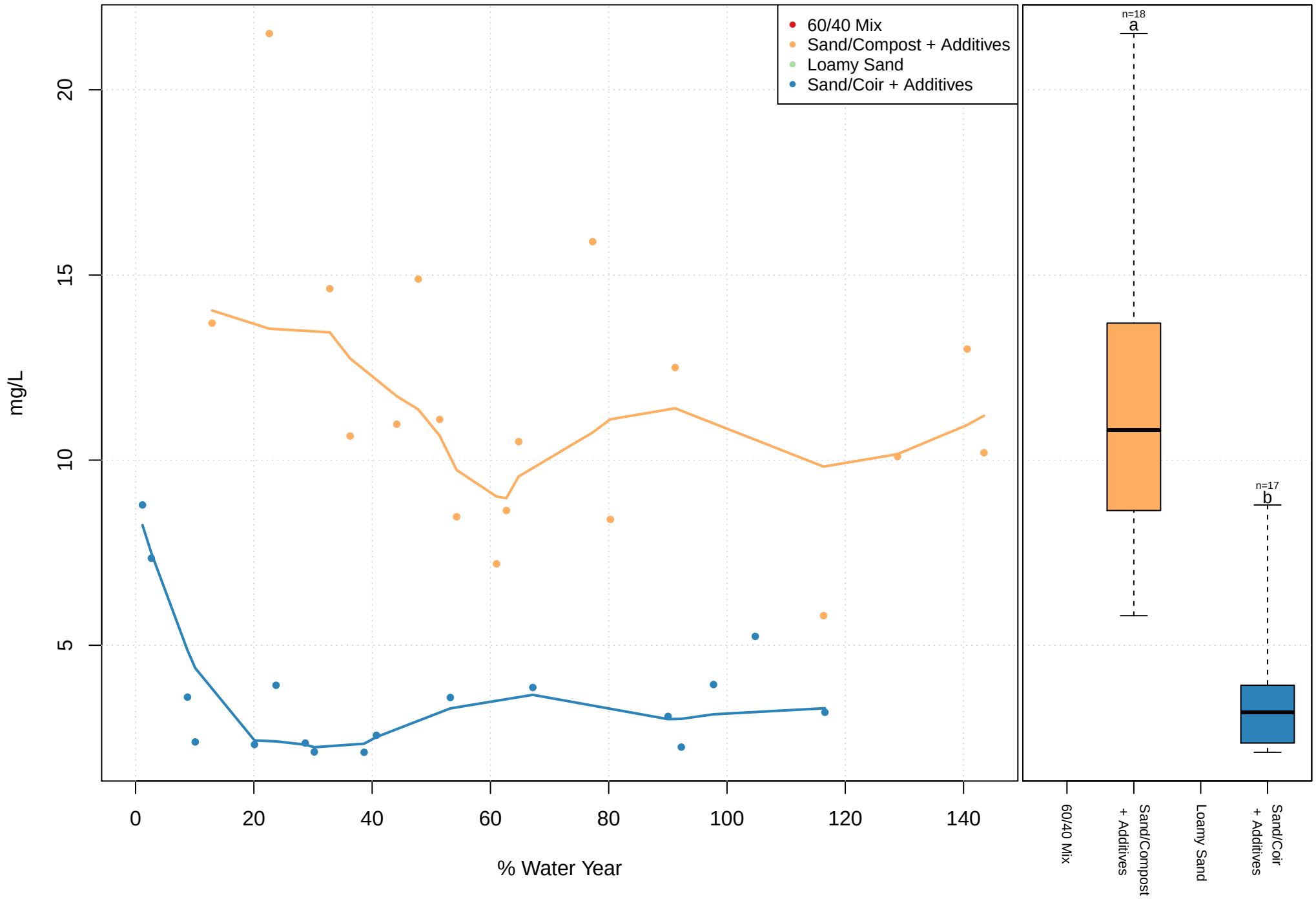
Chloride

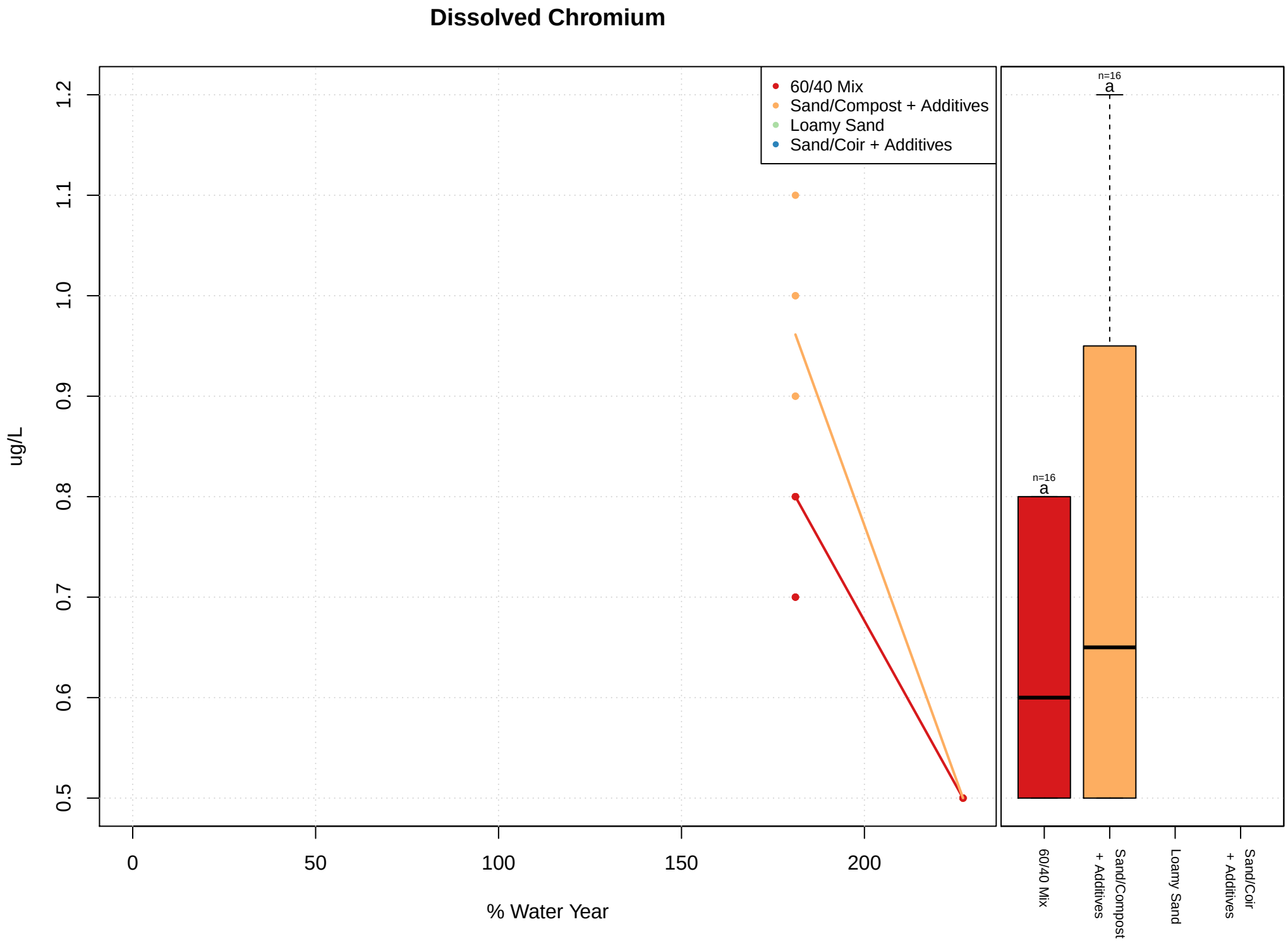

60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
50
100
150
200
250
300
% Water Year
0
50
100
150
200
n=46
a
n=44
b
n=40
ab
n=41
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

Dissolved Cadmium

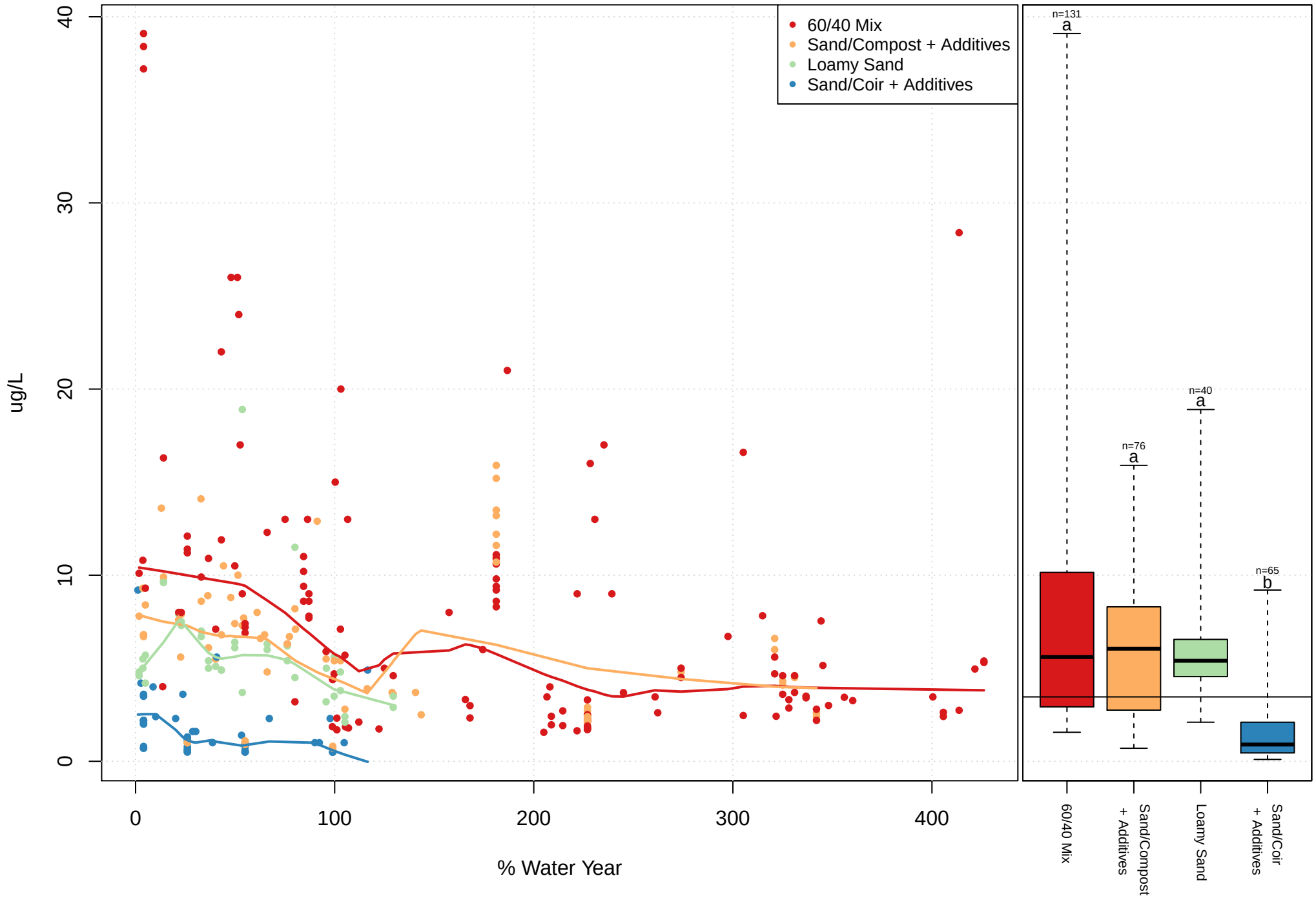


Dissolved Calcium

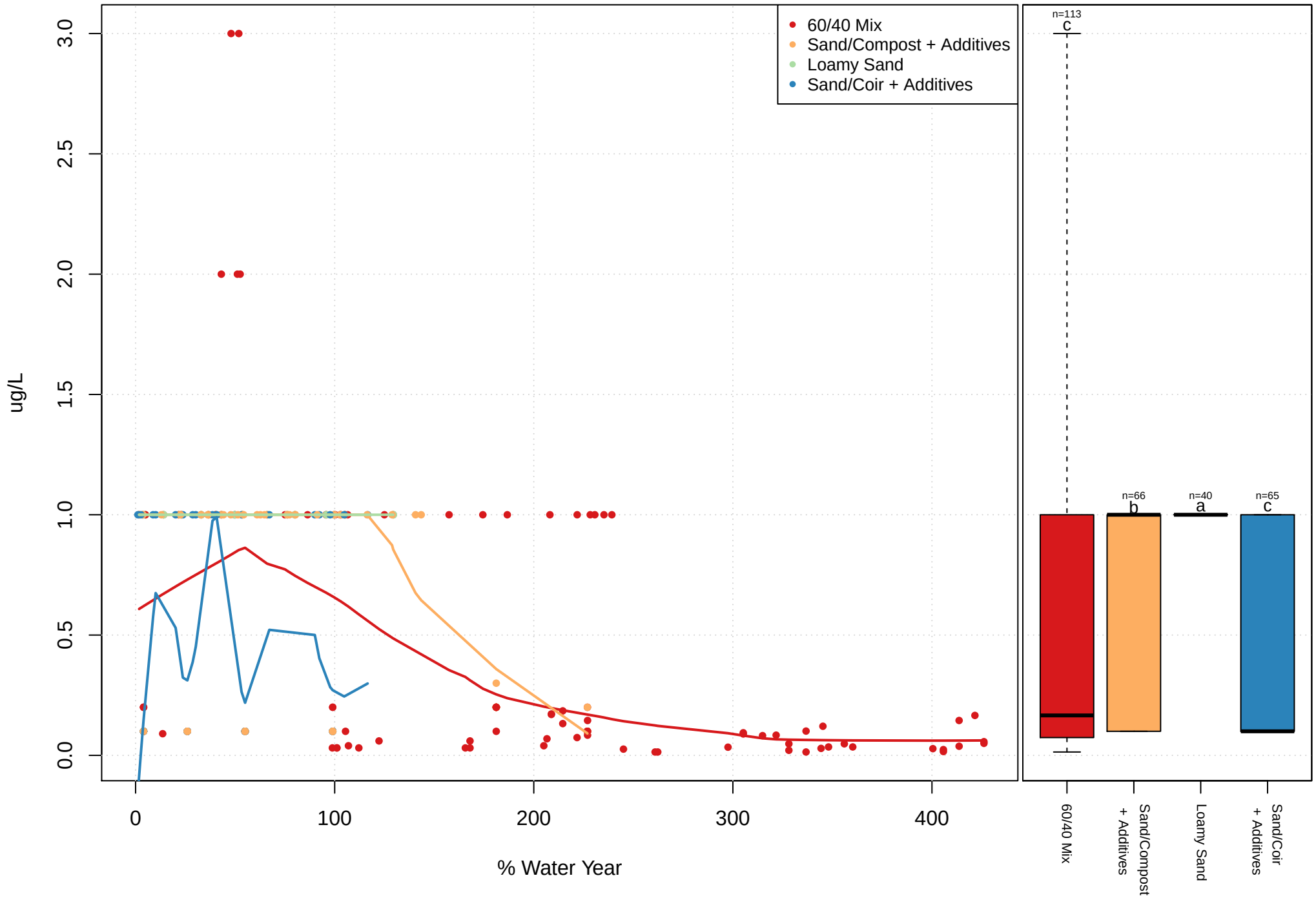



Dissolved Chromium
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
ug/L
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
50
100
150
200
% Water Year
n=16
a
n=16
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

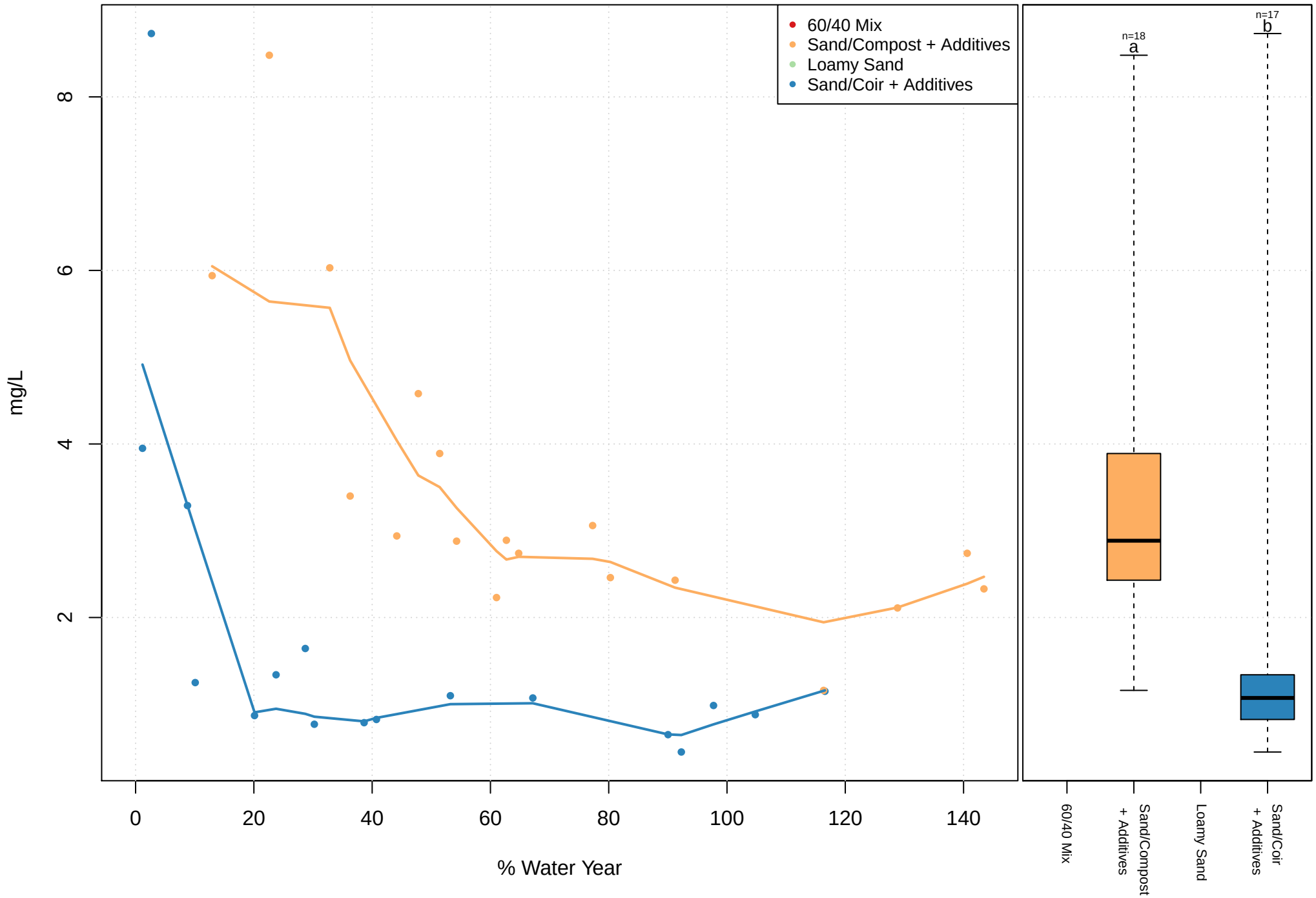
Dissolved Copper



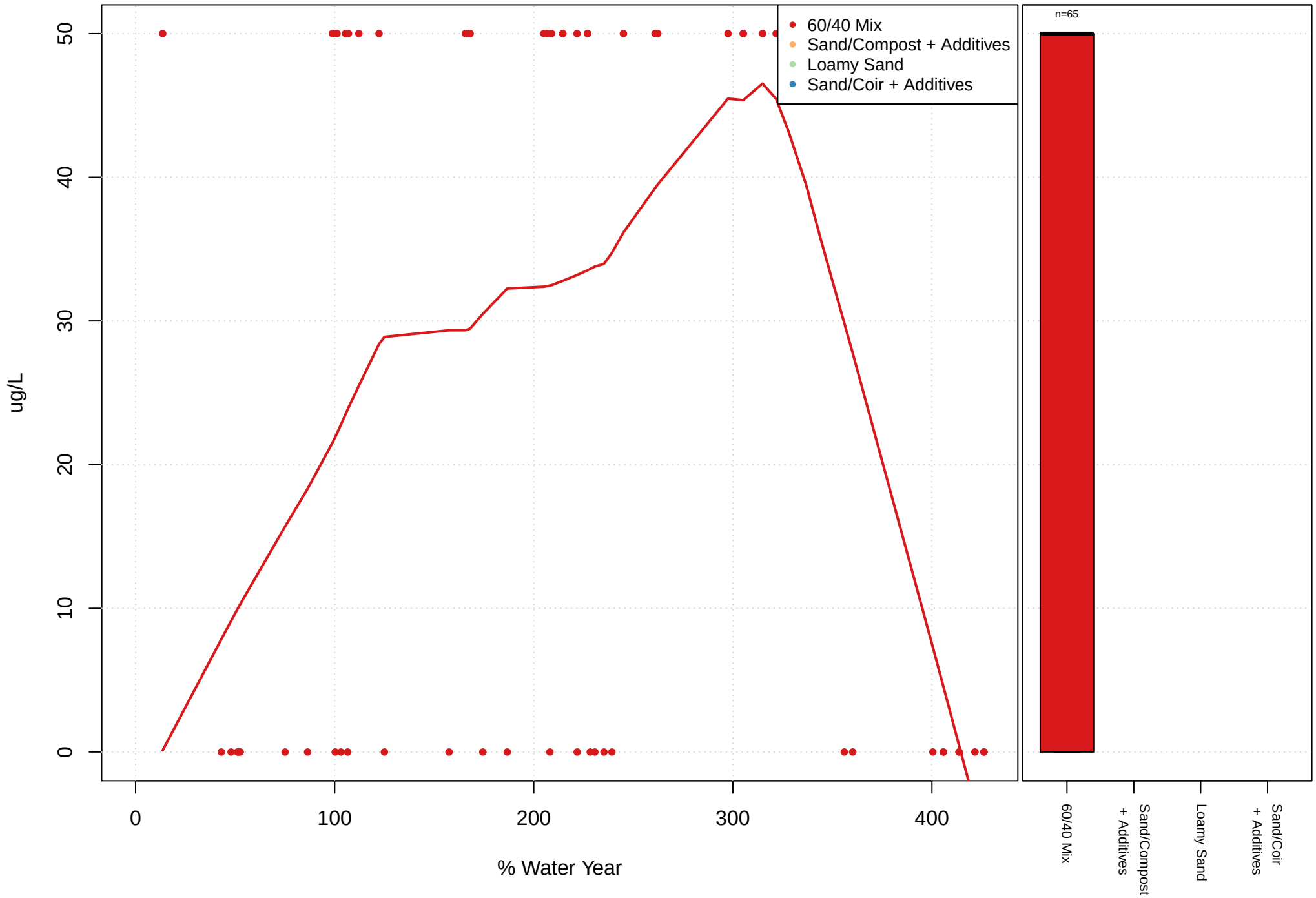
Dissolved Lead

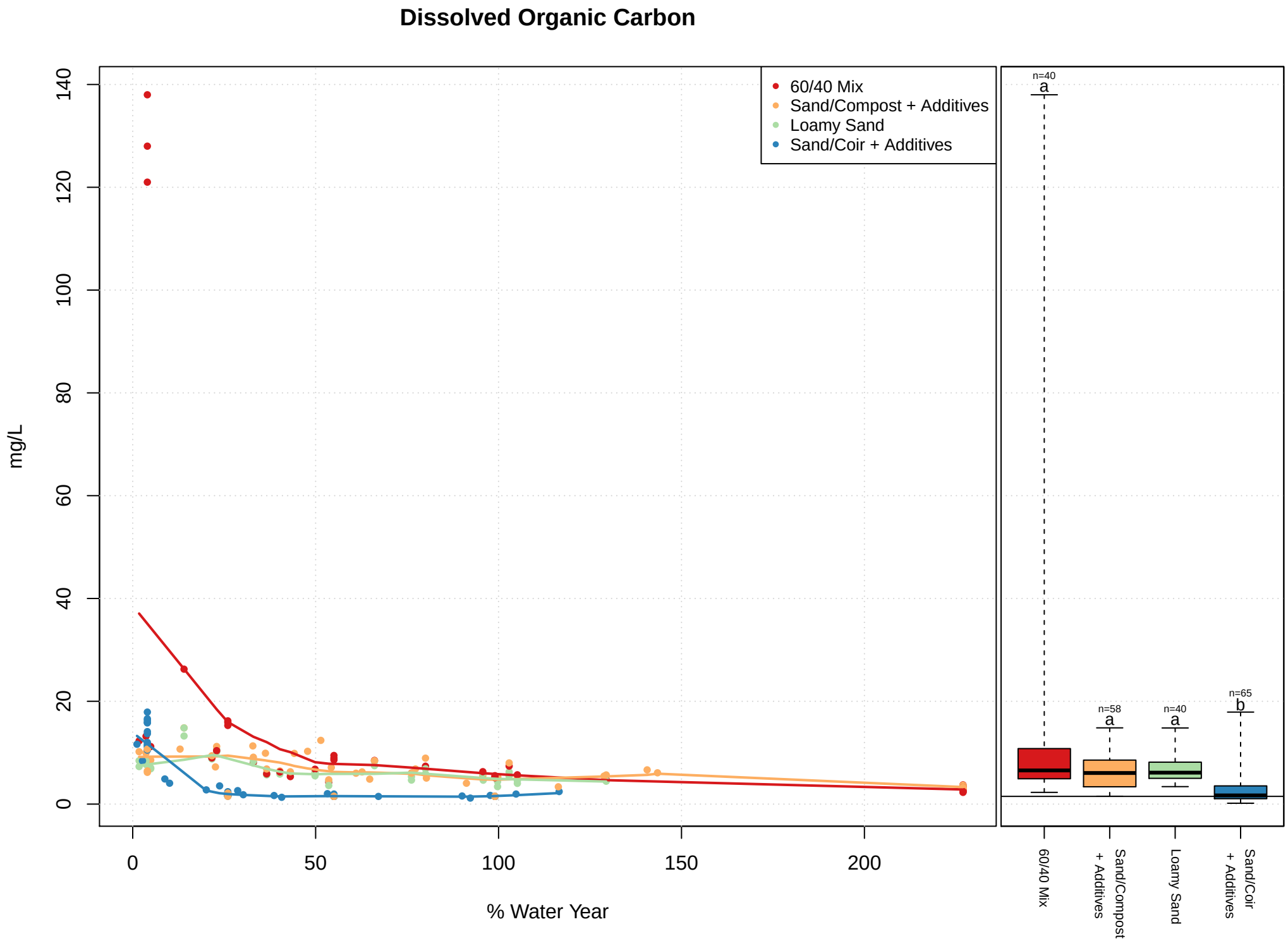


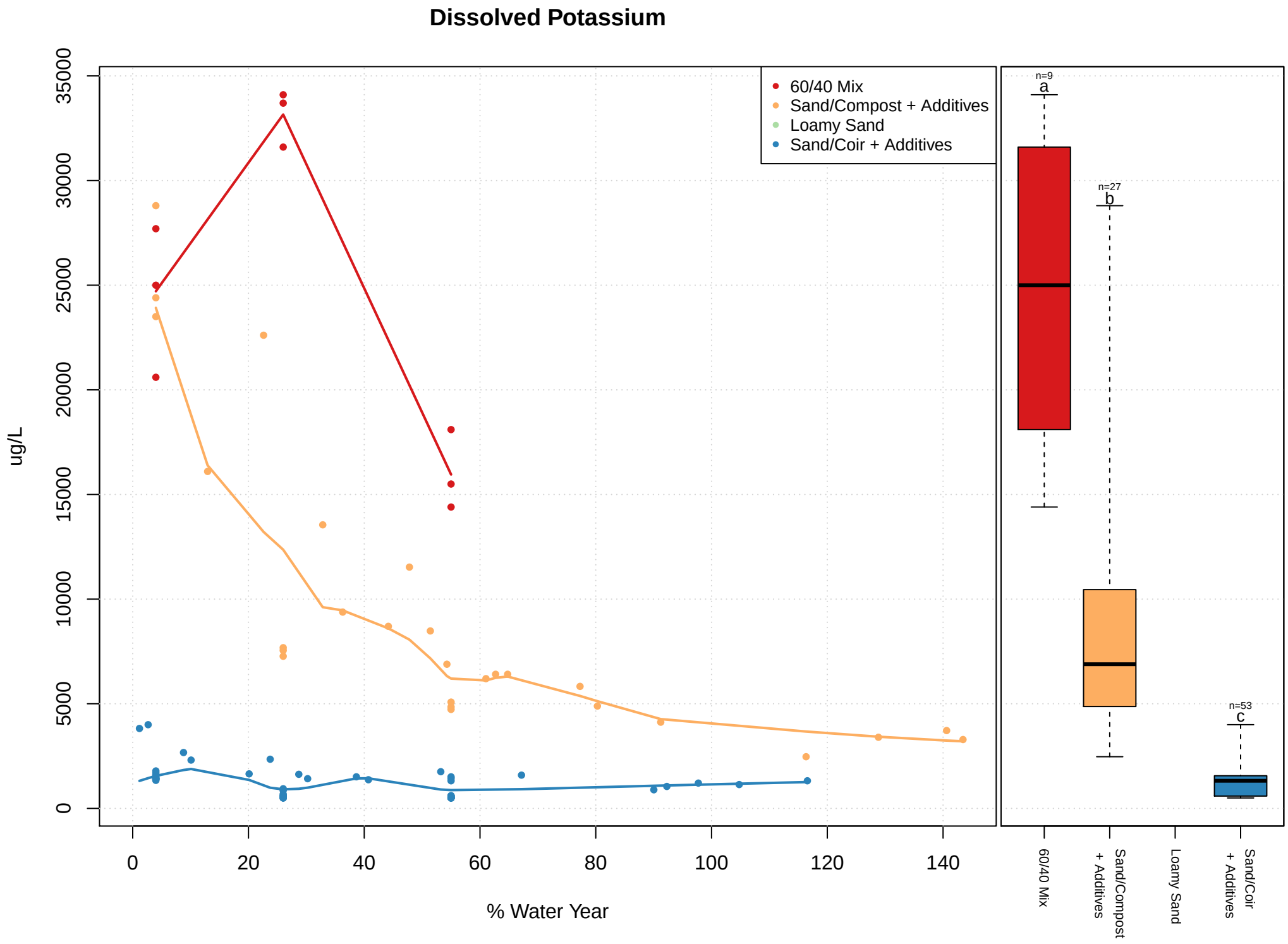
Dissolved Magnesium



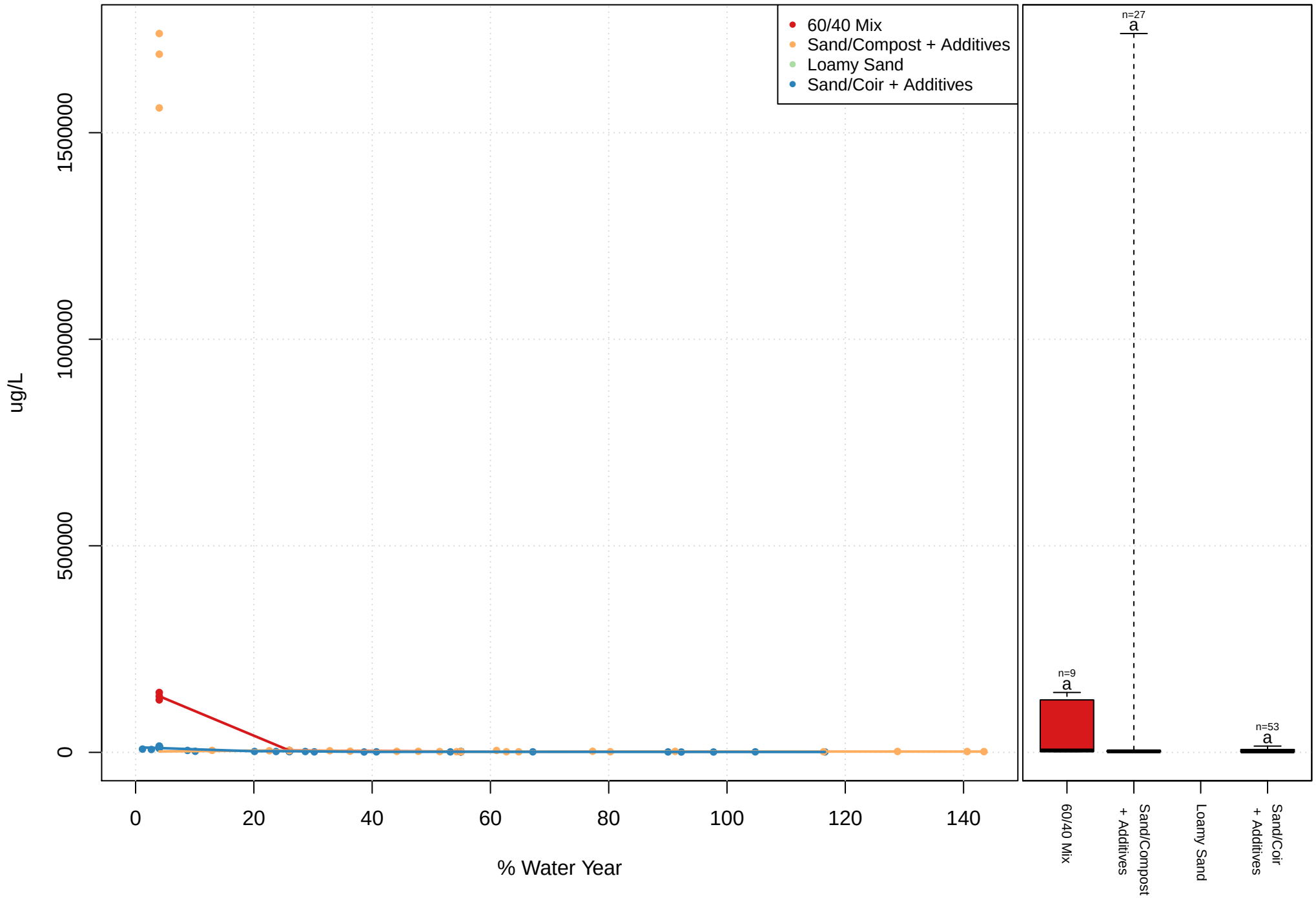
Dissolved Mercury



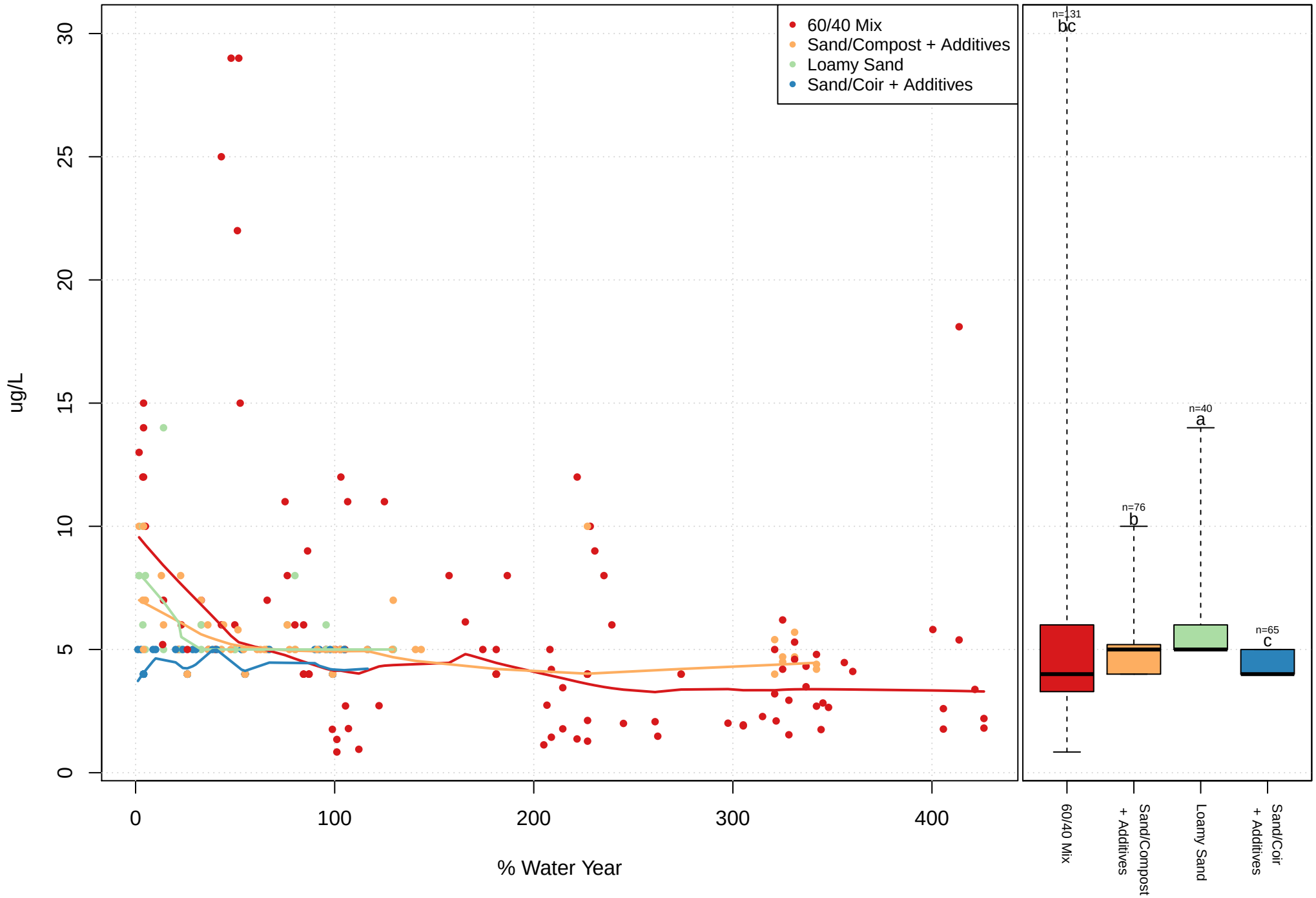

Dissolved Organic Carbon
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
20
40
60
80
100
120
140
0
50
100
150
200
% Water Year
n=40
a
n=58
a
n=40
a
n=65
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

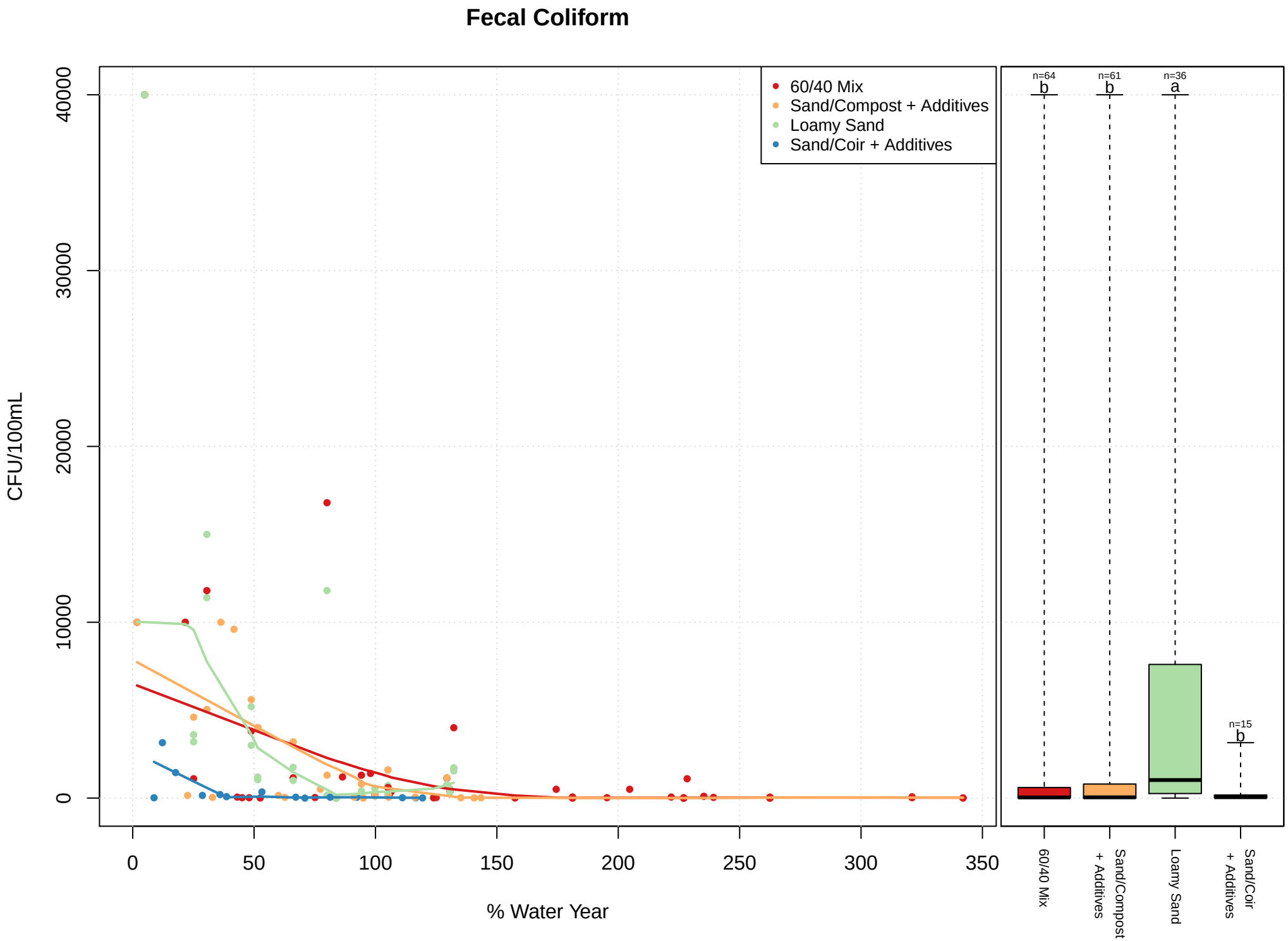

Dissolved Potassium
ug/L
35000
30000
25000
20000
15000
10000
5000
0
0
20
40
60
80
100
120
140
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=9
a
n=27
b
n=53
c
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

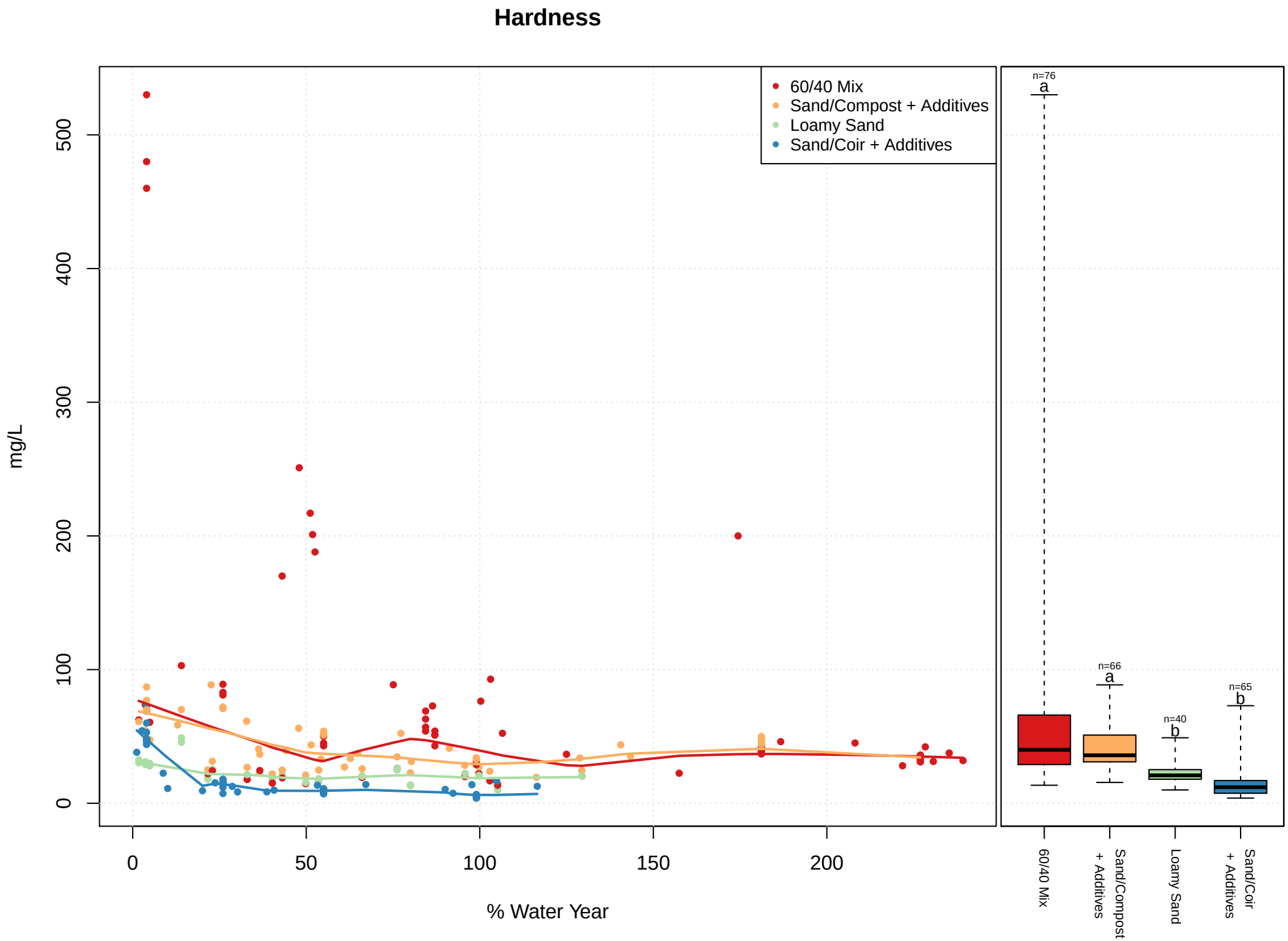
Dissolved Sodium

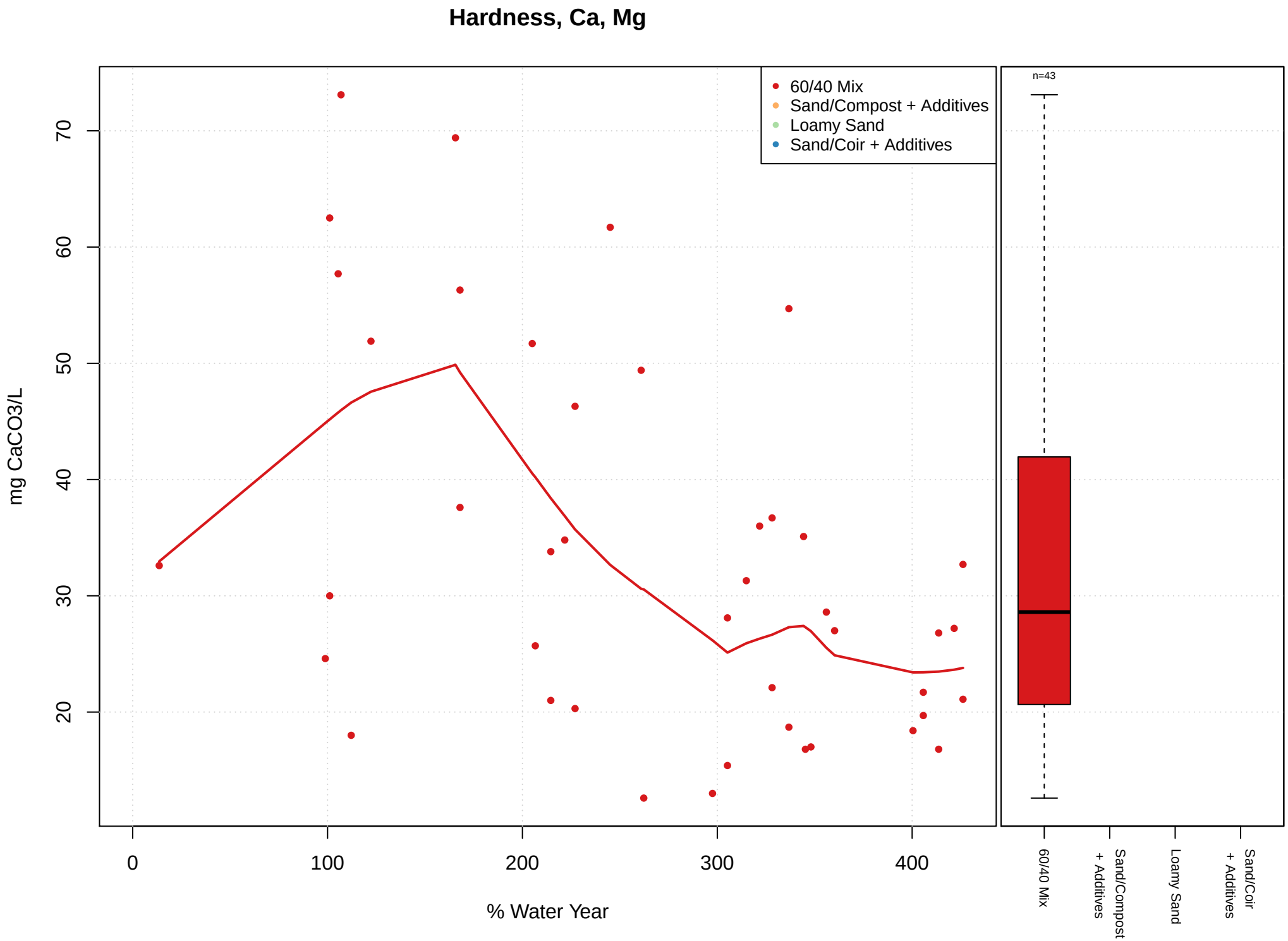


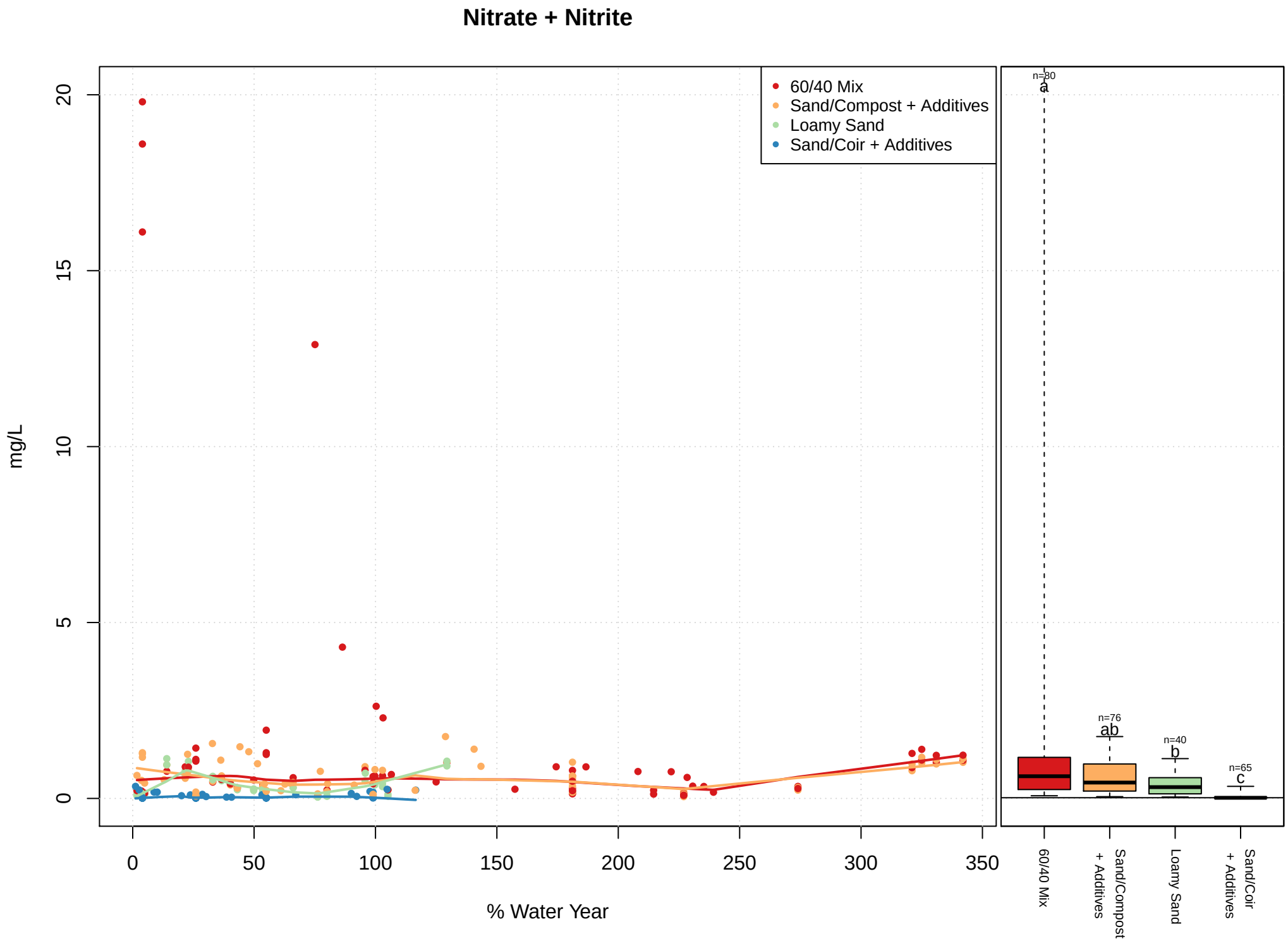
Dissolved Zinc

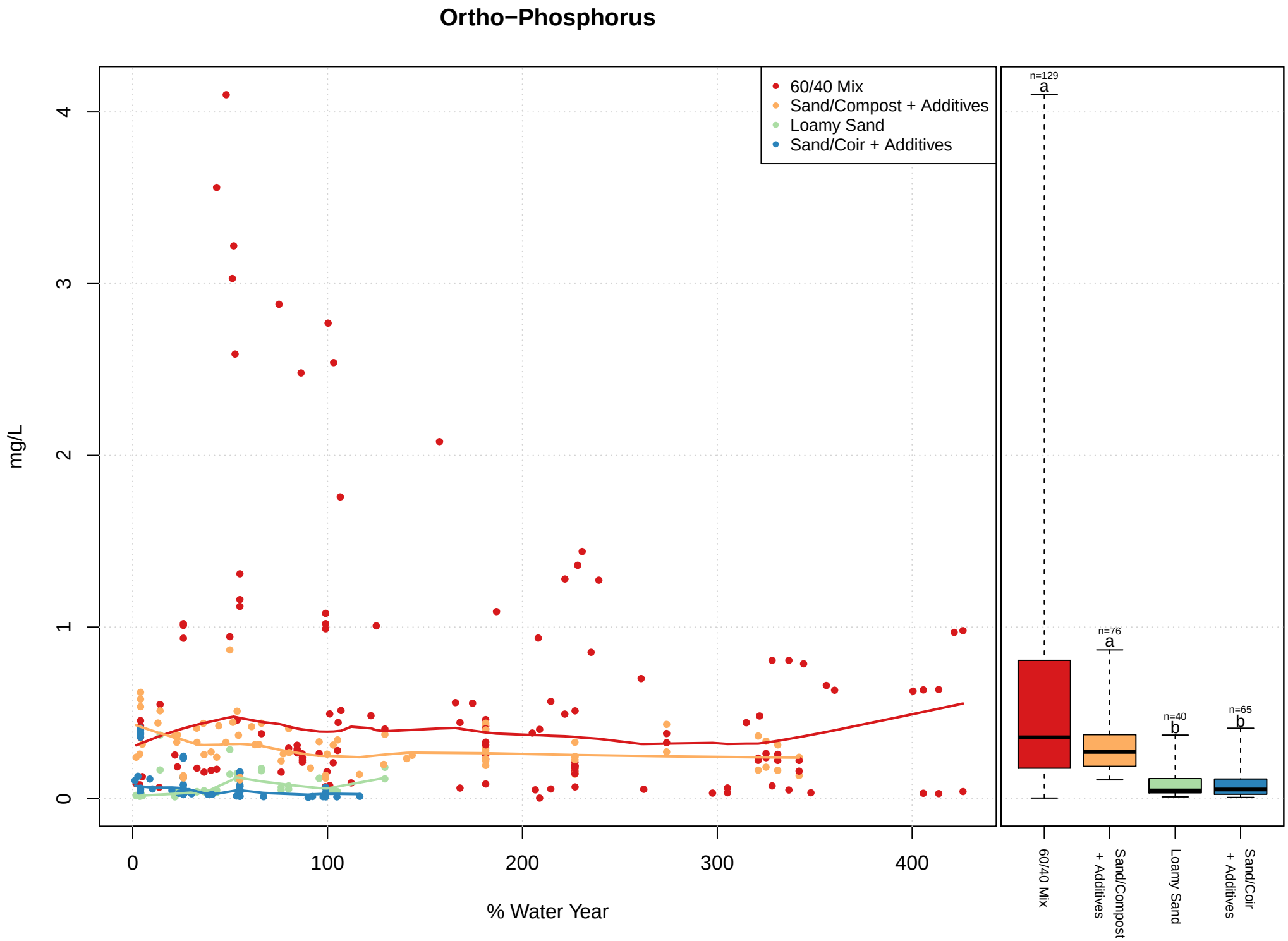


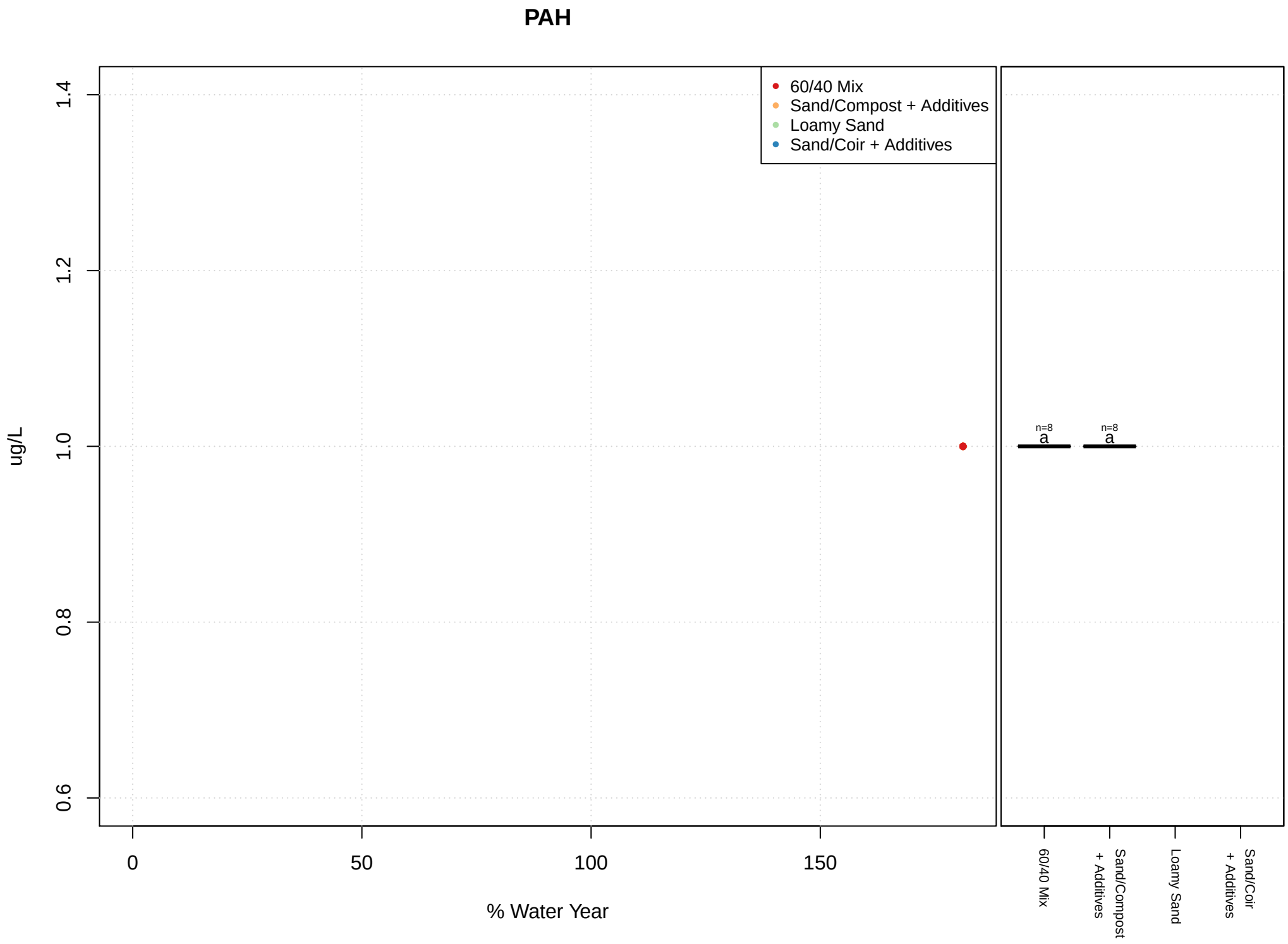

Fecal Coliform
CFU/100mL
40000
30000
20000
10000
0
0
50
100
150
200
250
300
350
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=64
b
n=61
b
n=36
a
n=15
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Hardness
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
100
200
300
400
500
0
50
100
150
200
% Water Year
n=76
a
n=66
a
n=40
b
n=65
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

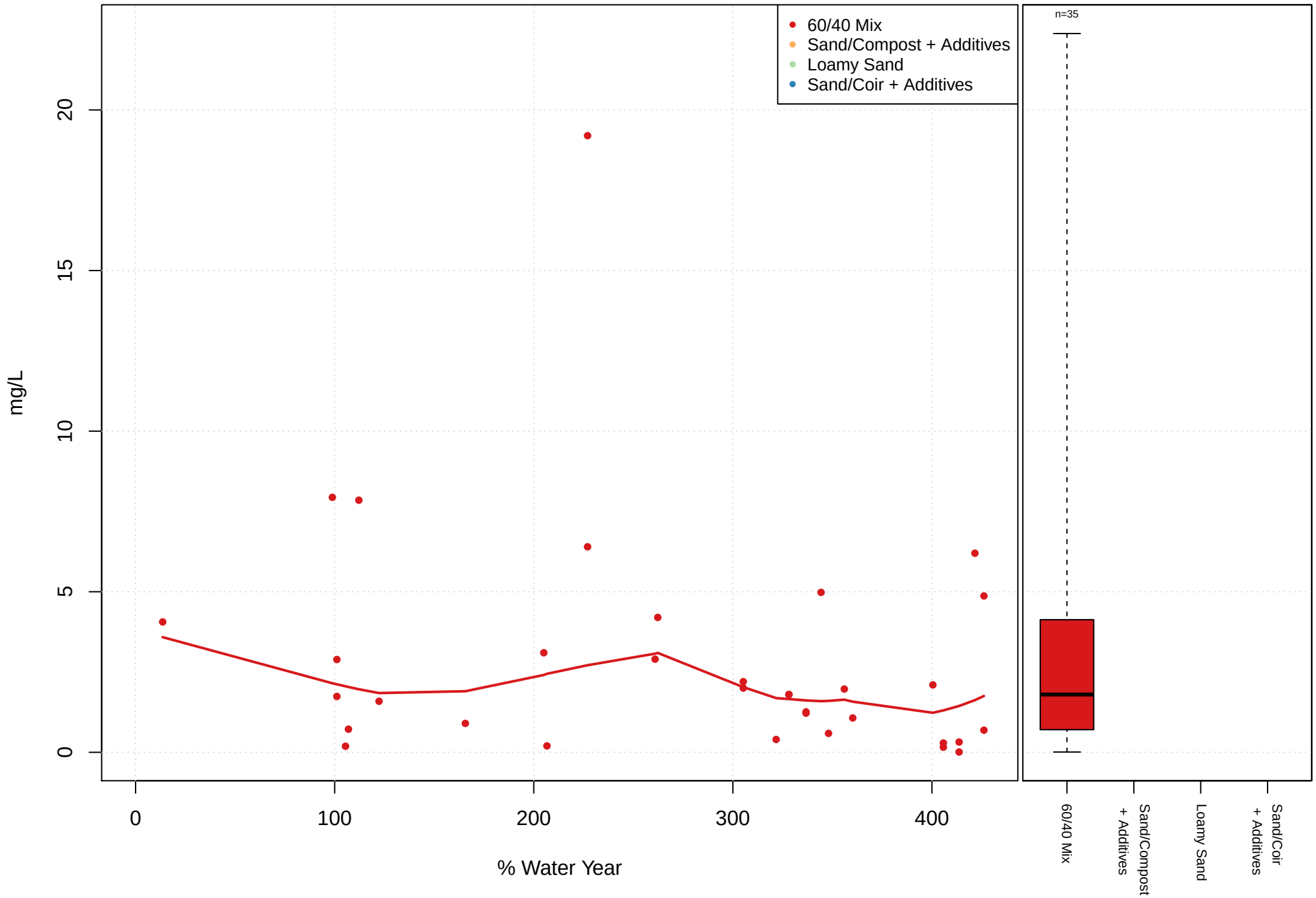

Hardness, Ca, Mg
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg CaCO3/L
20
30
40
50
60
70
0
100
200
300
400
% Water Year
n=43
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Nitrate + Nitrite
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
5
10
15
20
0
50
100
150
200
250
300
350
% Water Year
n=80
a
n=76
ab
n=40
b
n=65
c
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

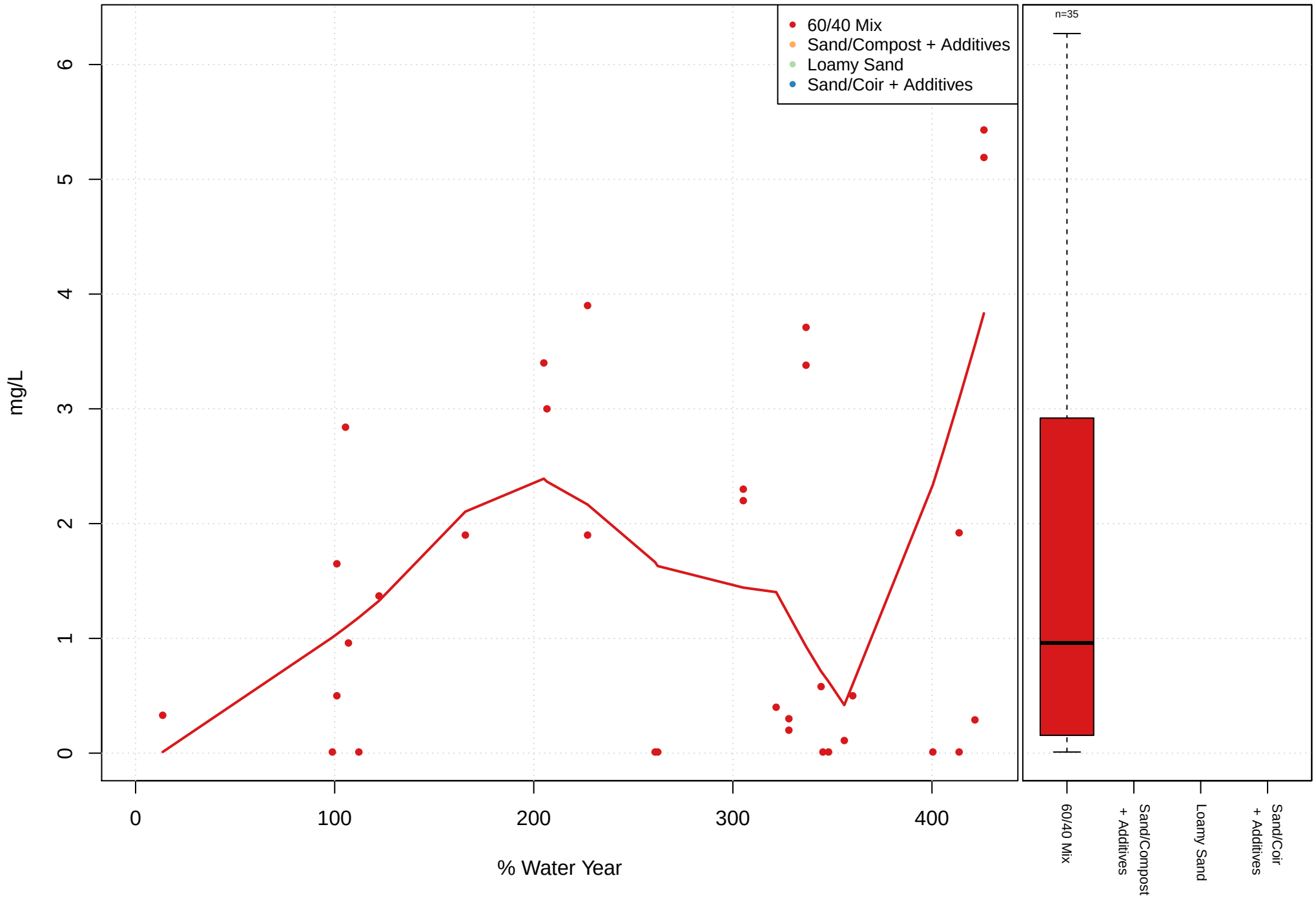

Ortho−Phosphorus
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
1
2
3
4
0
100
200
300
400
% Water Year
n=129
a
n=76
a
n=40
b
n=65
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


PAH
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
ug/L
1.4
1.2
1.0
0.8
0.6
0
50
100
150
% Water Year
n=8
a
n=8
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

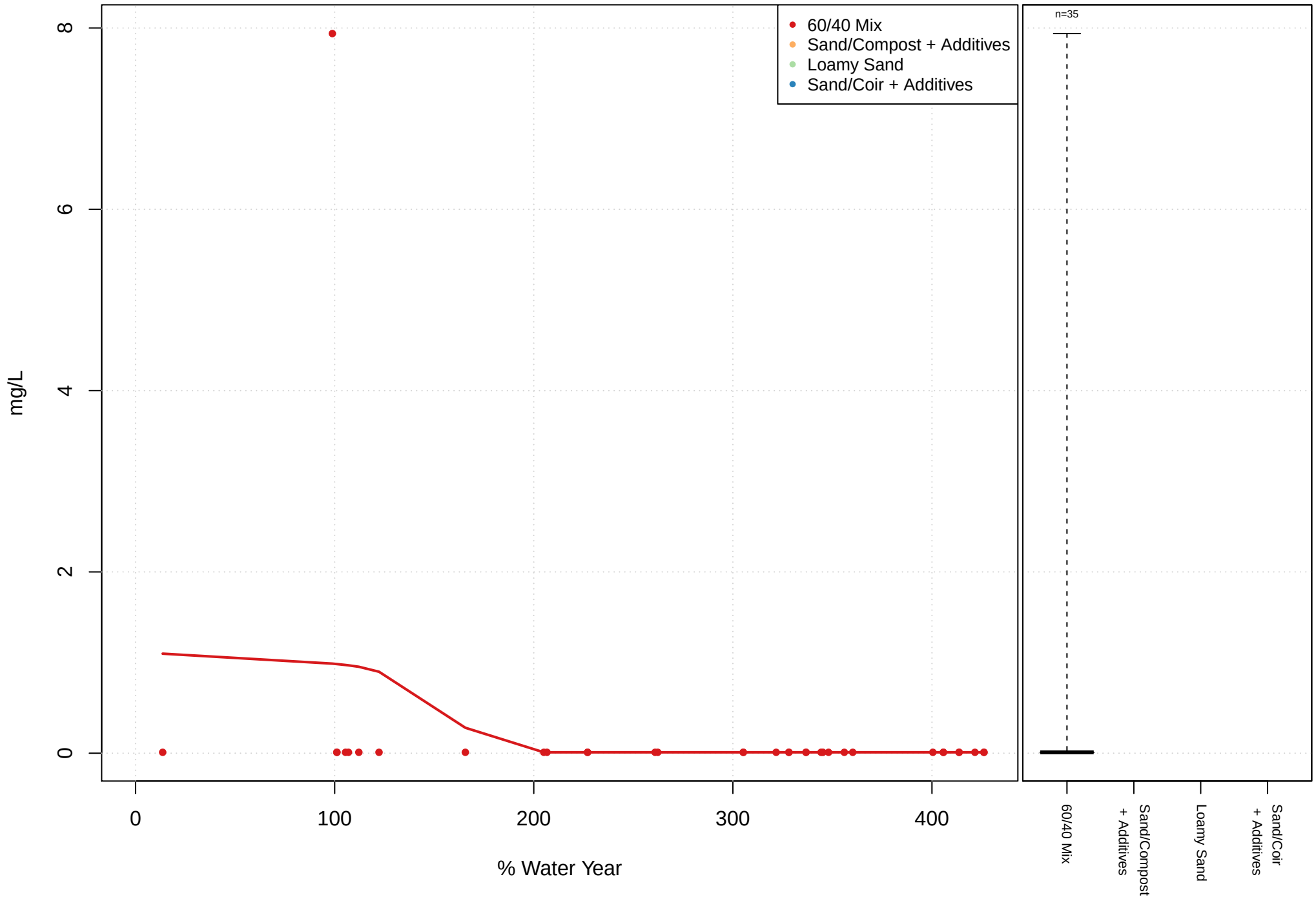
Particle Size, Sediment Conc. < 1 um



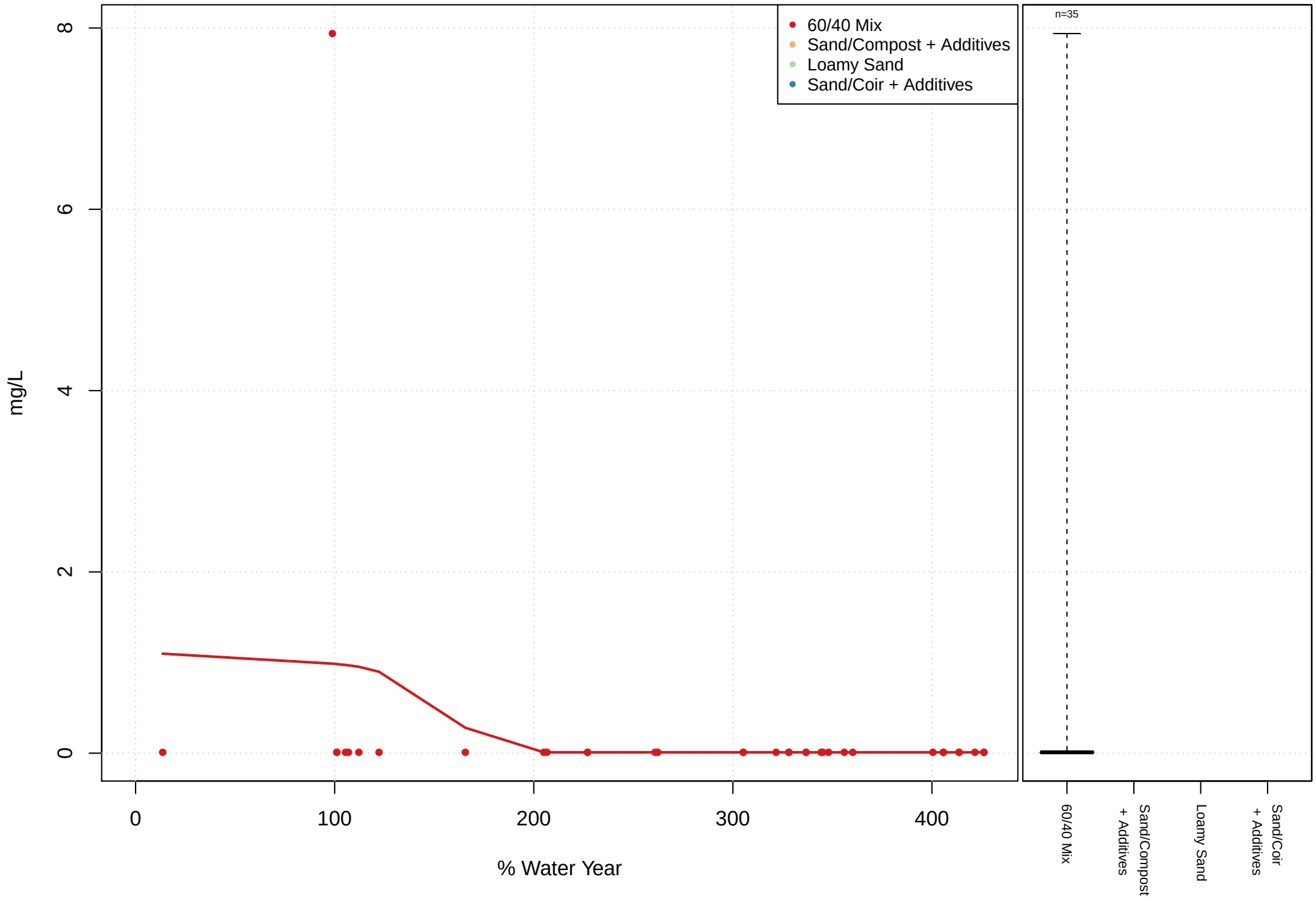
Particle Size, Sediment Conc. > 500 um



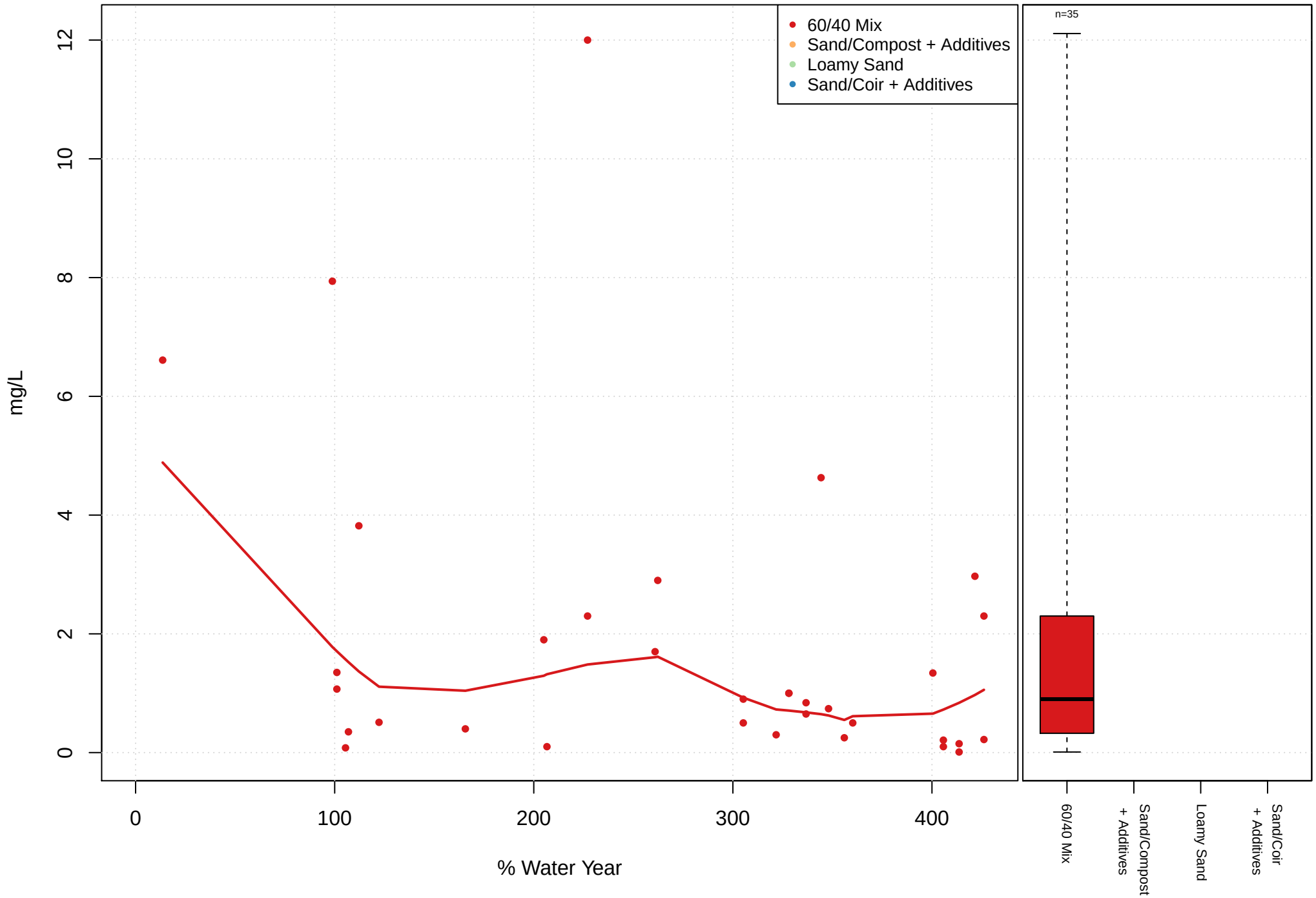
Particle Size, Sediment Conc. 125 to 62.5 um



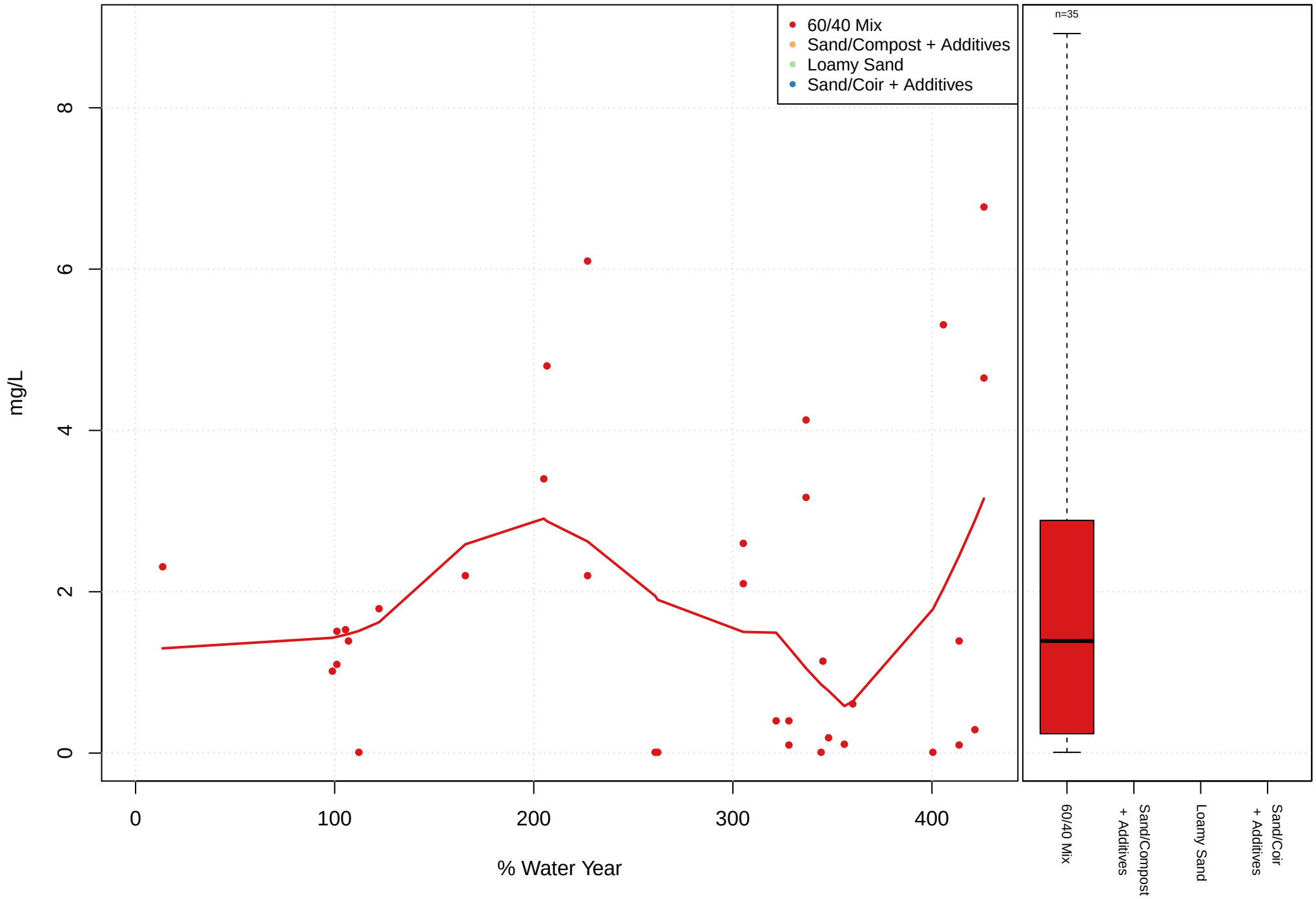
Particle Size, Sediment Conc. 250 to 125 um



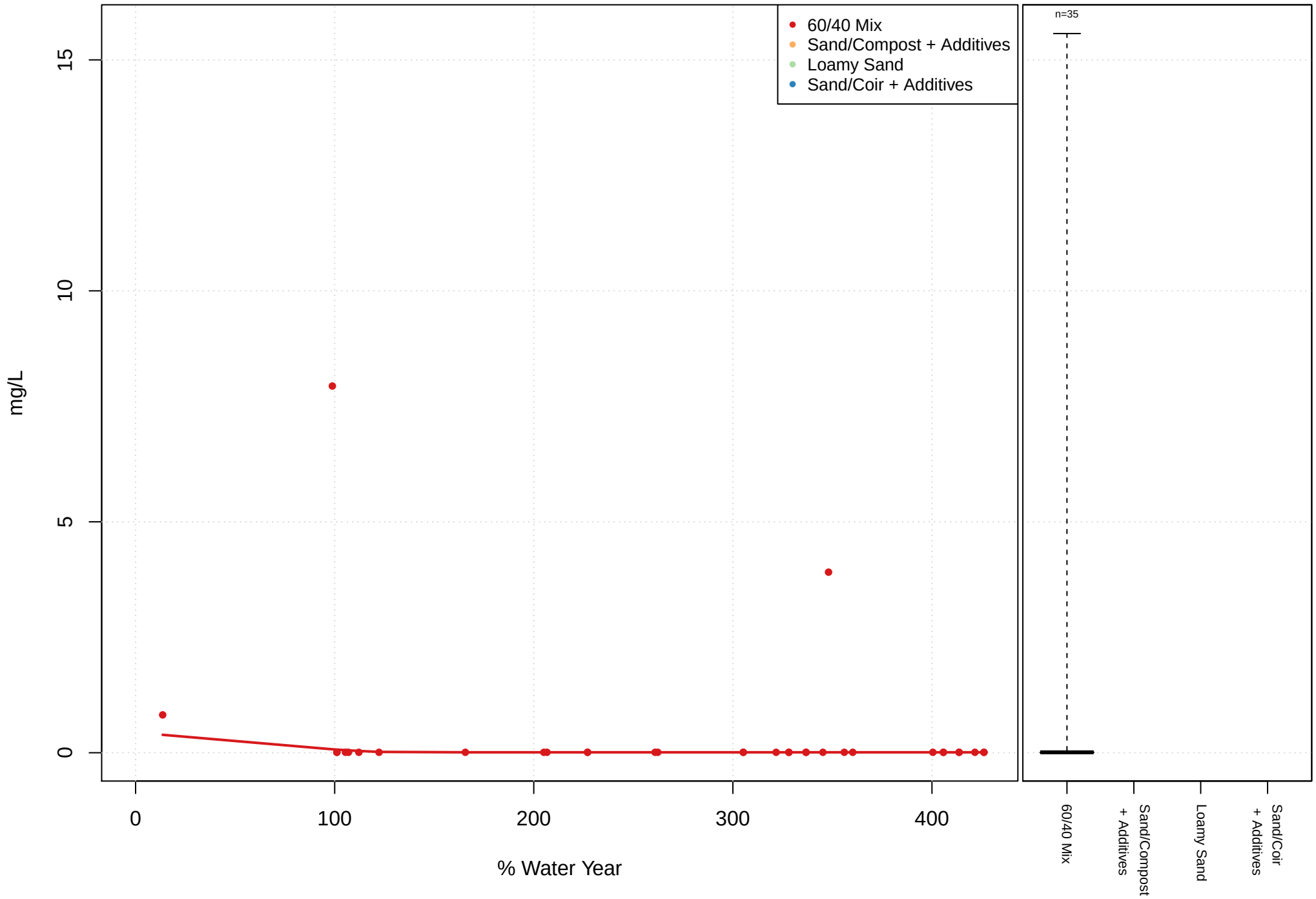
Particle Size, Sediment Conc. 3.9 to 1 um

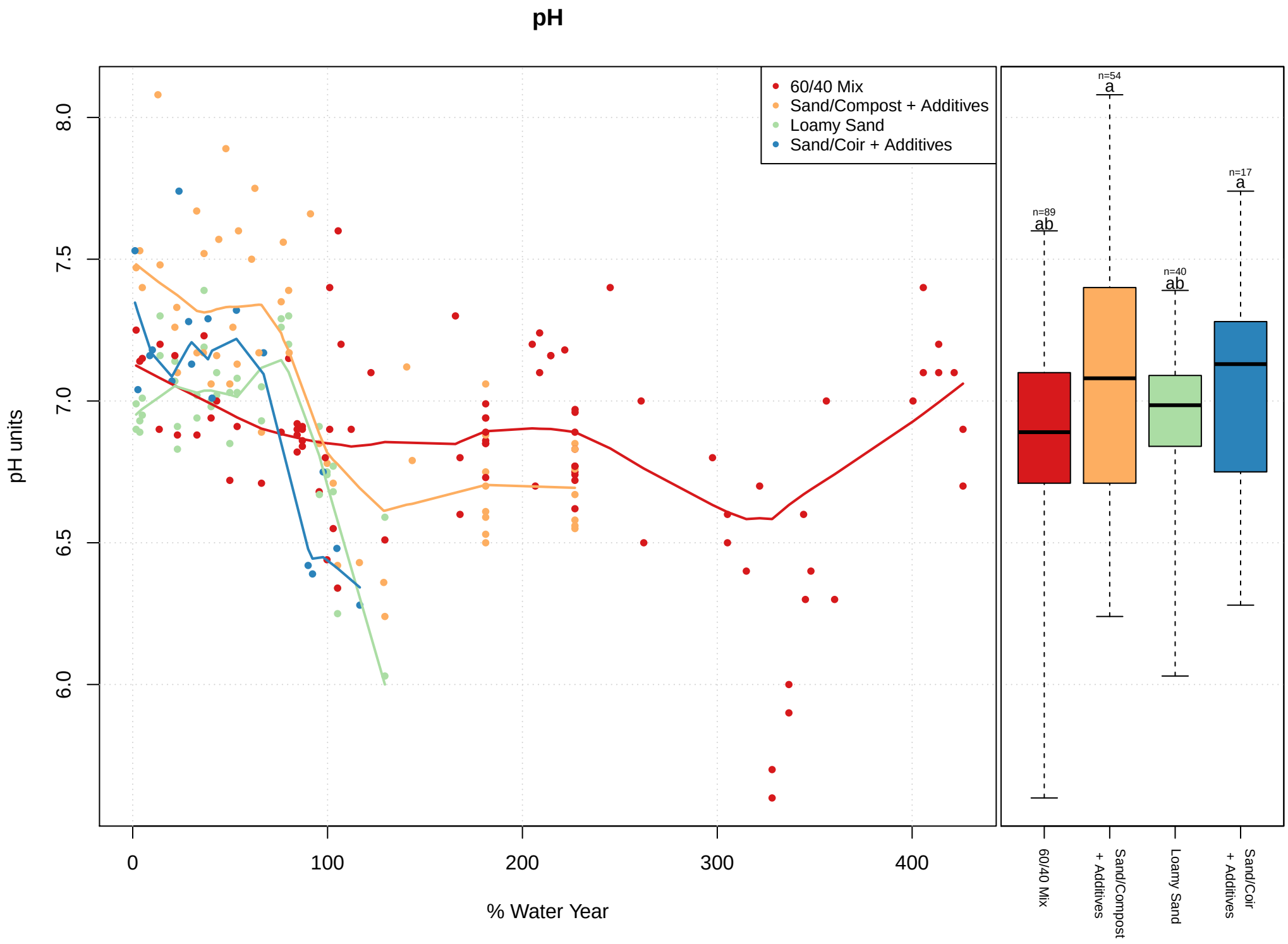


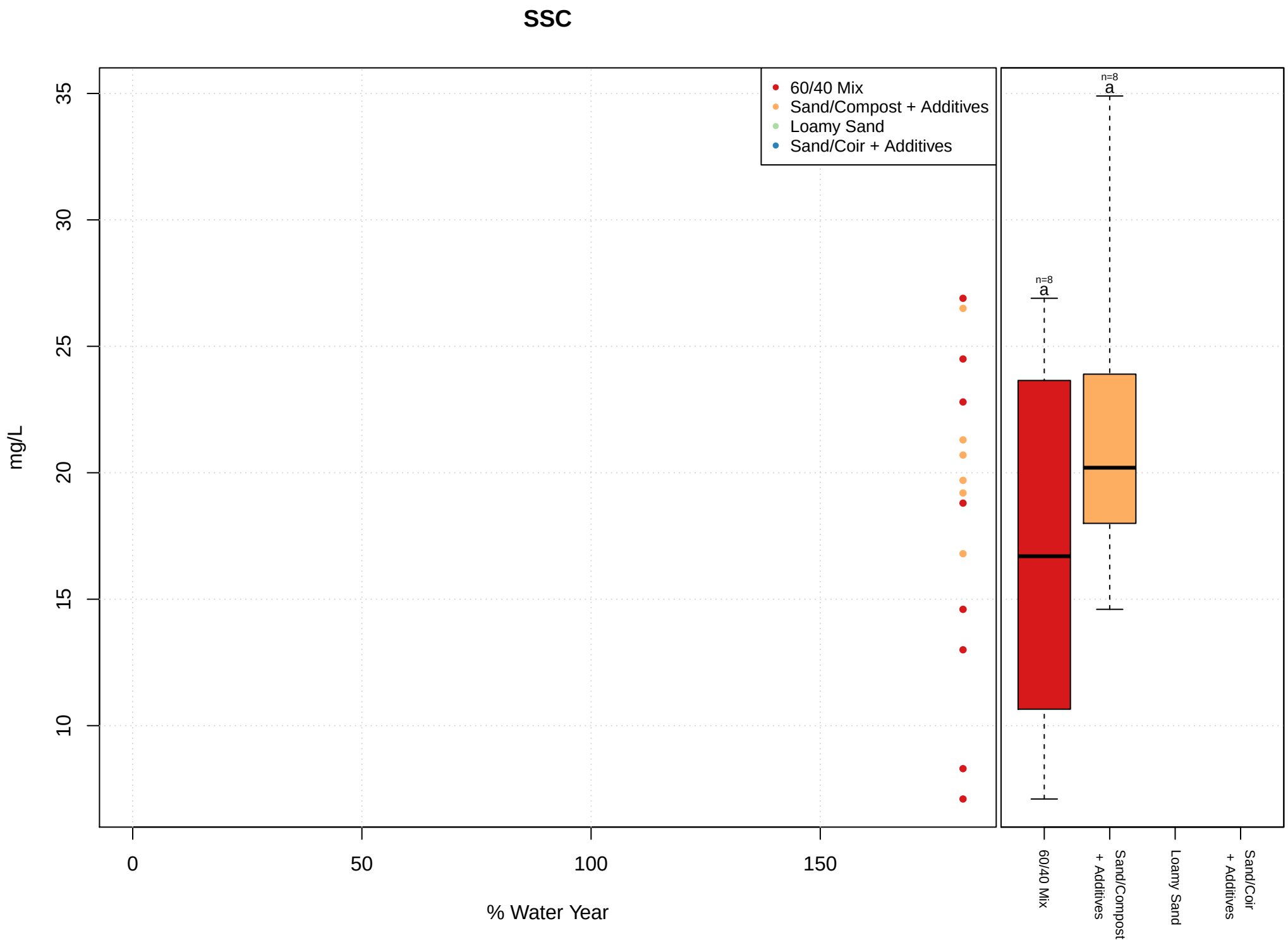
Particle Size, Sediment Conc. 500 to 250 um

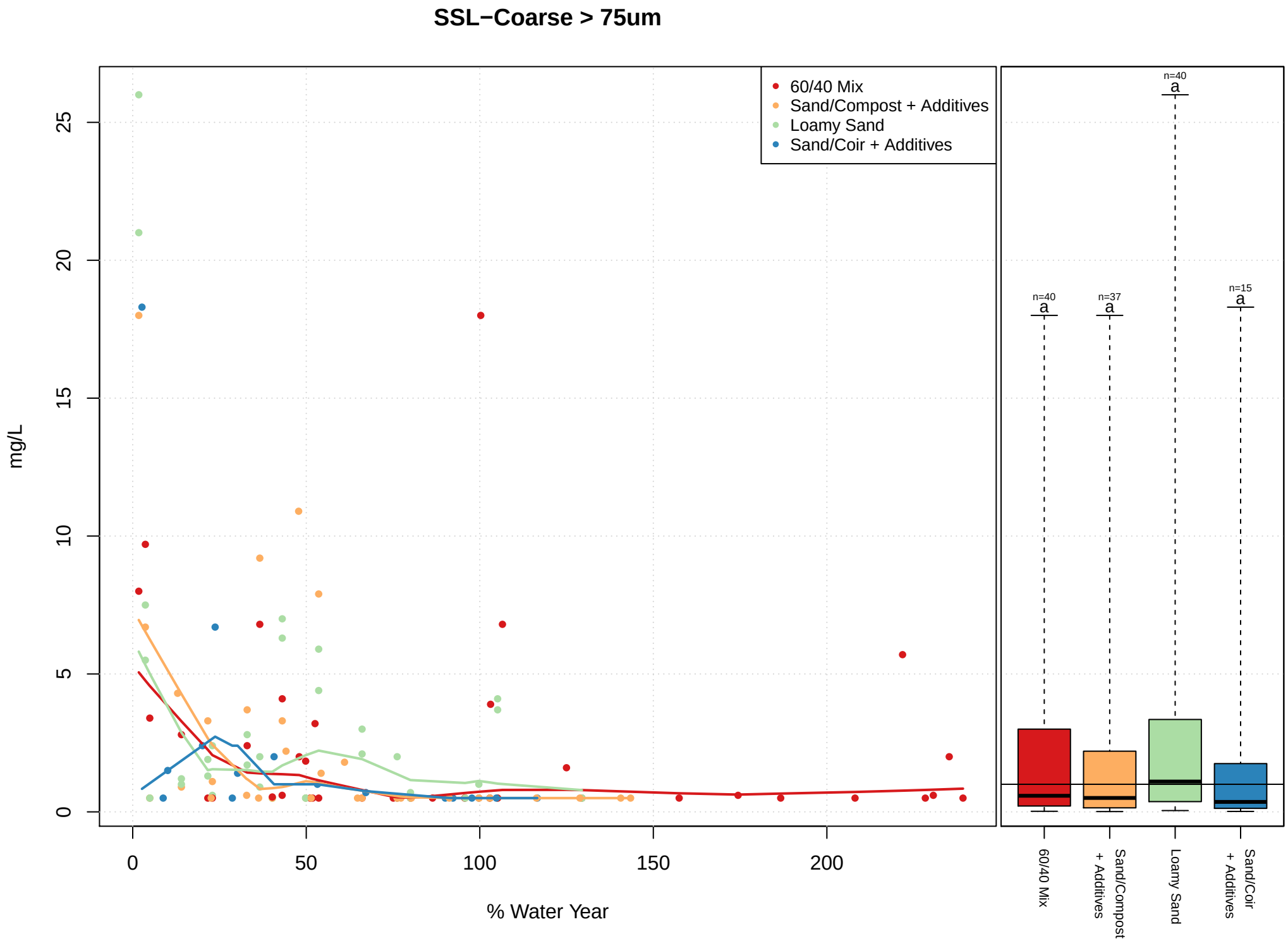


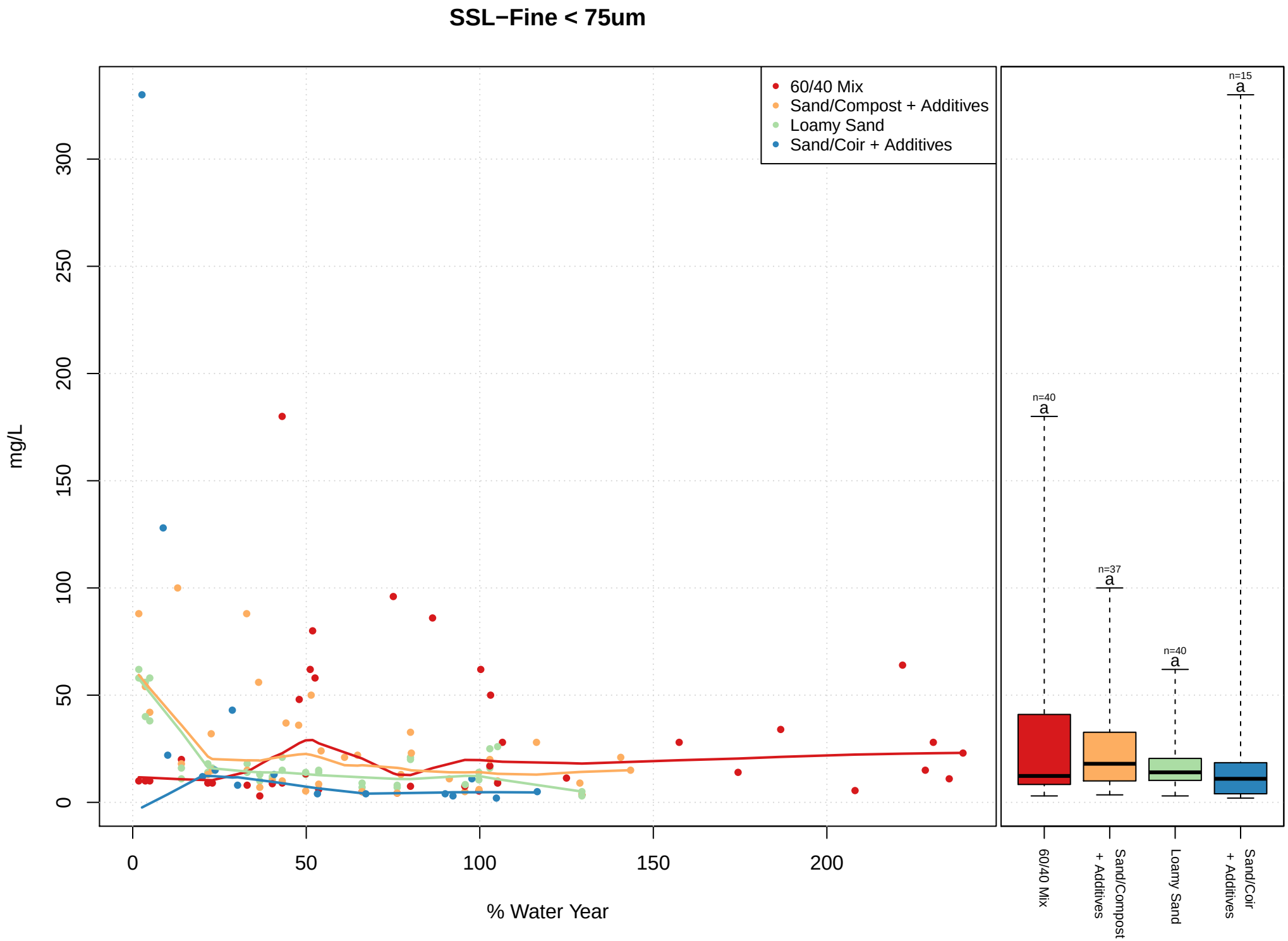
Particle Size, Sediment Conc. 62.5 to 3.9 um

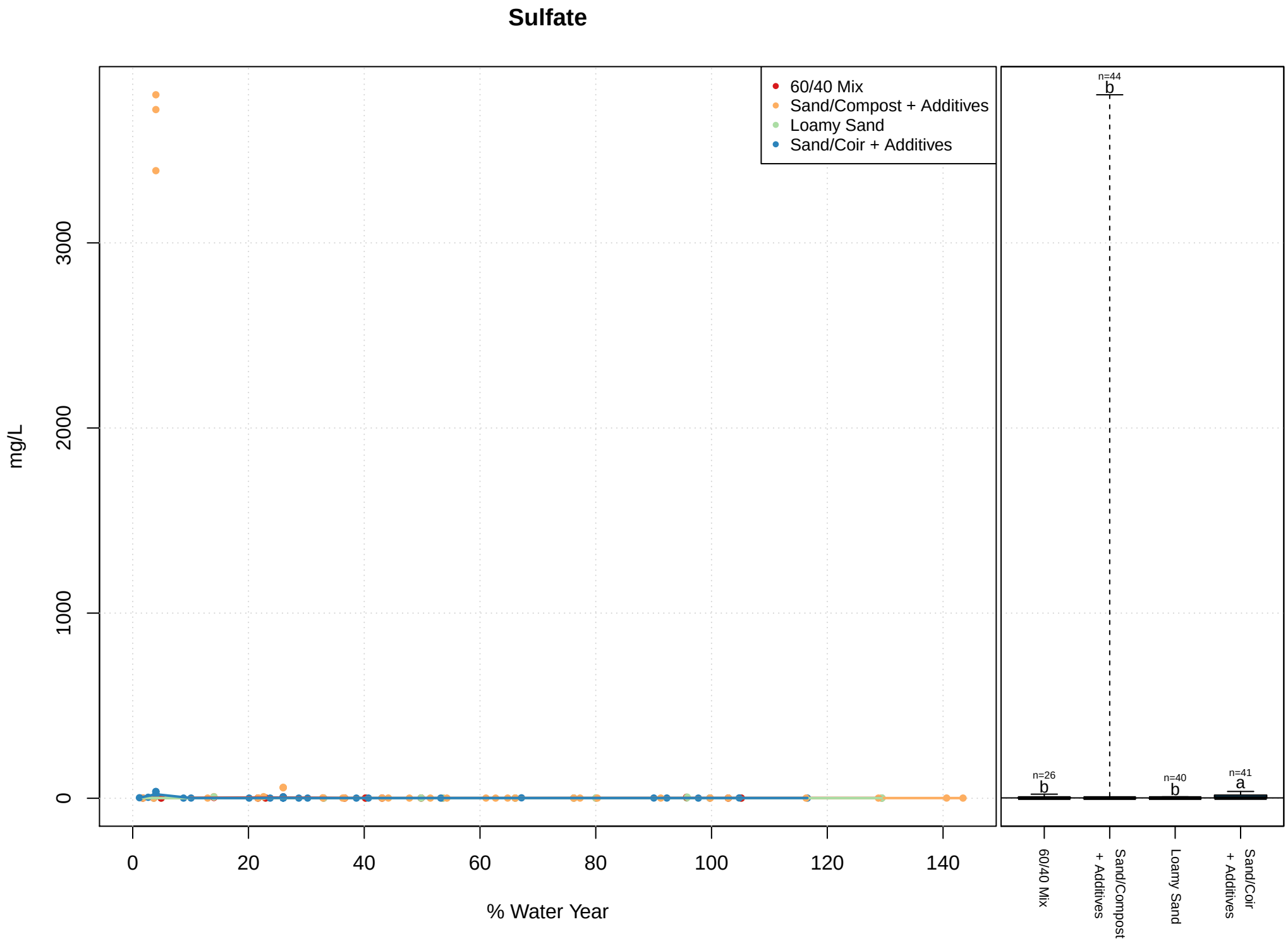


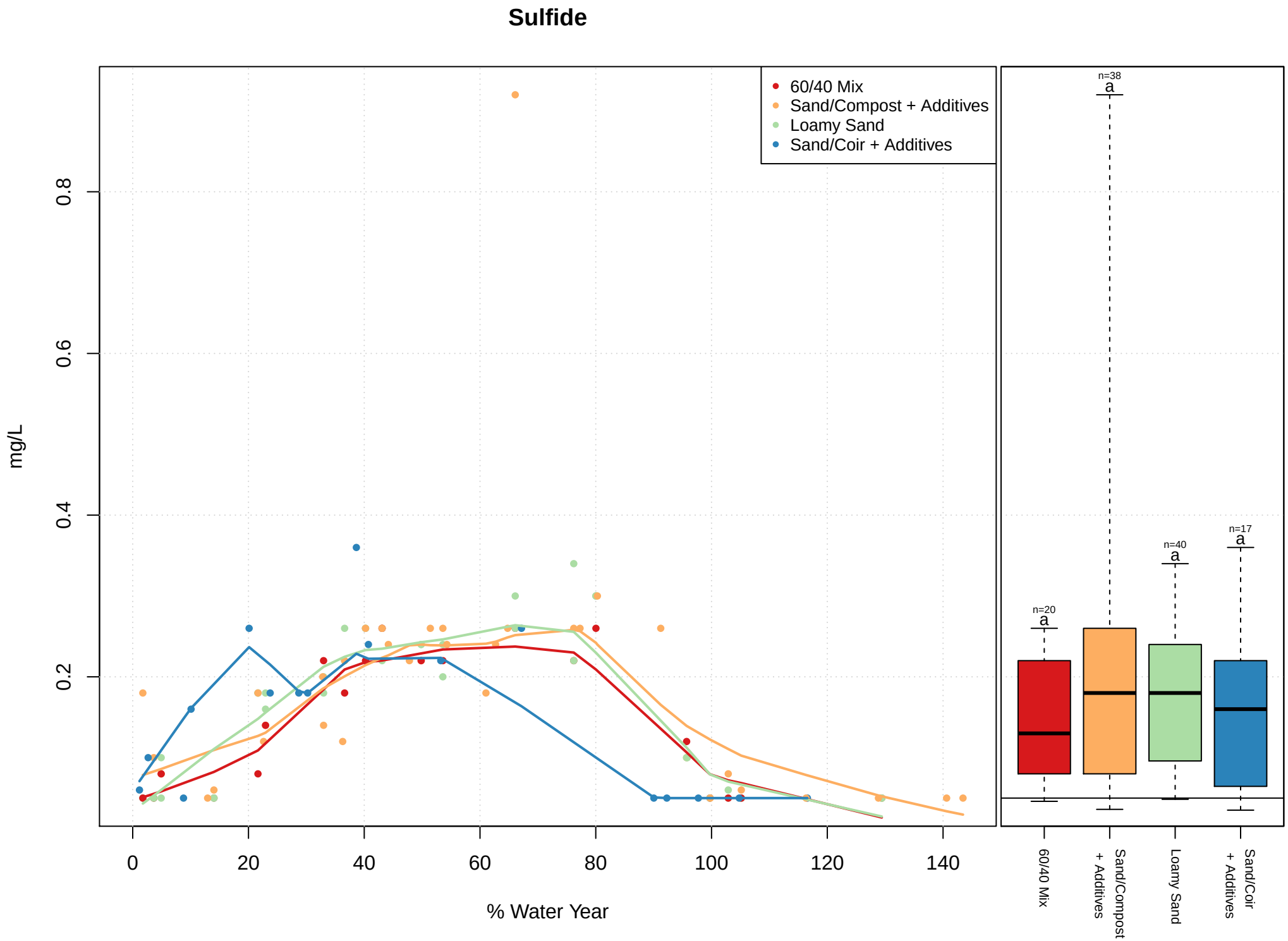

pH
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
pH units
8.0
7.5
7.0
6.5
6.0
0
100
200
300
400
% Water Year
n=89
ab
n=54
a
n=40
ab
n=17
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

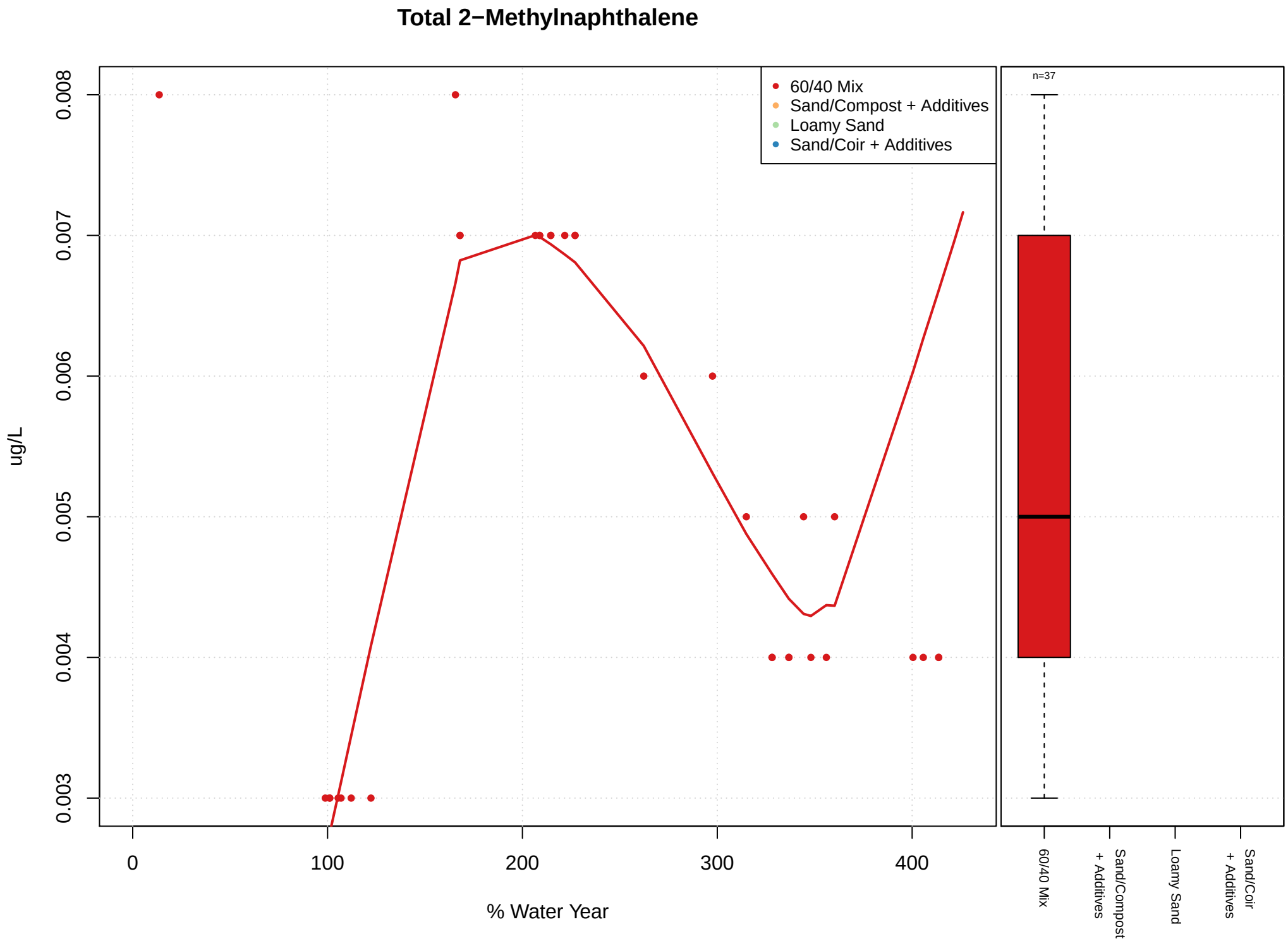

SSC
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
35
30
25
20
15
10
0
50
100
150
% Water Year
n=8
a
n=8
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


SSL−Coarse > 75um
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
5
10
15
20
25
0
50
100
150
200
% Water Year
n=40
a
n=37
a
n=40
a
n=15
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

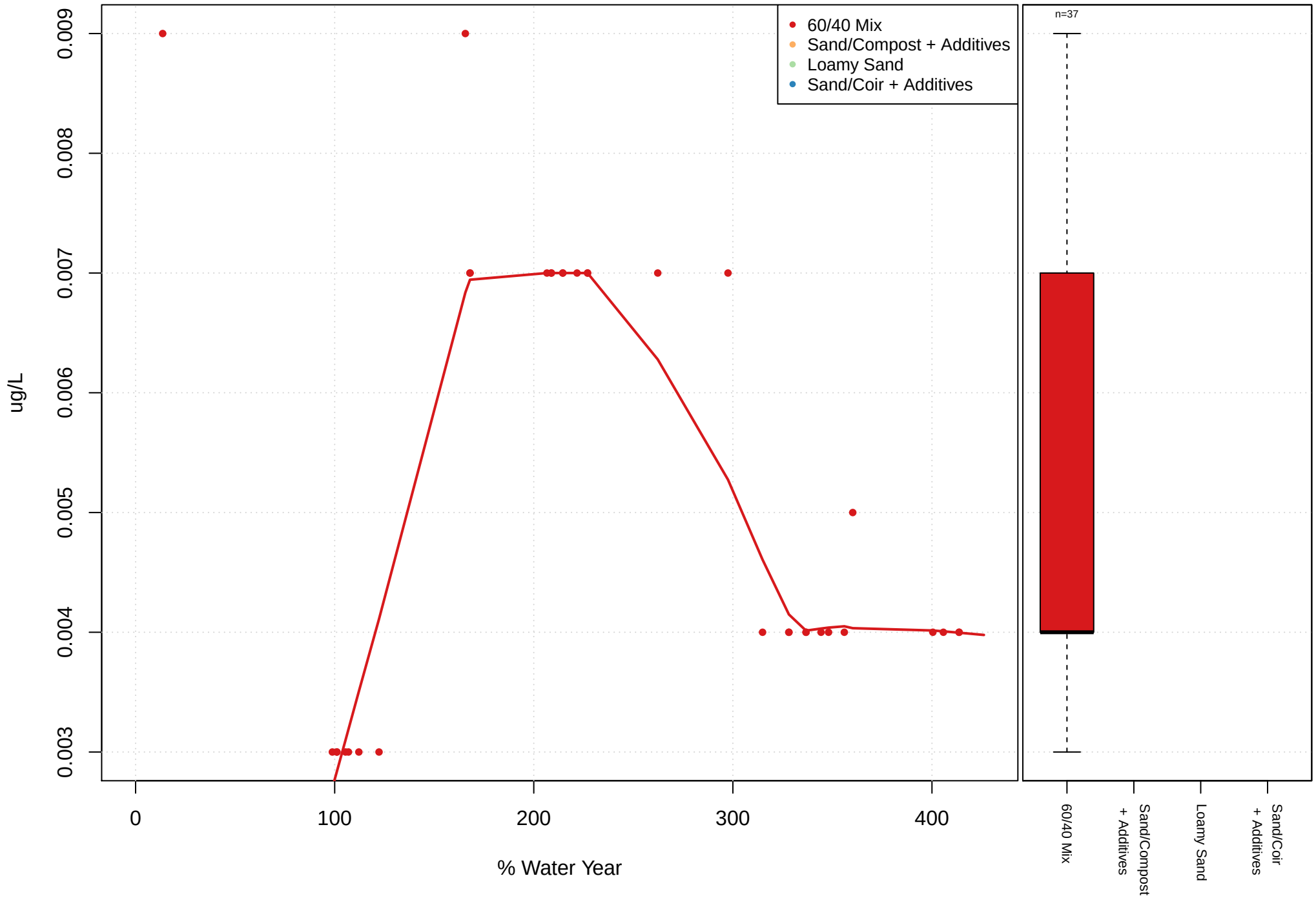

SSL−Fine < 75um
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
% Water Year
0
50
100
150
200
250
300
n=40
a
n=37
a
n=40
a
n=15
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Sulfate
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
1000
2000
3000
0
20
40
60
80
100
120
140
% Water Year
n=26
b
n=44
b
n=40
b
n=41
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

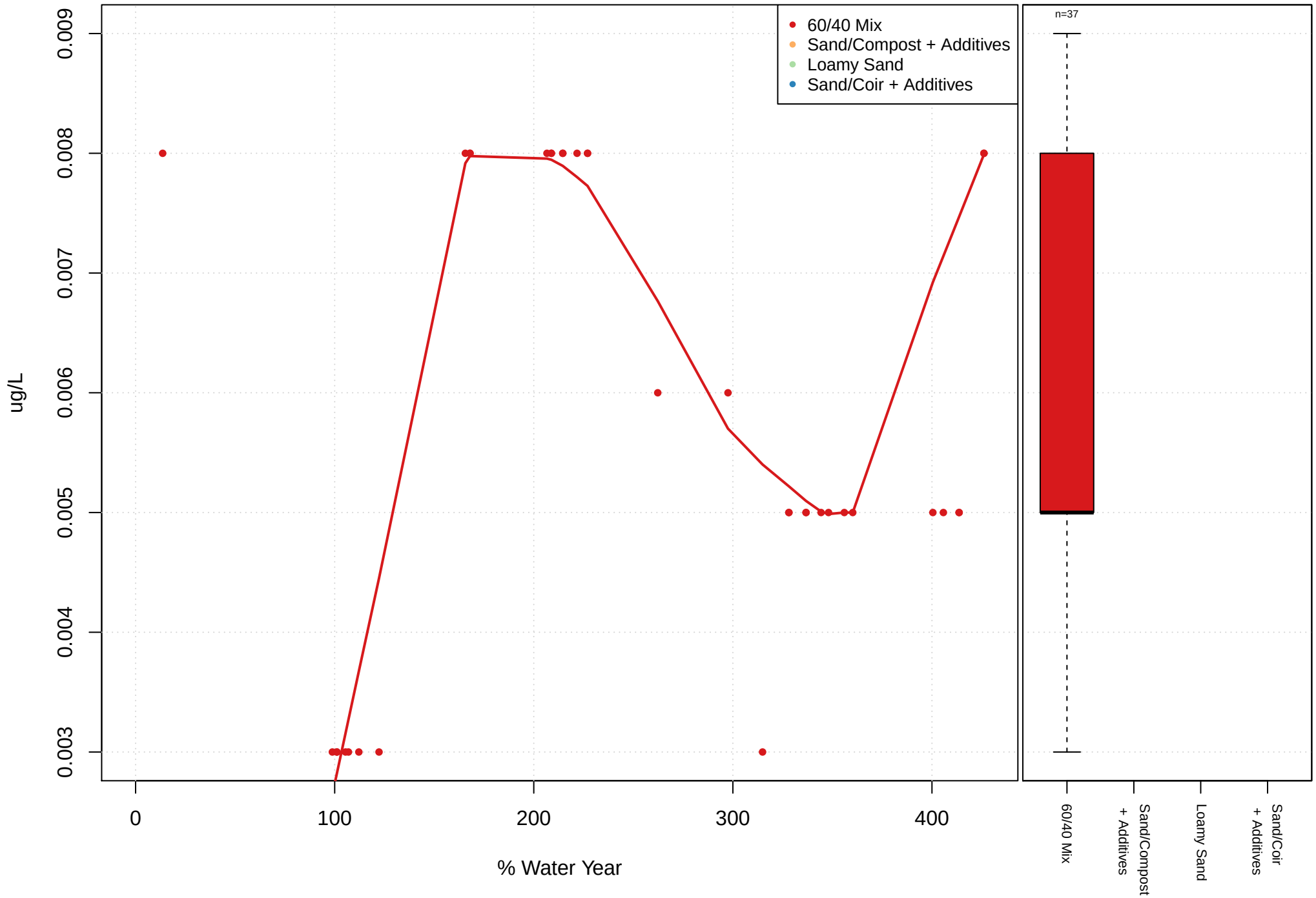

Sulfide
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0.2
0.4
0.6
0.8
0
20
40
60
80
100
120
140
% Water Year
n=20
a
n=38
a
n=40
a
n=17
a
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Total 2−Methylnaphthalene
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=37
ug/L
0.003
0.004
0.005
0.006
0.007
0.008
0
100
200
300
400
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

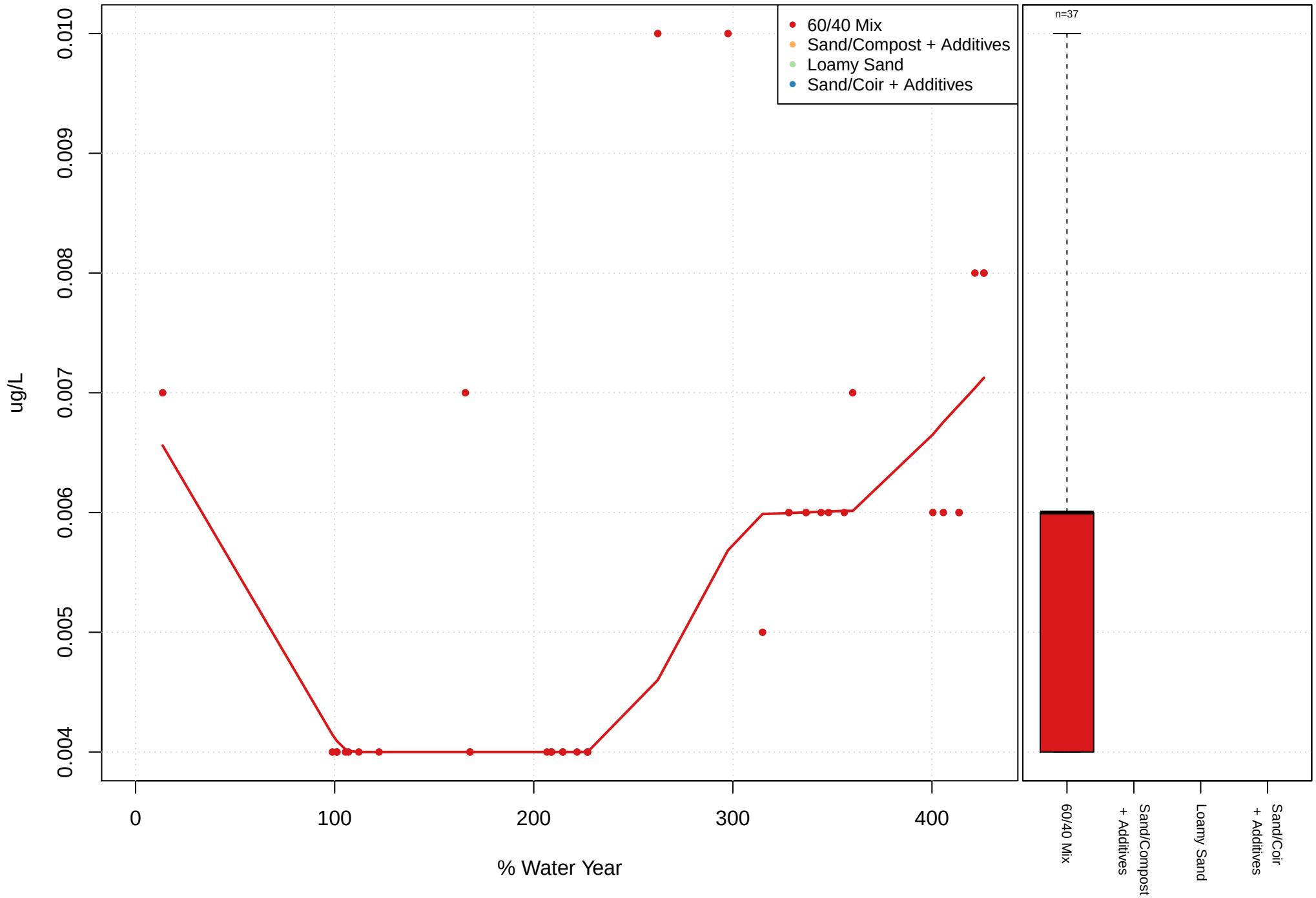
Total Acenaphthene



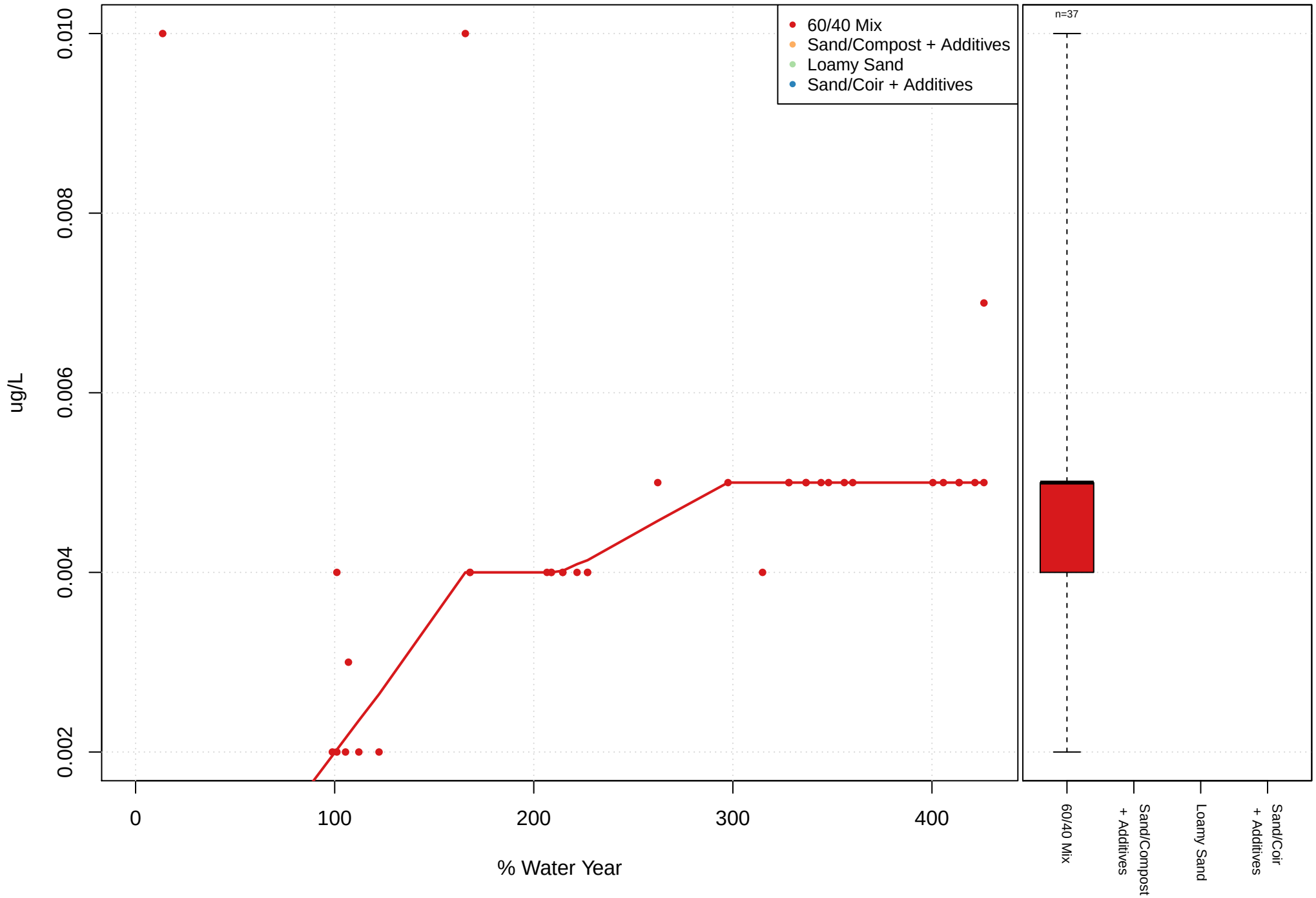
Total Acenaphthylene

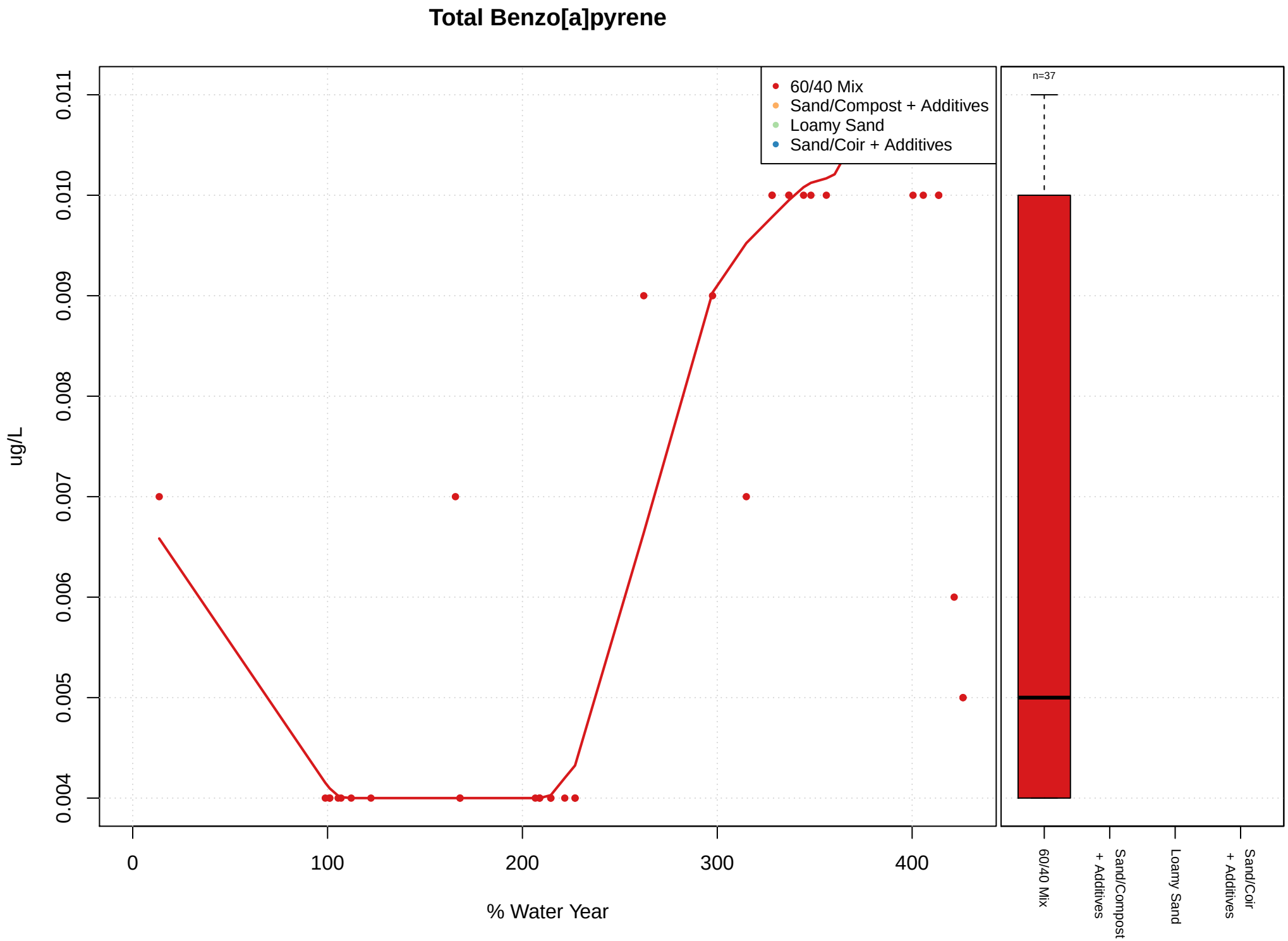


Total Anthracene

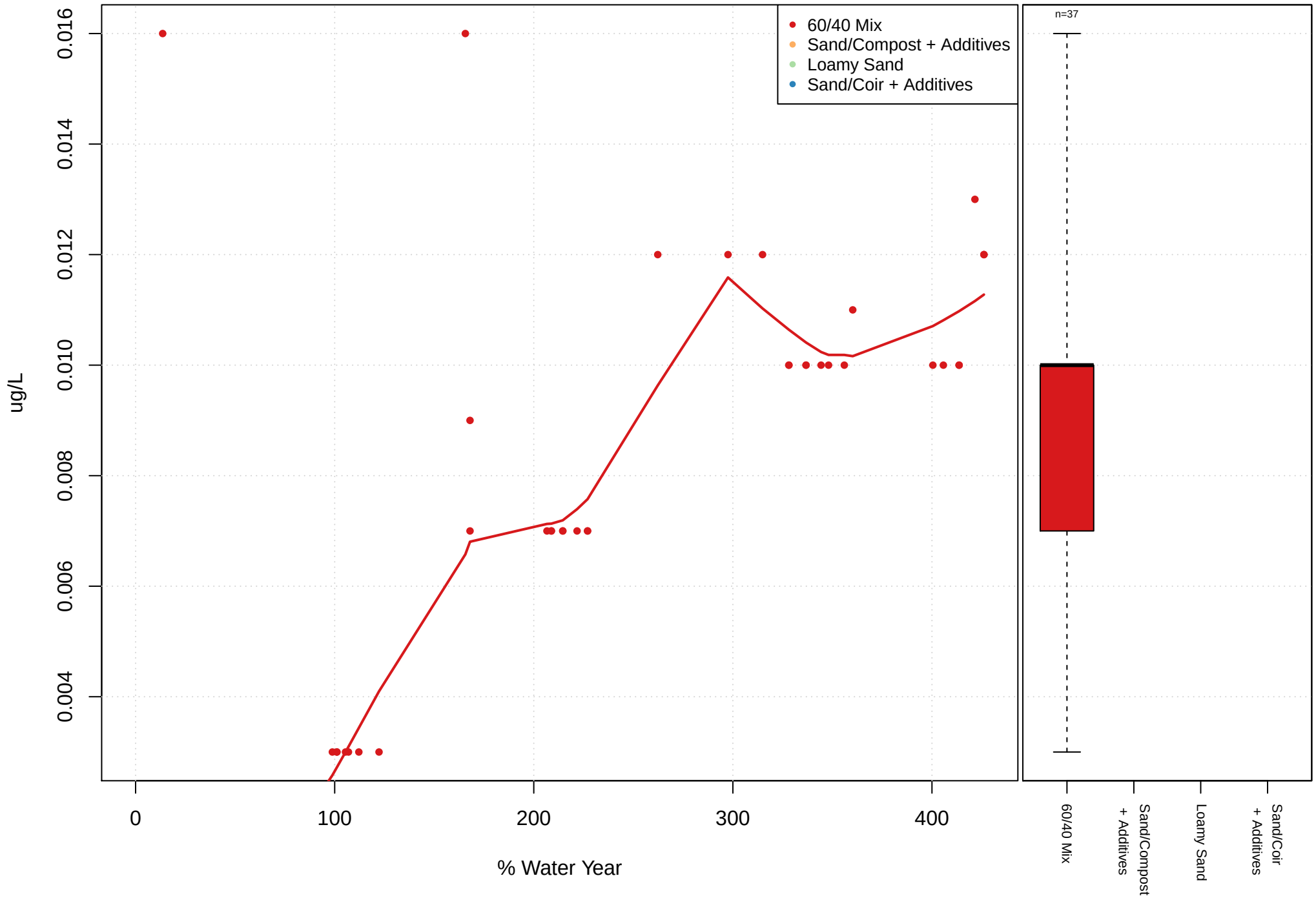


Total Benzo[a]anthracene

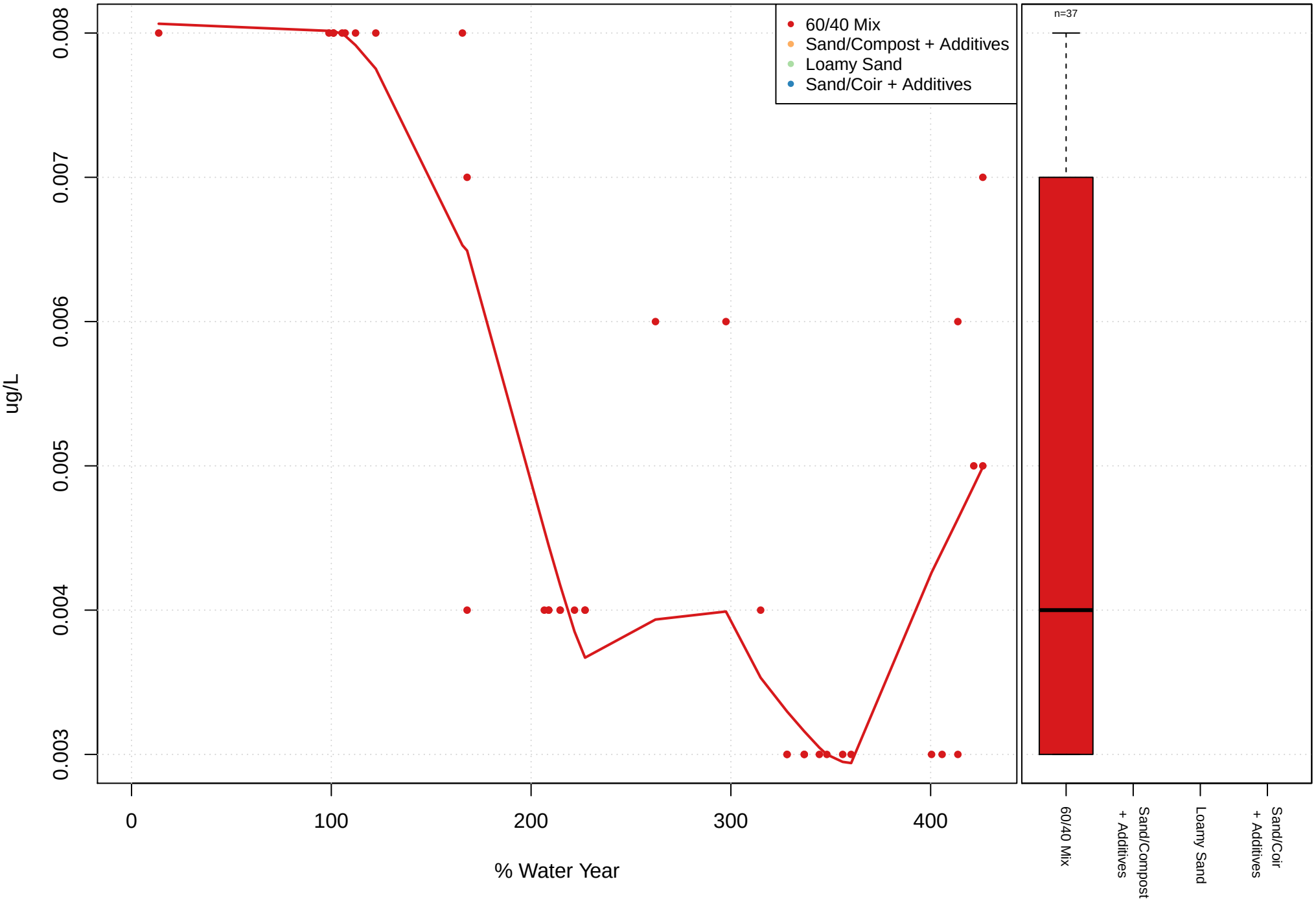



Total Benzo[a]pyrene
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=37
ug/L
0.004
0.005
0.006
0.007
0.008
0.009
0.010
0.011
0
100
200
300
400
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

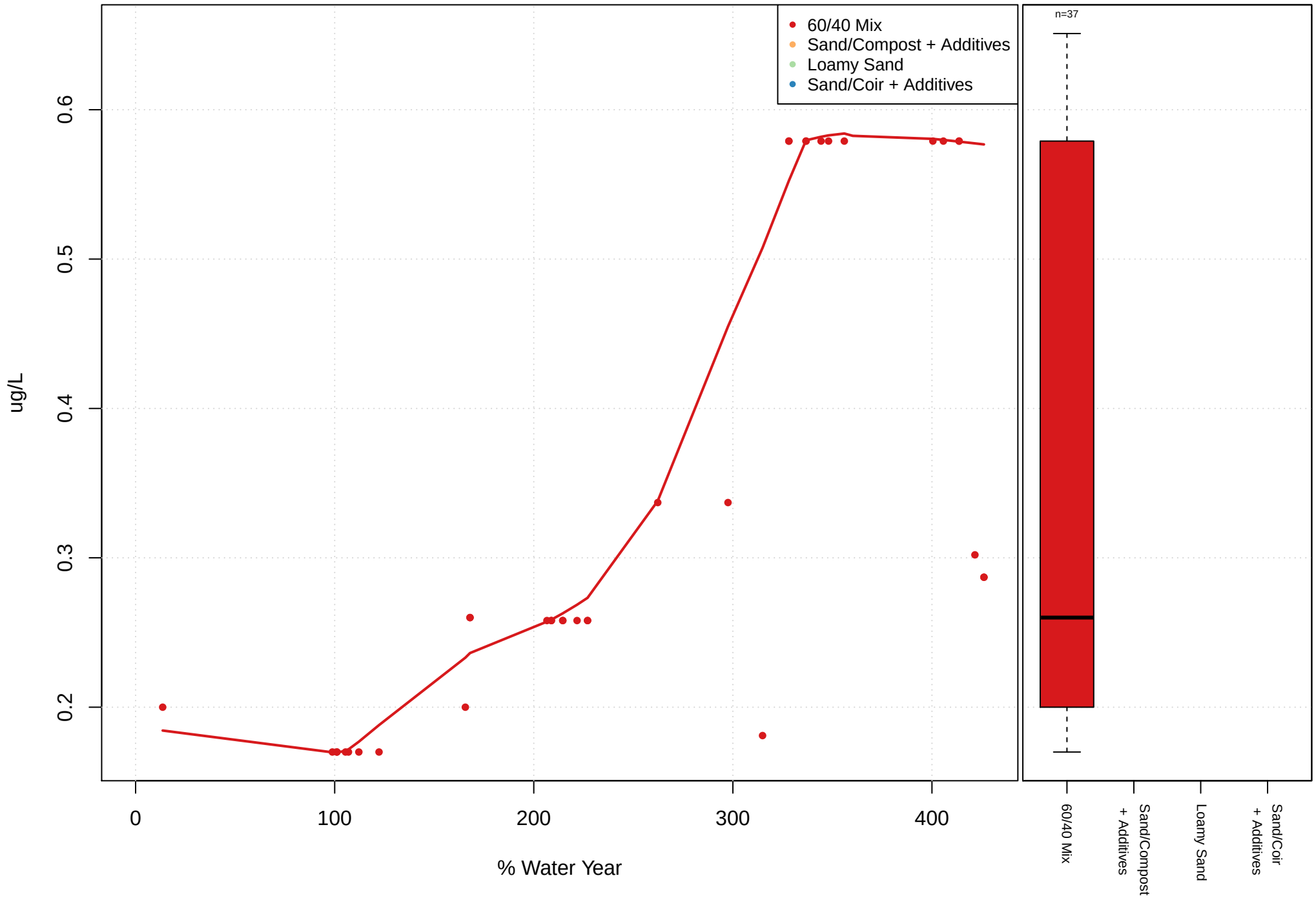
Total Benzo[bk]fluoranthene



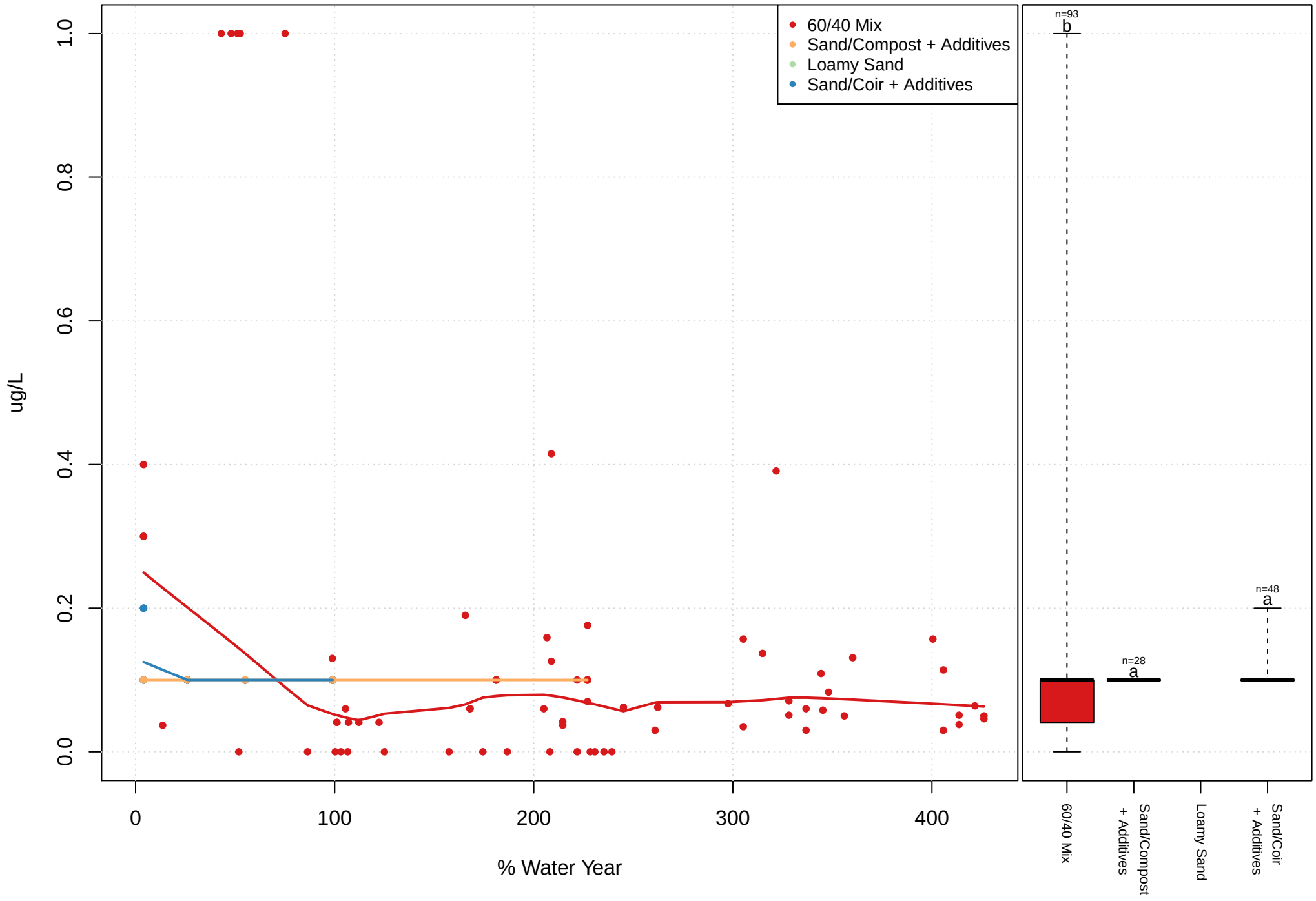
Total Benzo[ghi]perylene

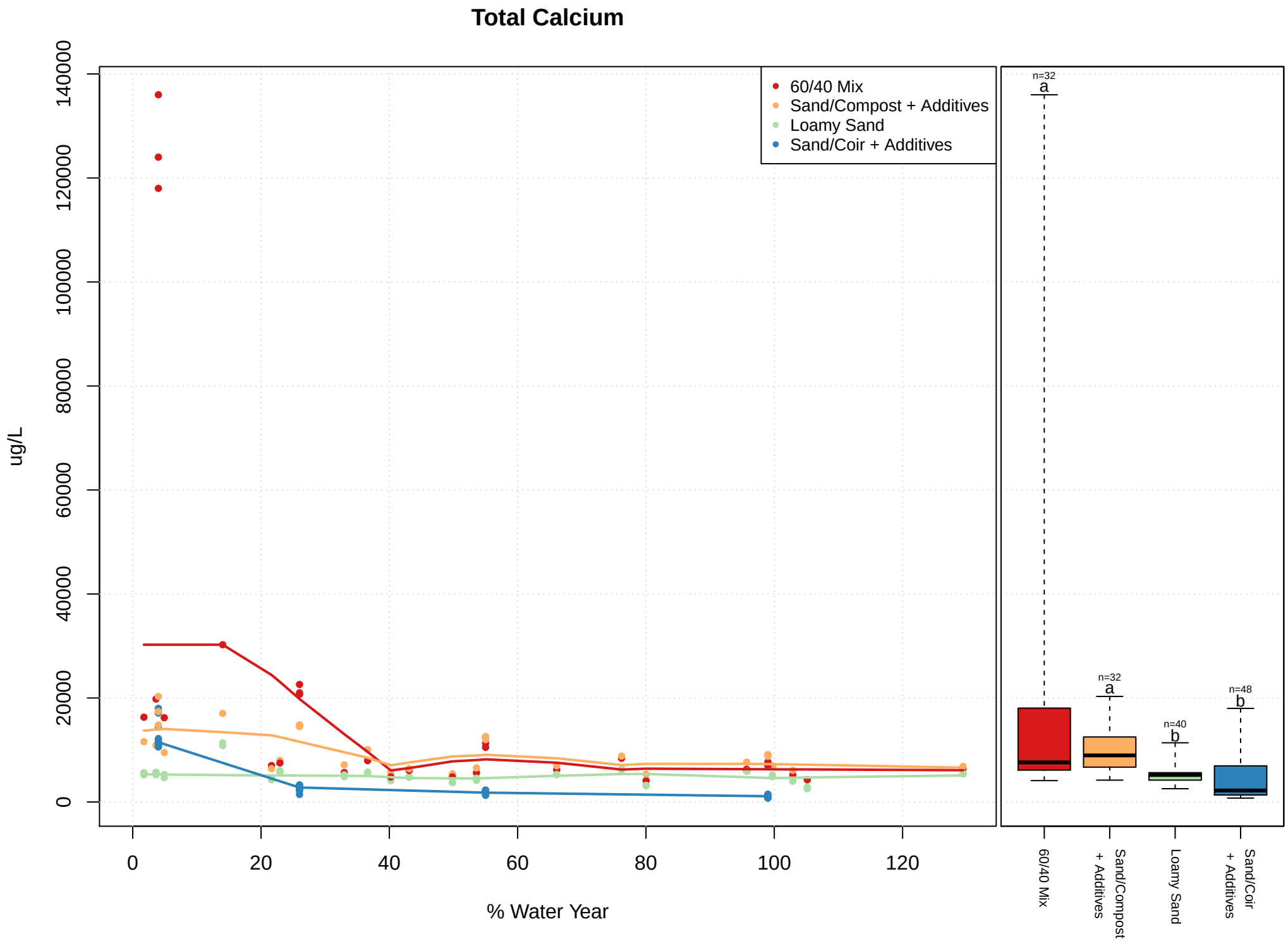


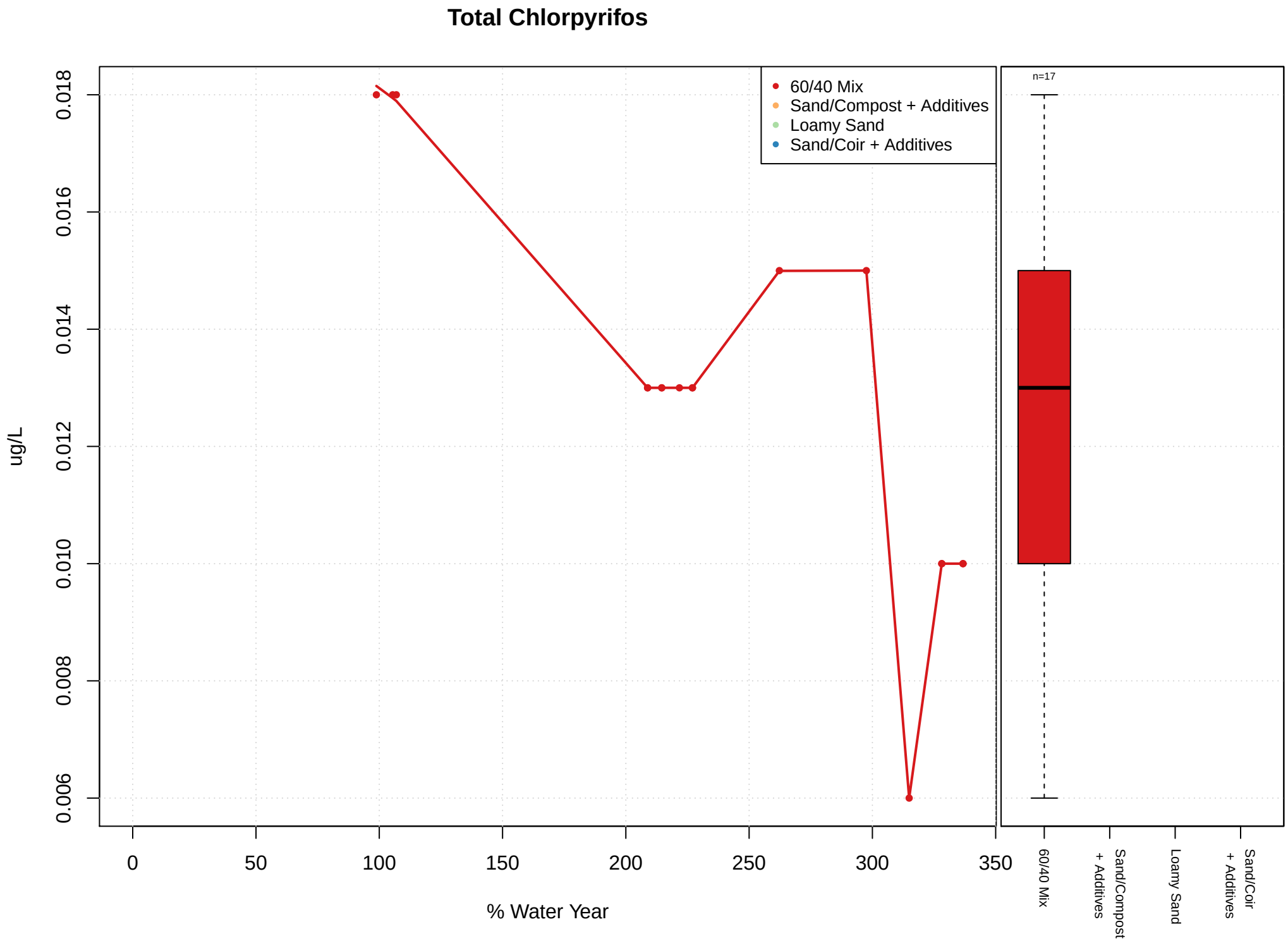
Total Butyl benzyl phthalate



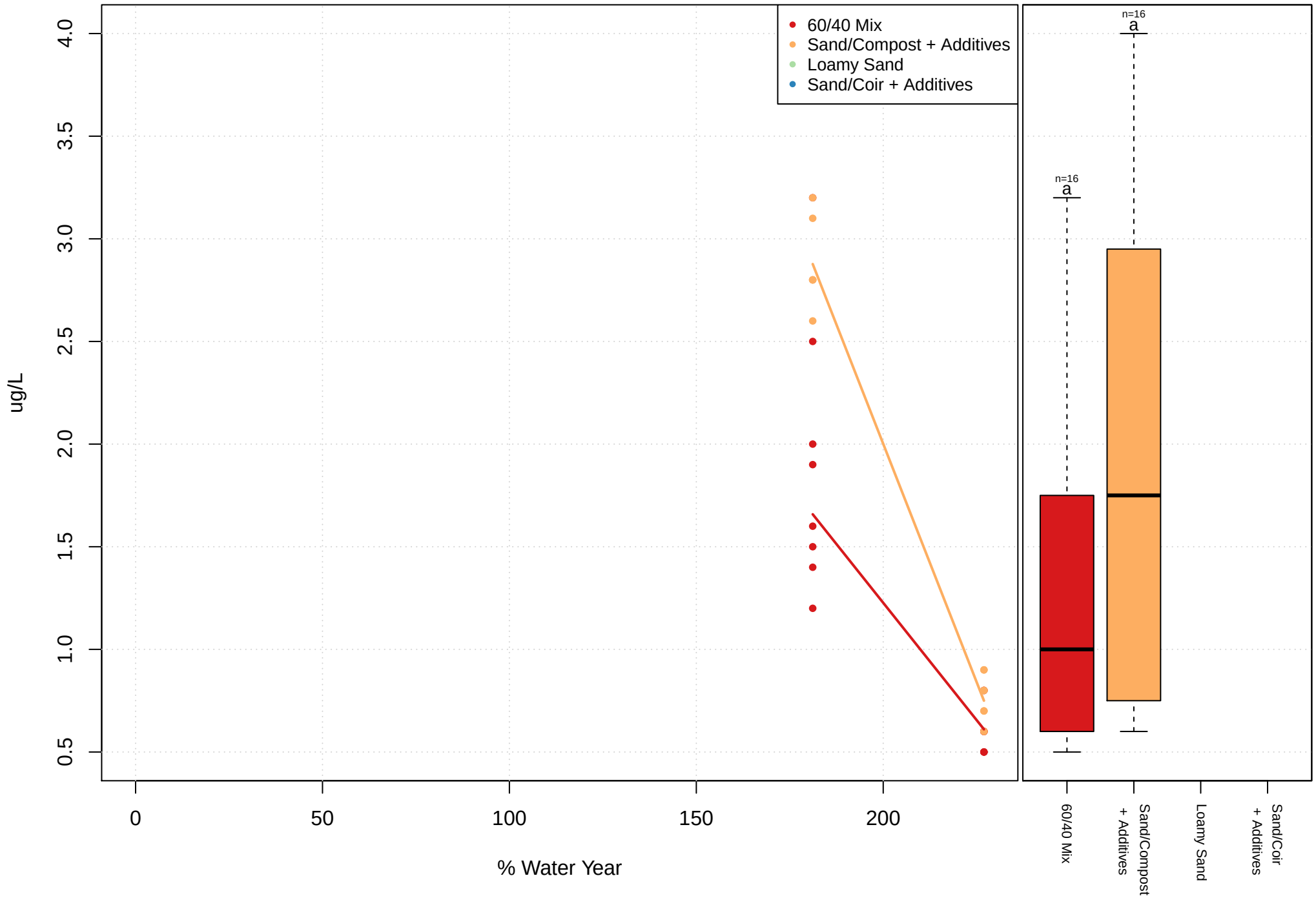
Total Cadmium

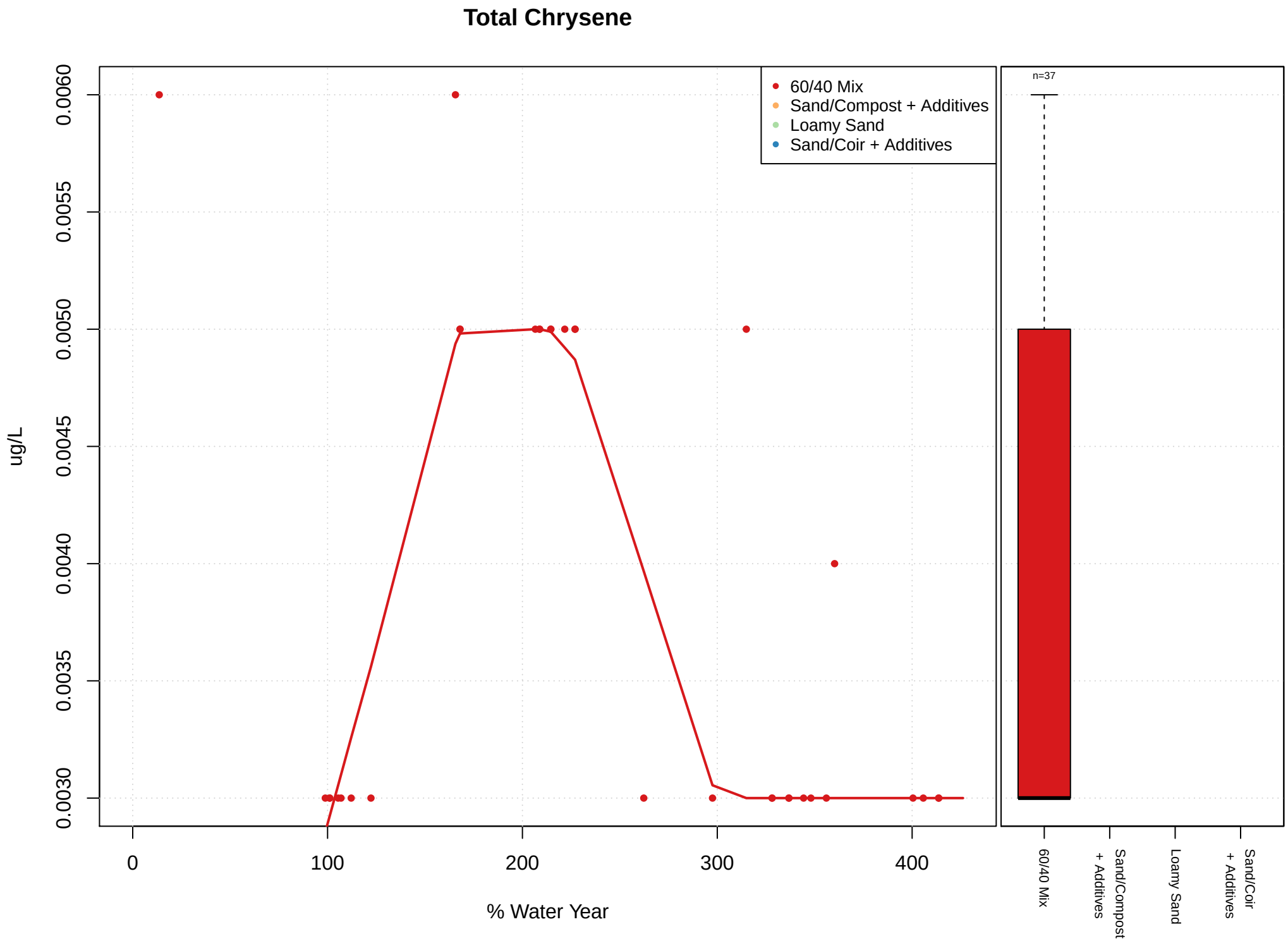


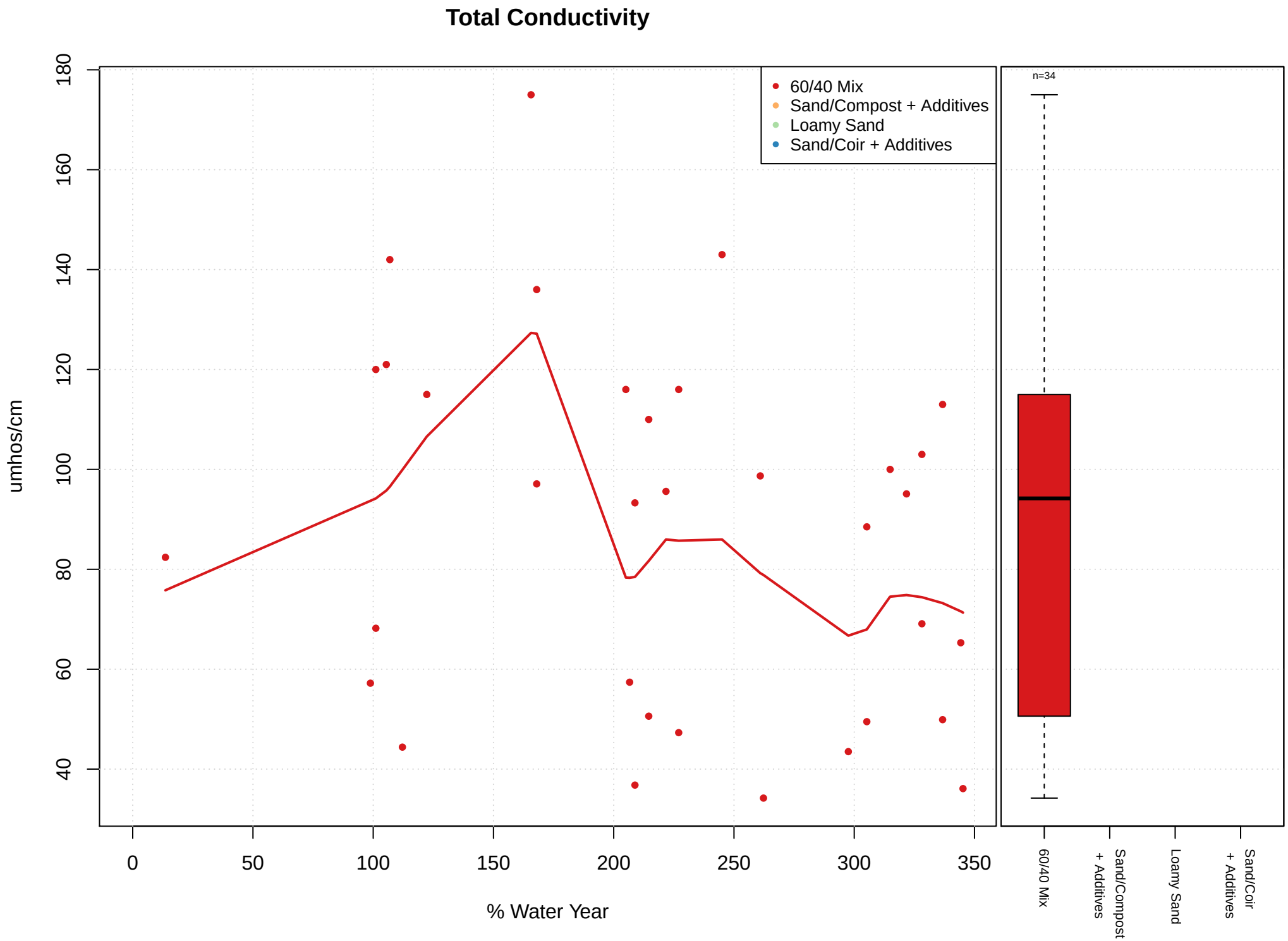

Total Calcium
ug/L
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=32
a
n=32
a
n=40
b
n=48
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Total Chlorpyrifos
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=17
ug/L
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0
50
100
150
200
250
300
350
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

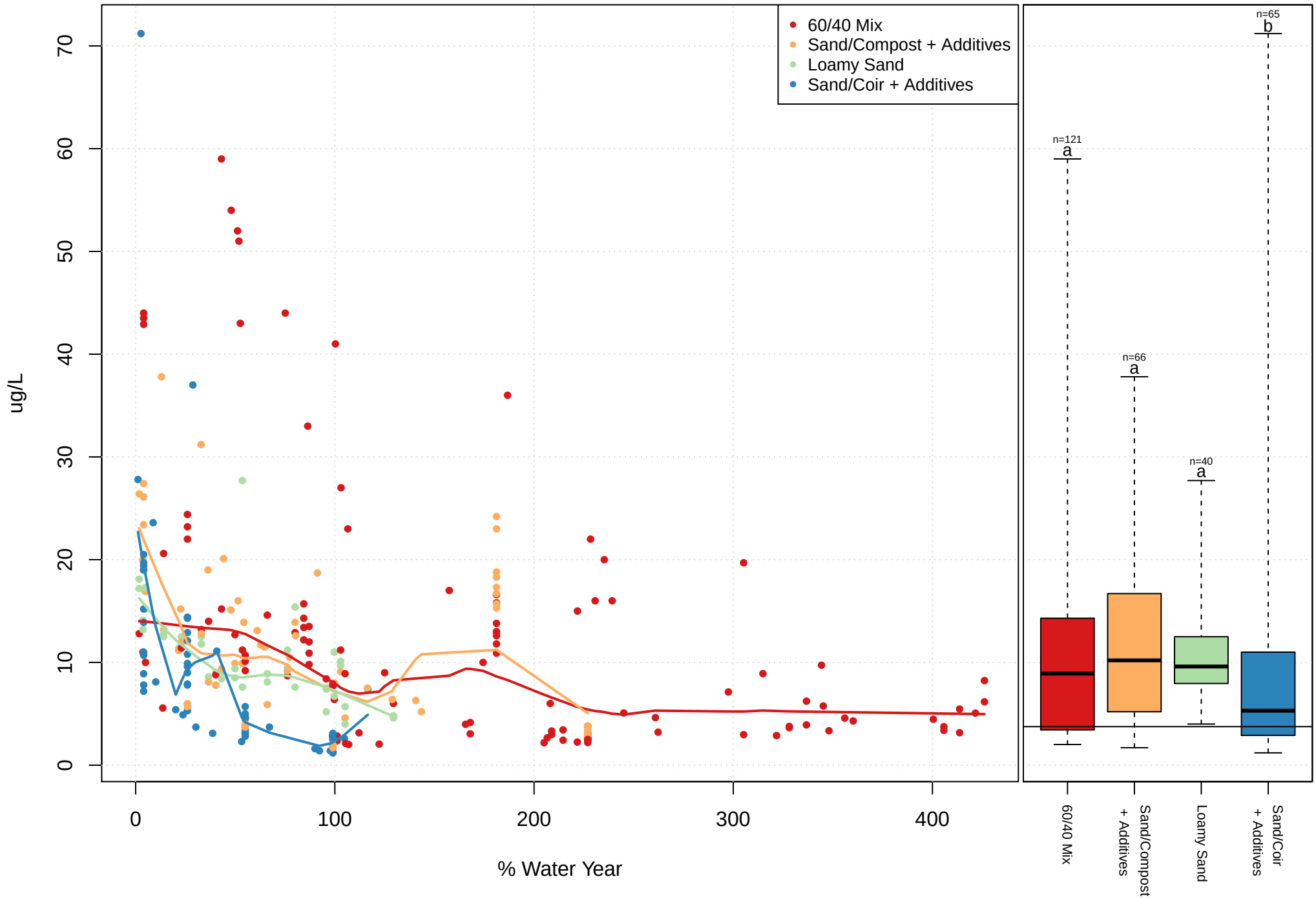
Total Chromium



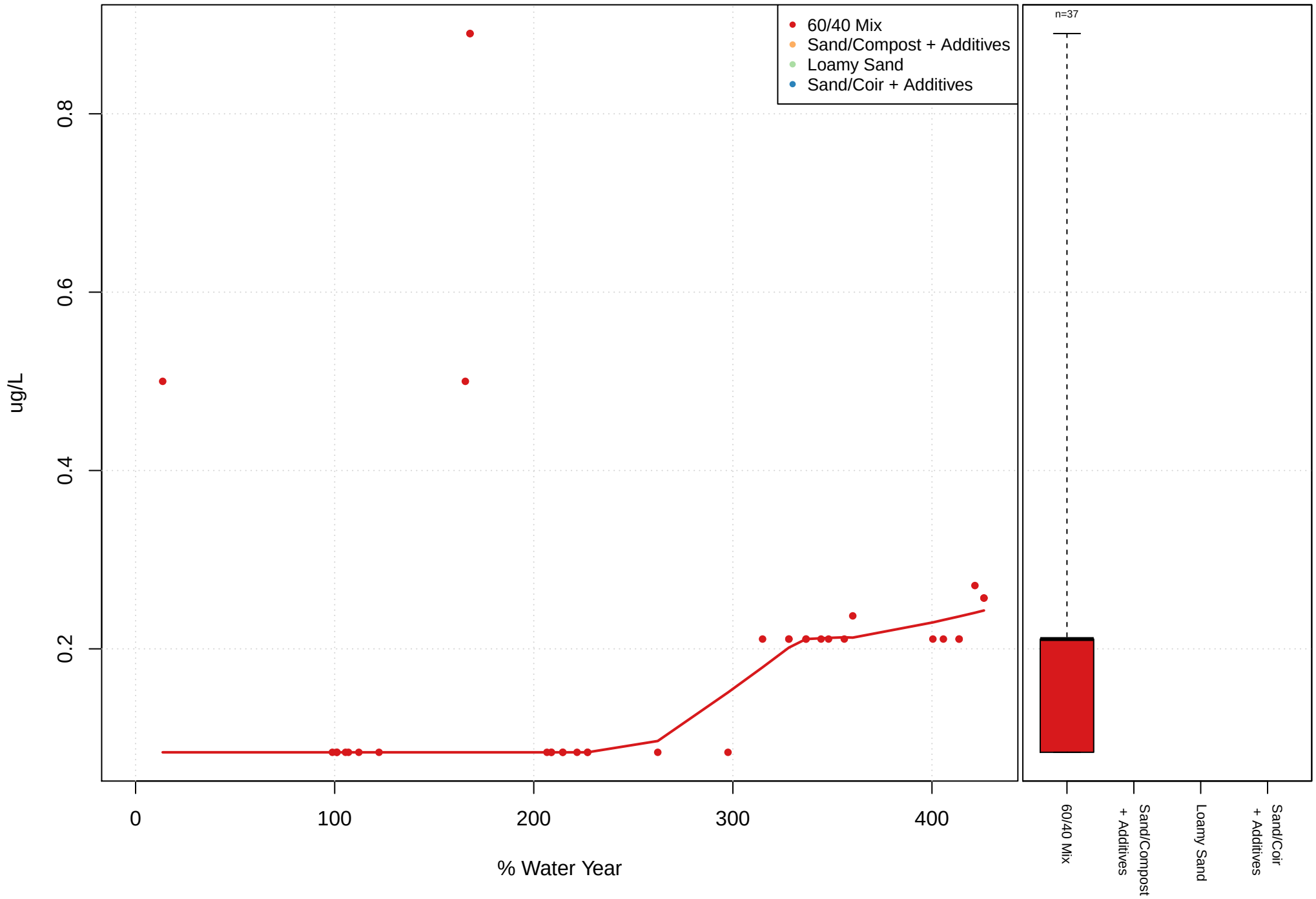

Total Chrysene
ug/L
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
0.0060
0
100
200
300
400
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=37
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Total Conductivity
umhos/cm
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=34
0
50
100
150
200
250
300
350
40
60
80
100
120
140
160
180
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

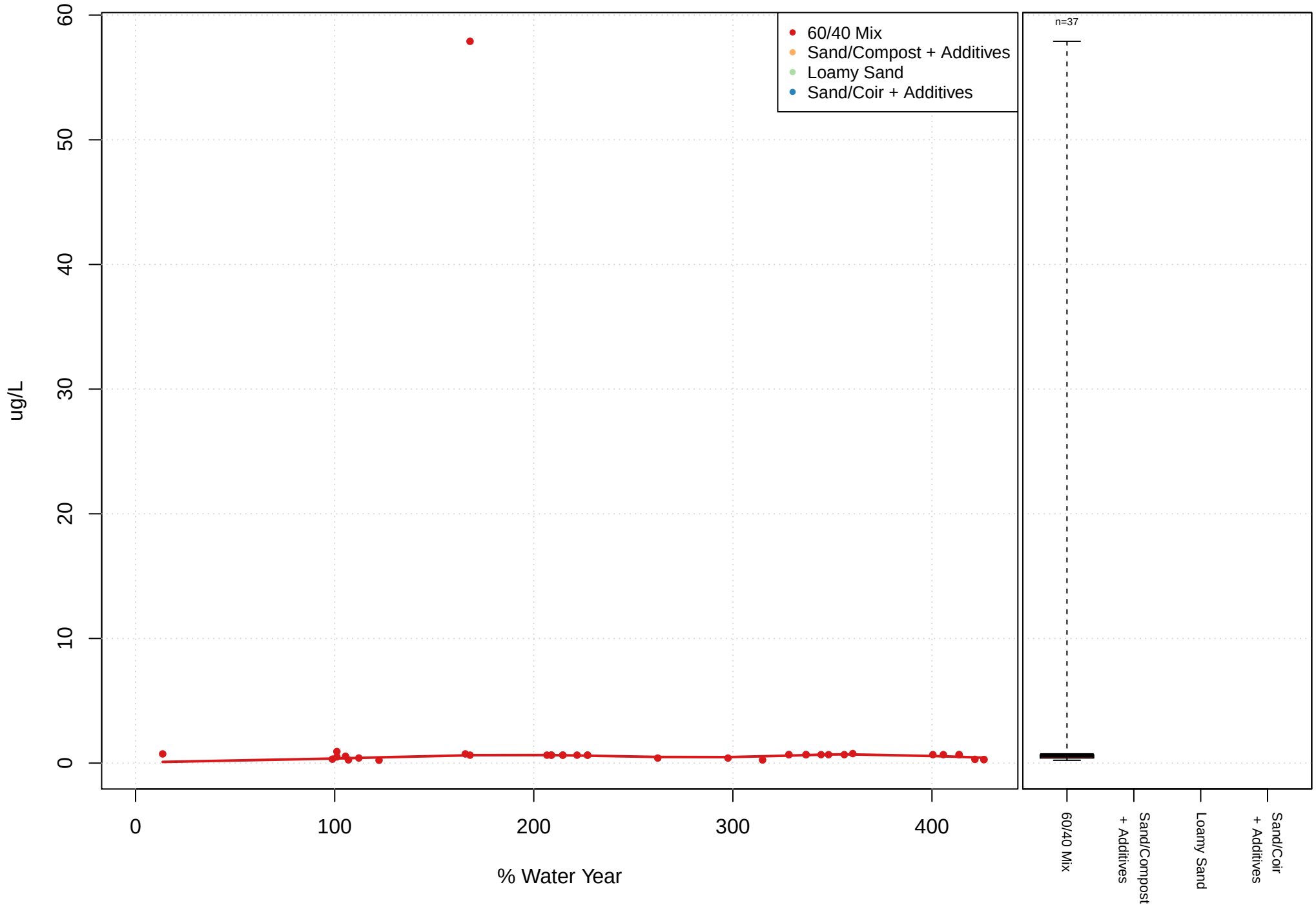
Total Copper



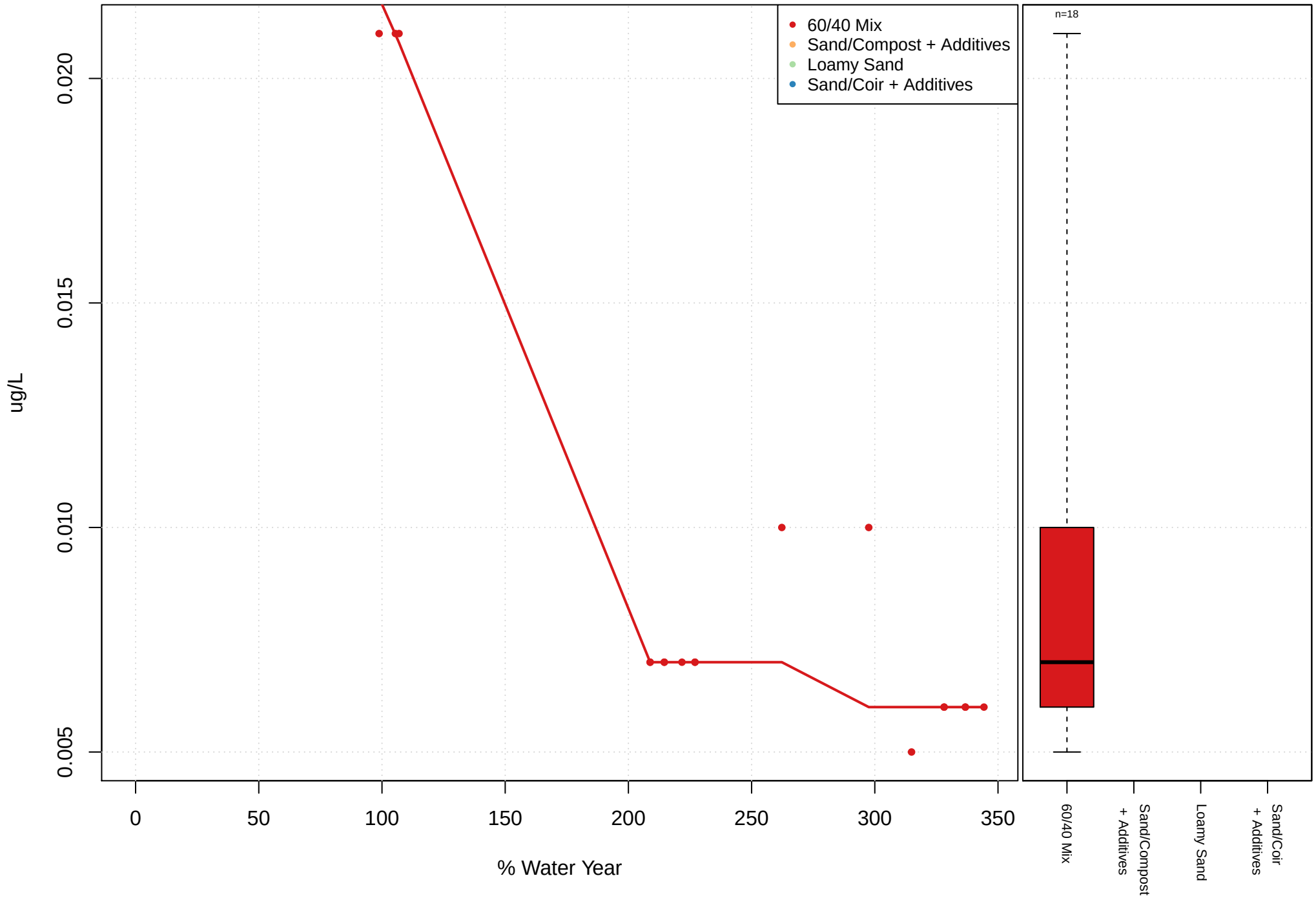
Total Di−n−octyl phthalate



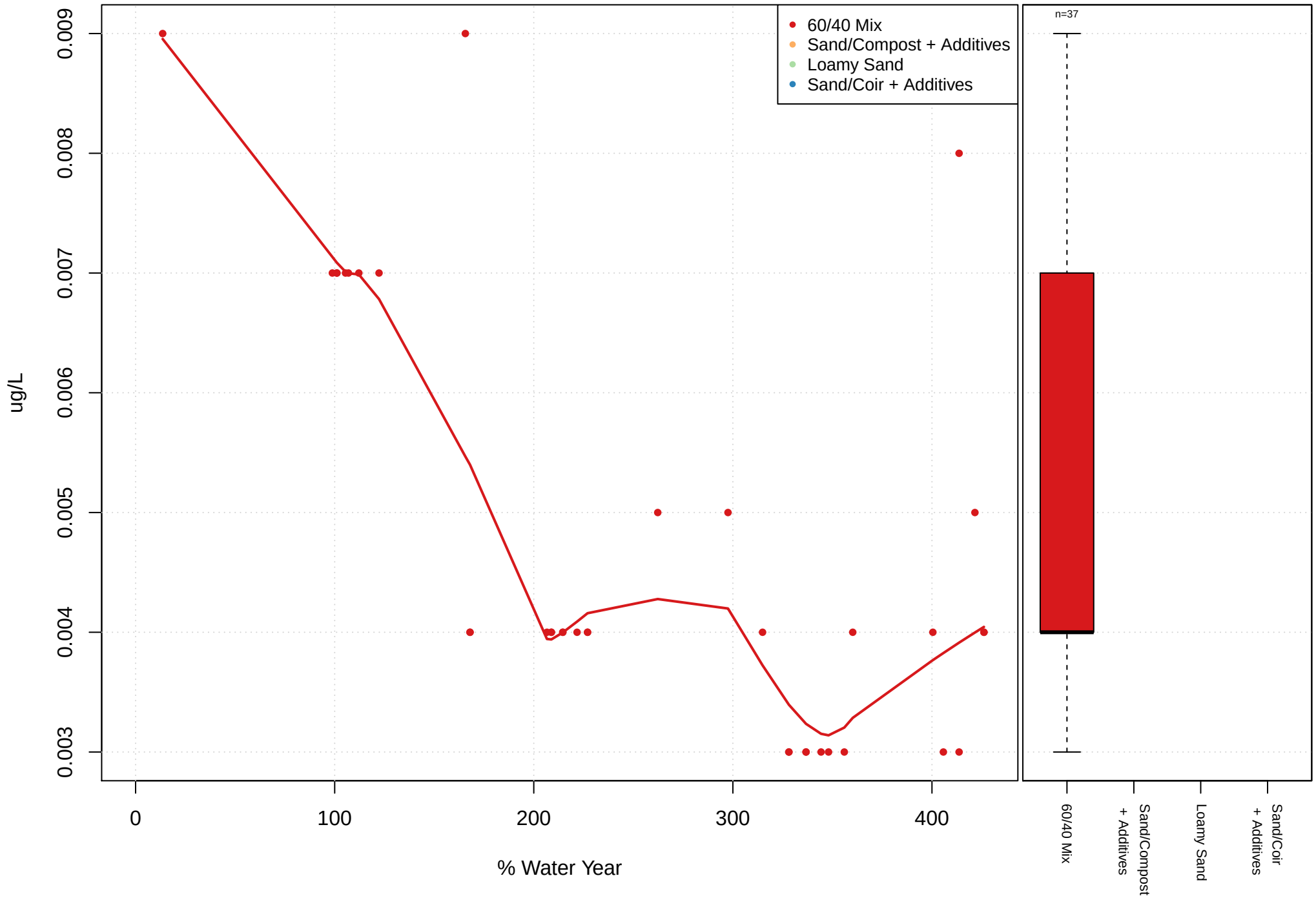
Total Di(2−ethylhexyl) phthalate



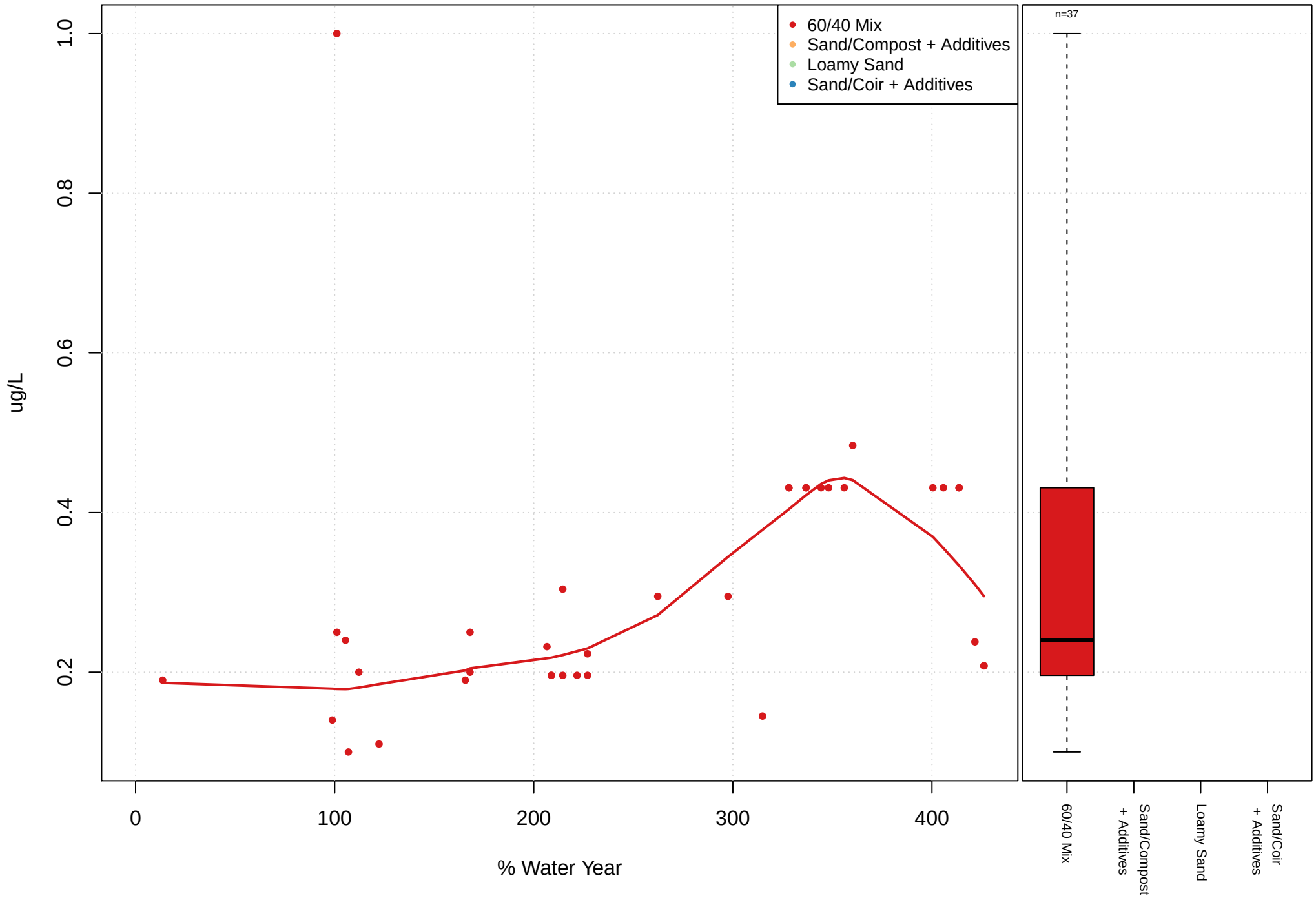
Total Diazinon



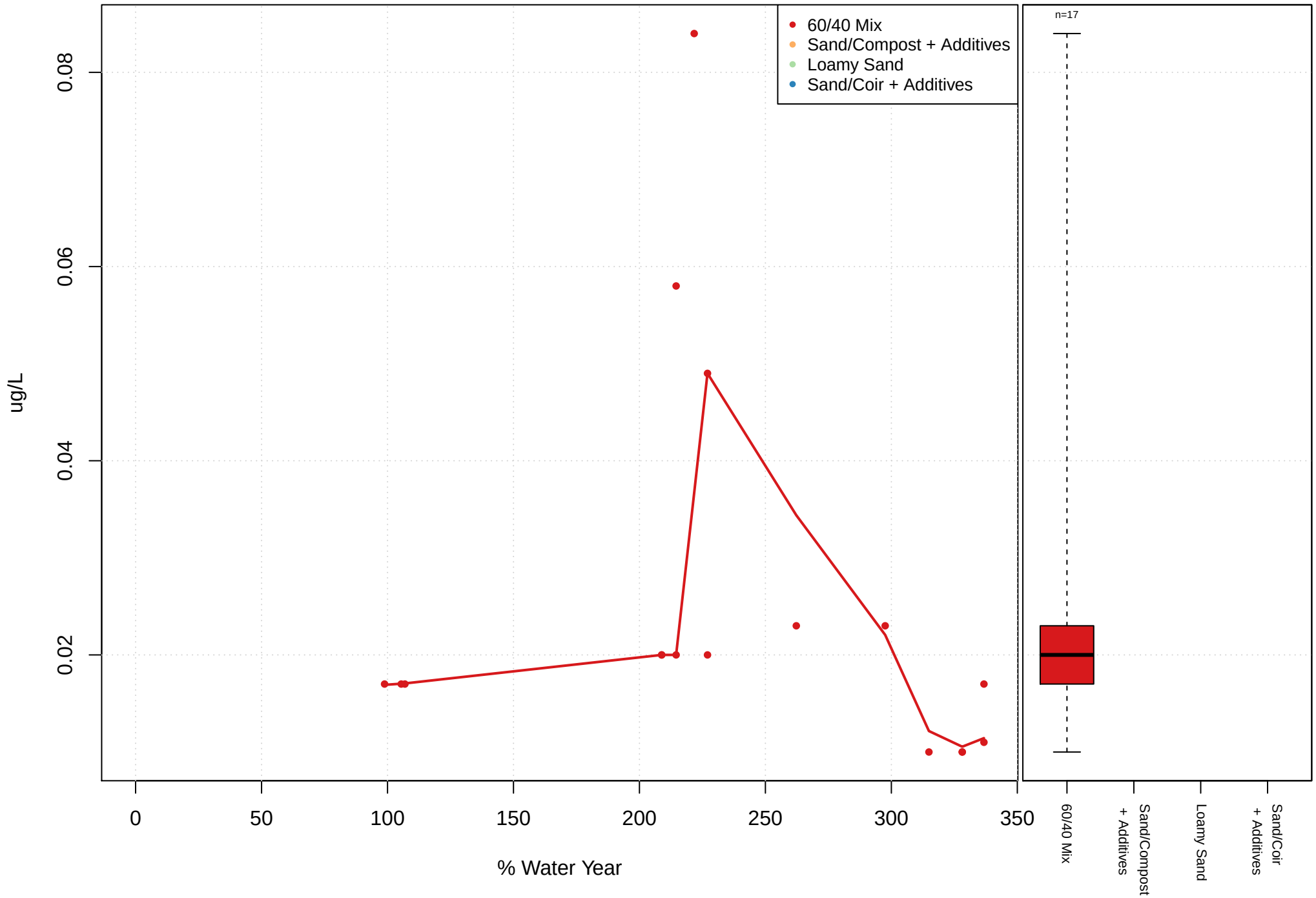
Total Dibenz[a,h]anthracene



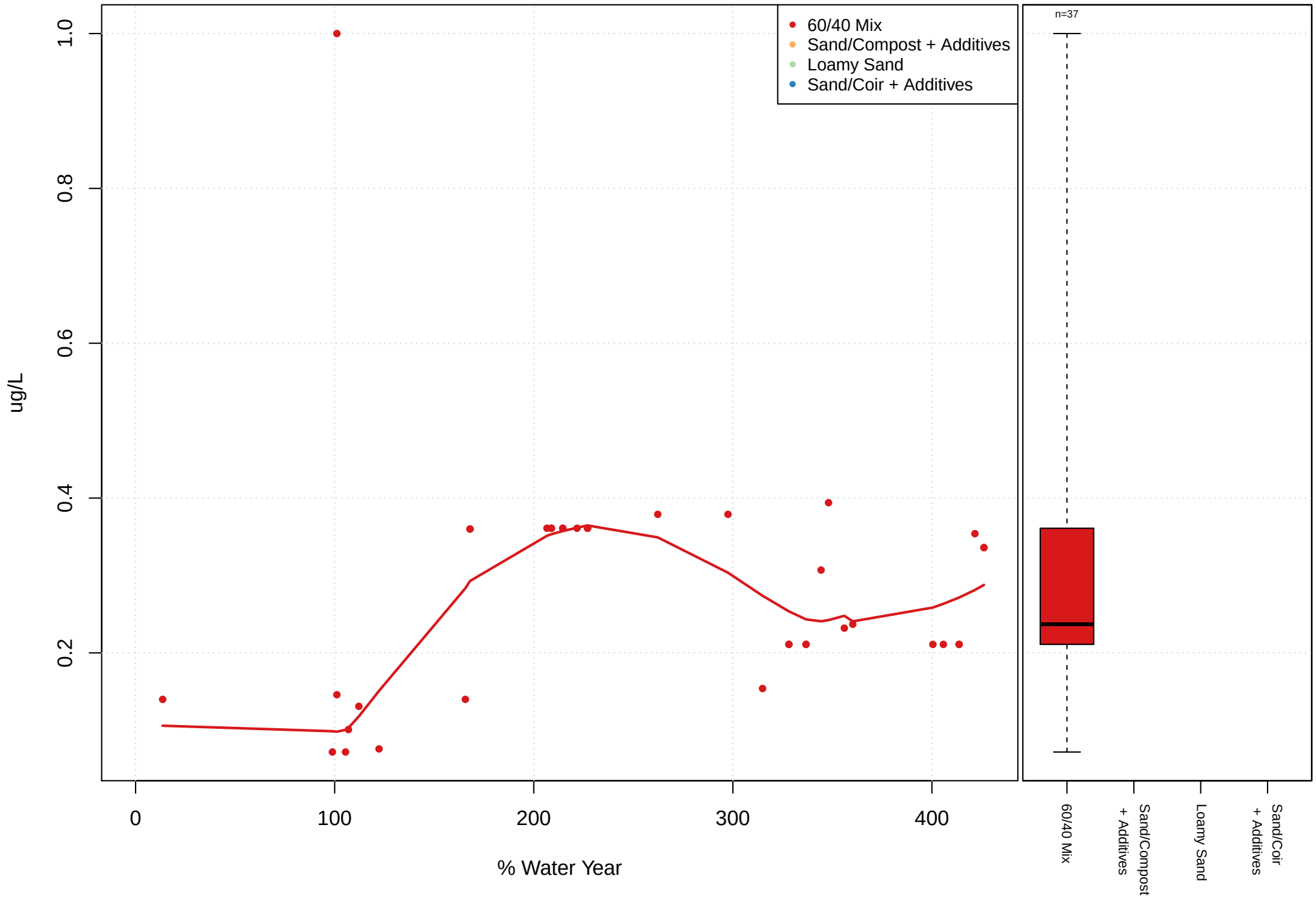
Total Dibutyl phthalate

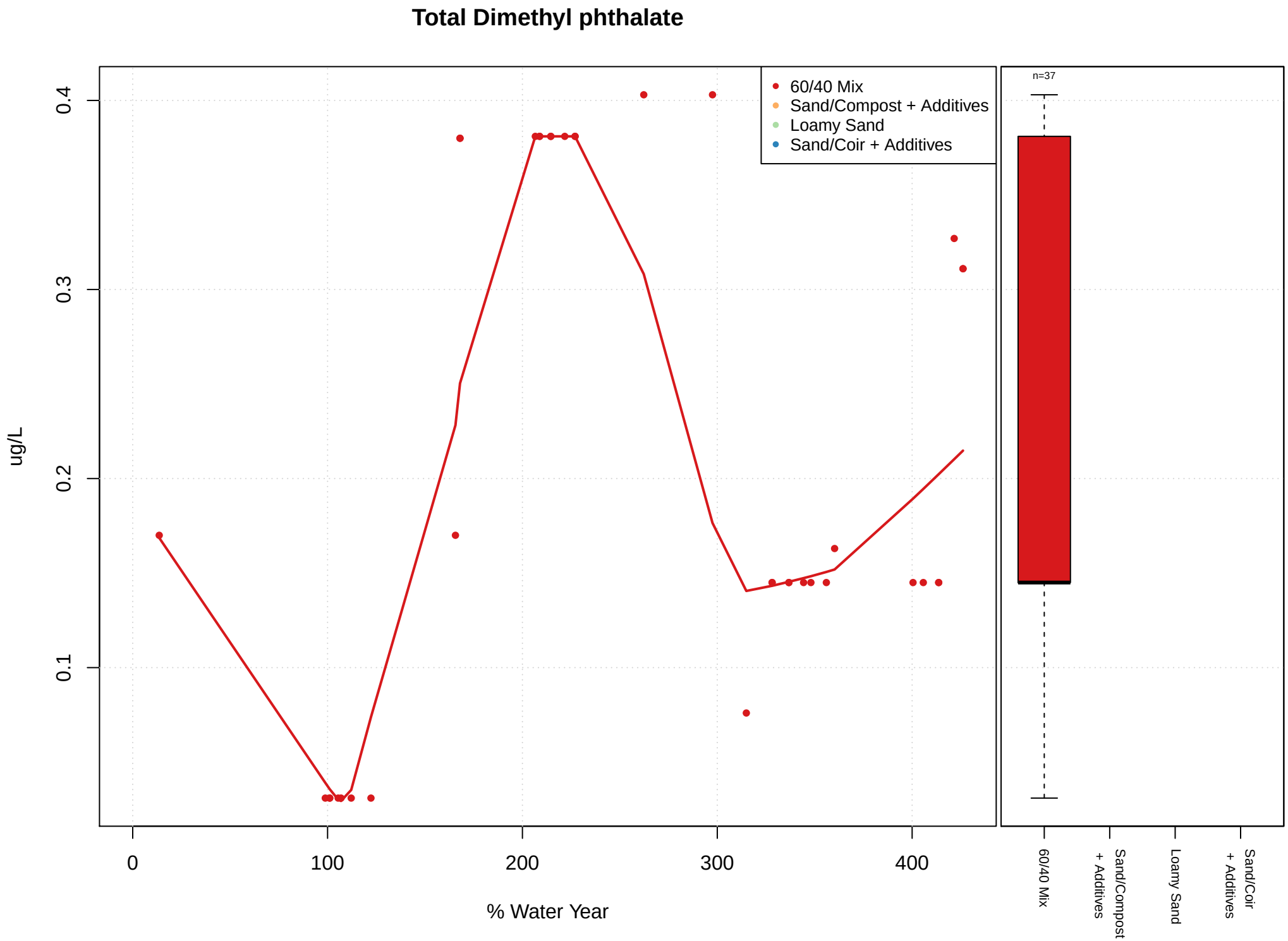


Total Dichlobenil

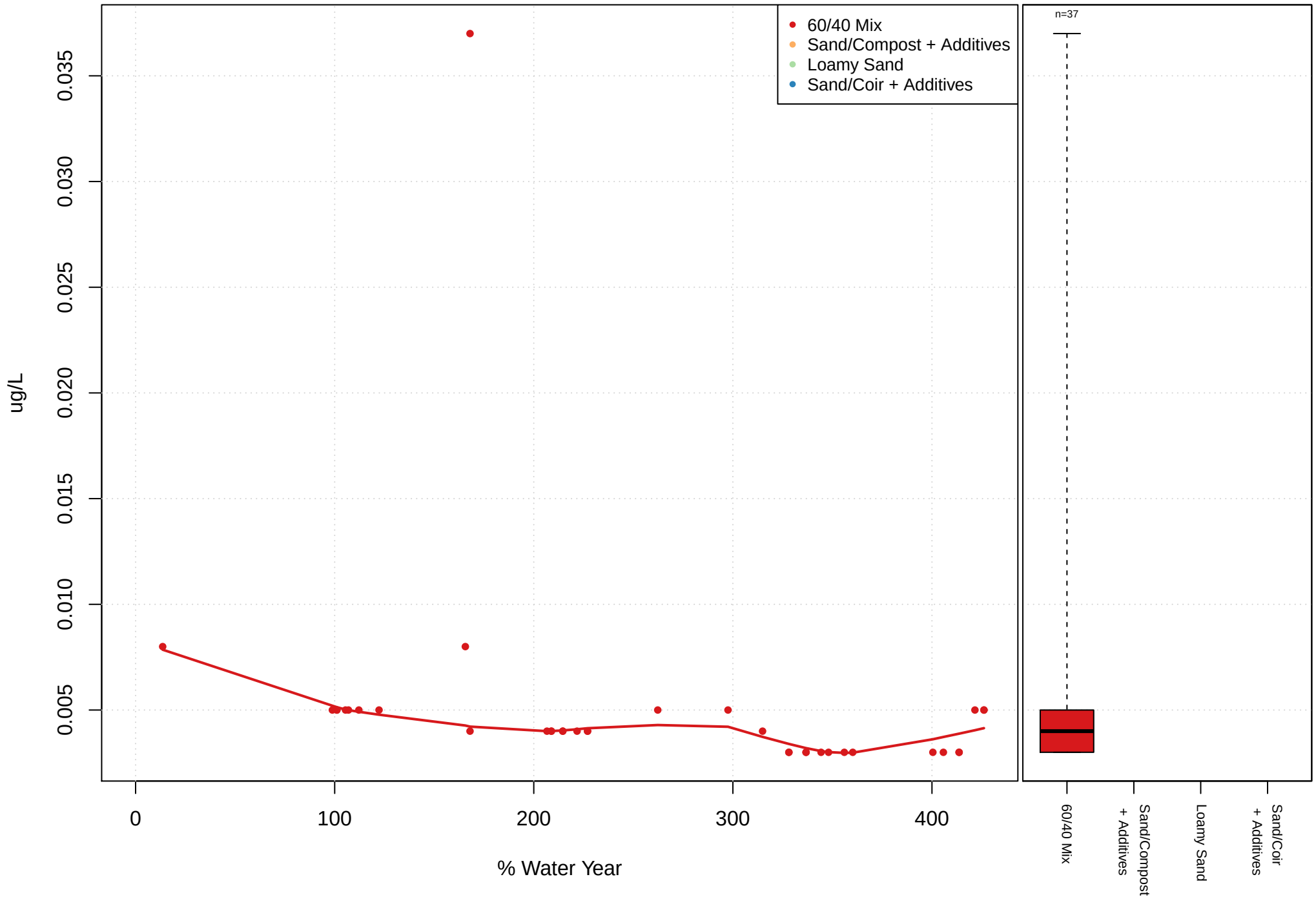


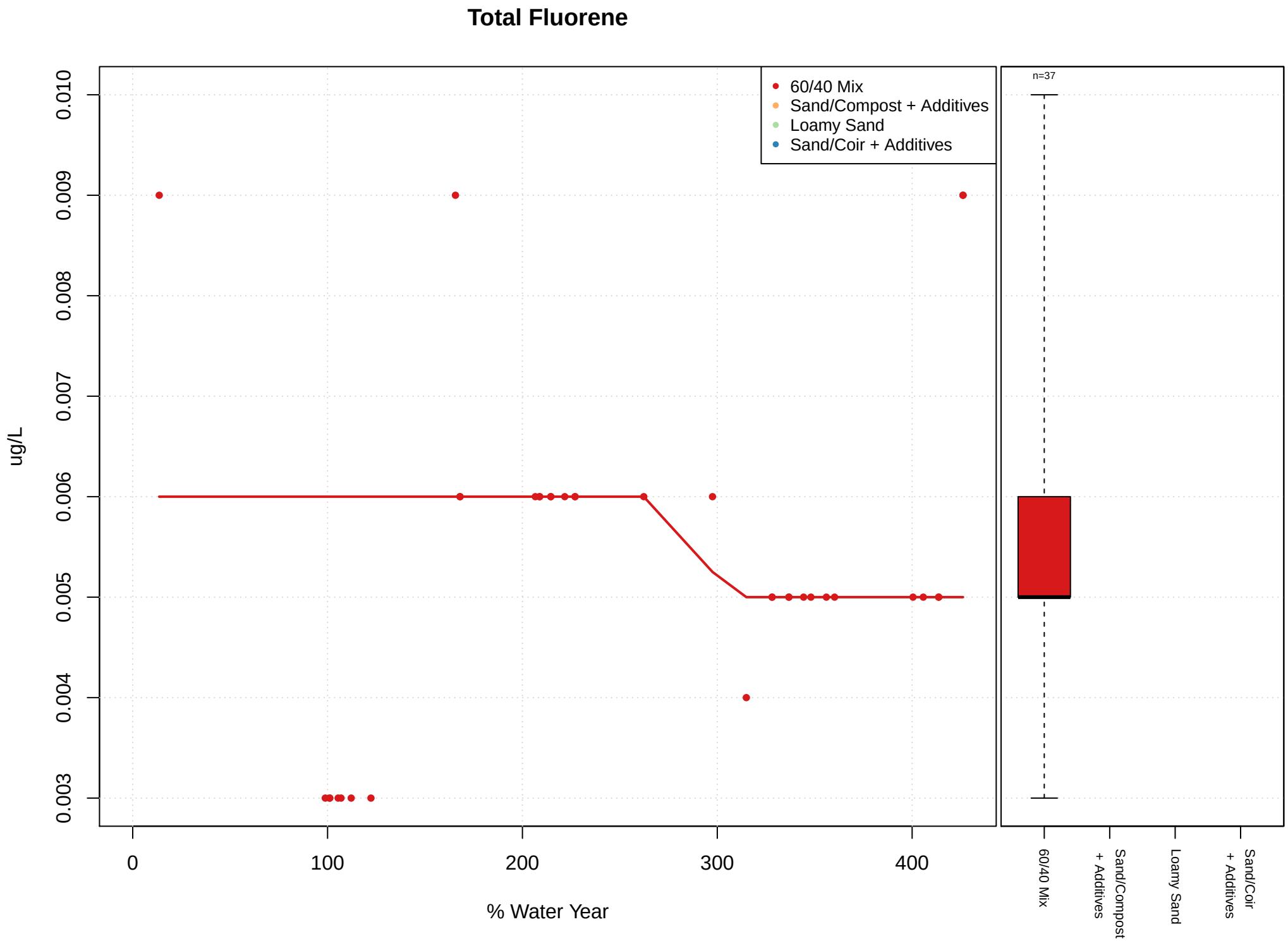
Total Diethyl phthalate

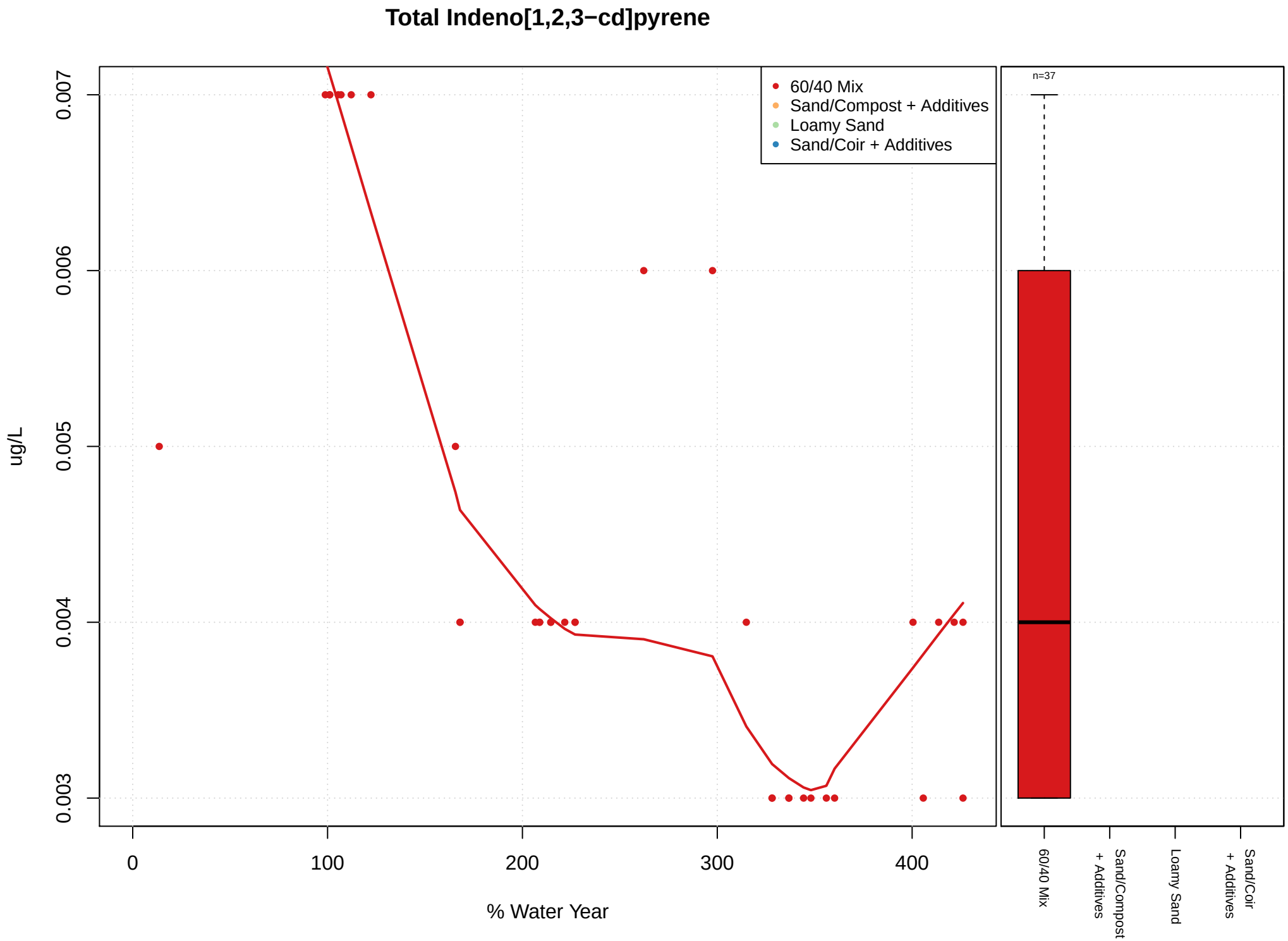



Total Dimethyl phthalate
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
ug/L
0.1
0.2
0.3
0.4
0
100
200
300
400
% Water Year
n=37
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

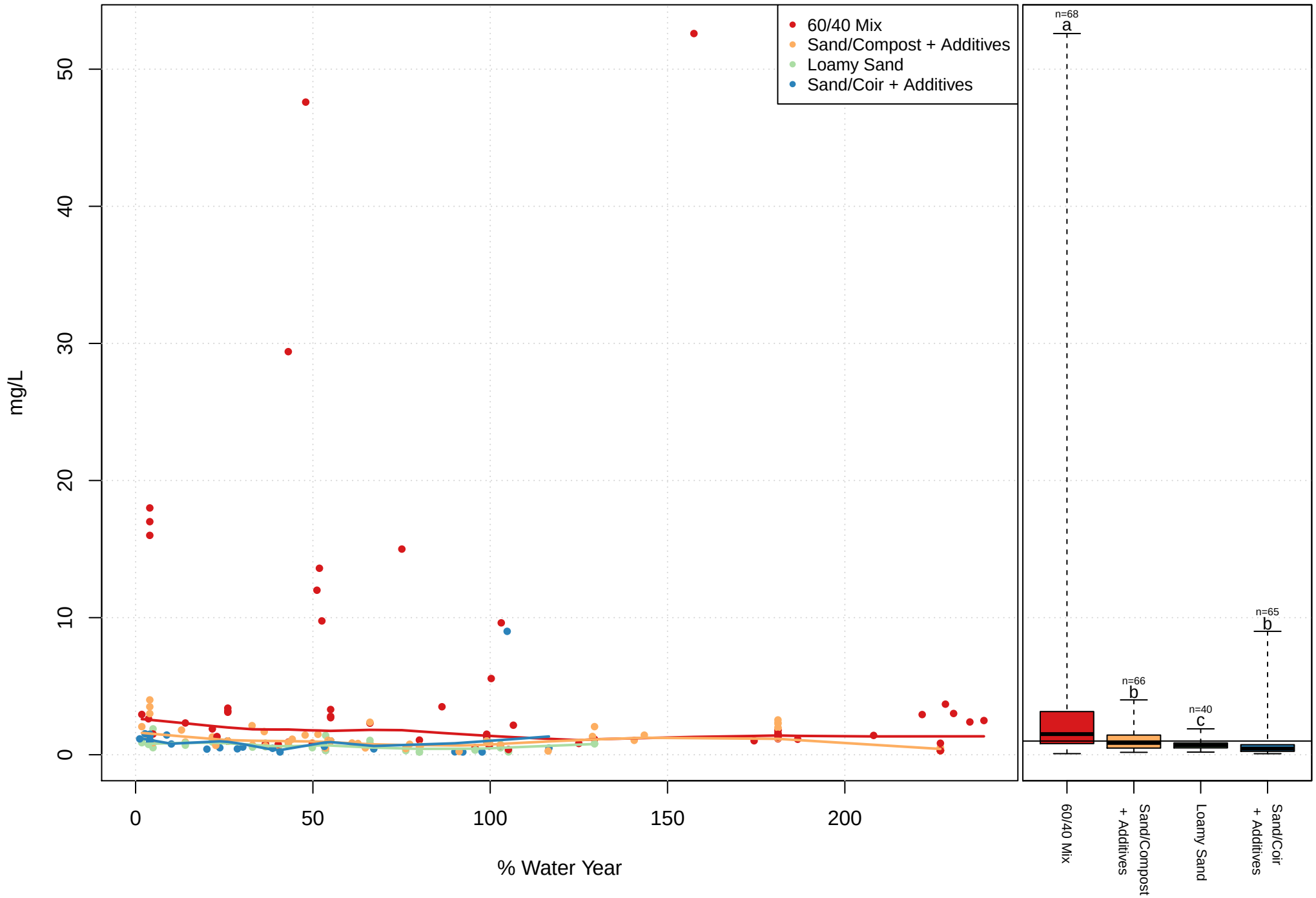
Total Fluoranthene



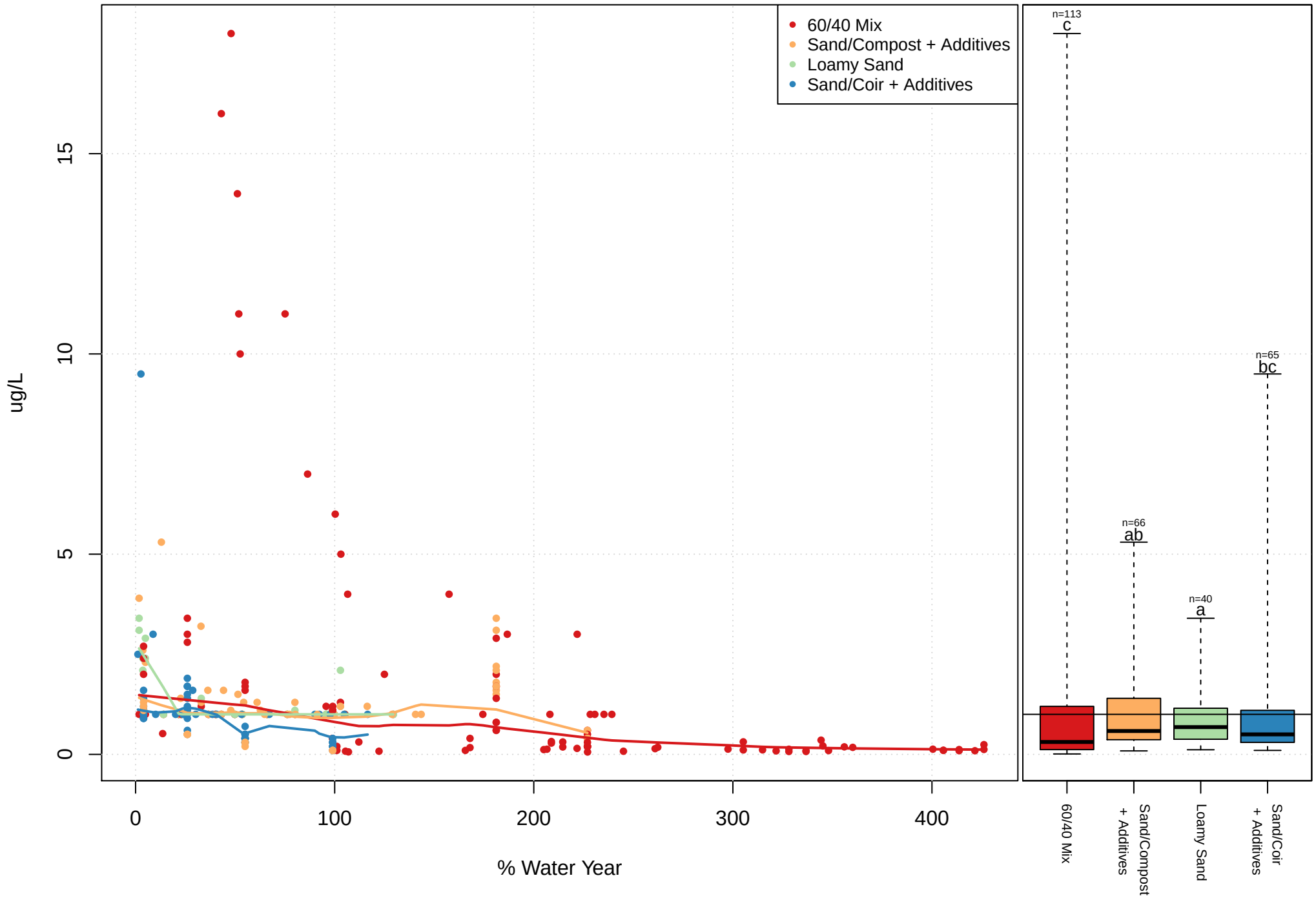

Total Fluorene
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=37
ug/L
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
0
100
200
300
400
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives


Total Indeno[1,2,3−cd]pyrene
ug/L
0.003
0.004
0.005
0.006
0.007
0
100
200
300
400
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=37
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

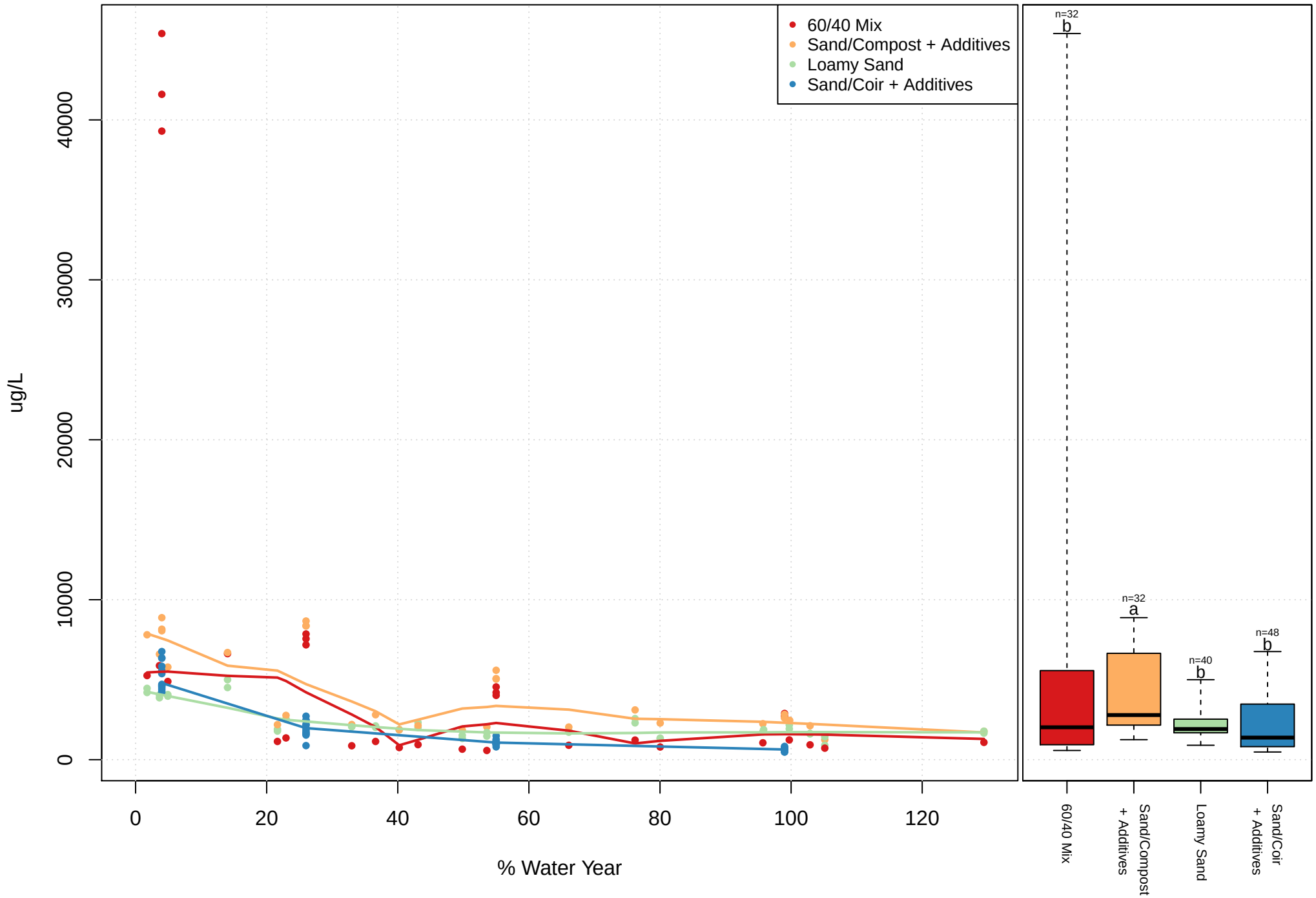
Total Kjeldahl Nitrogen



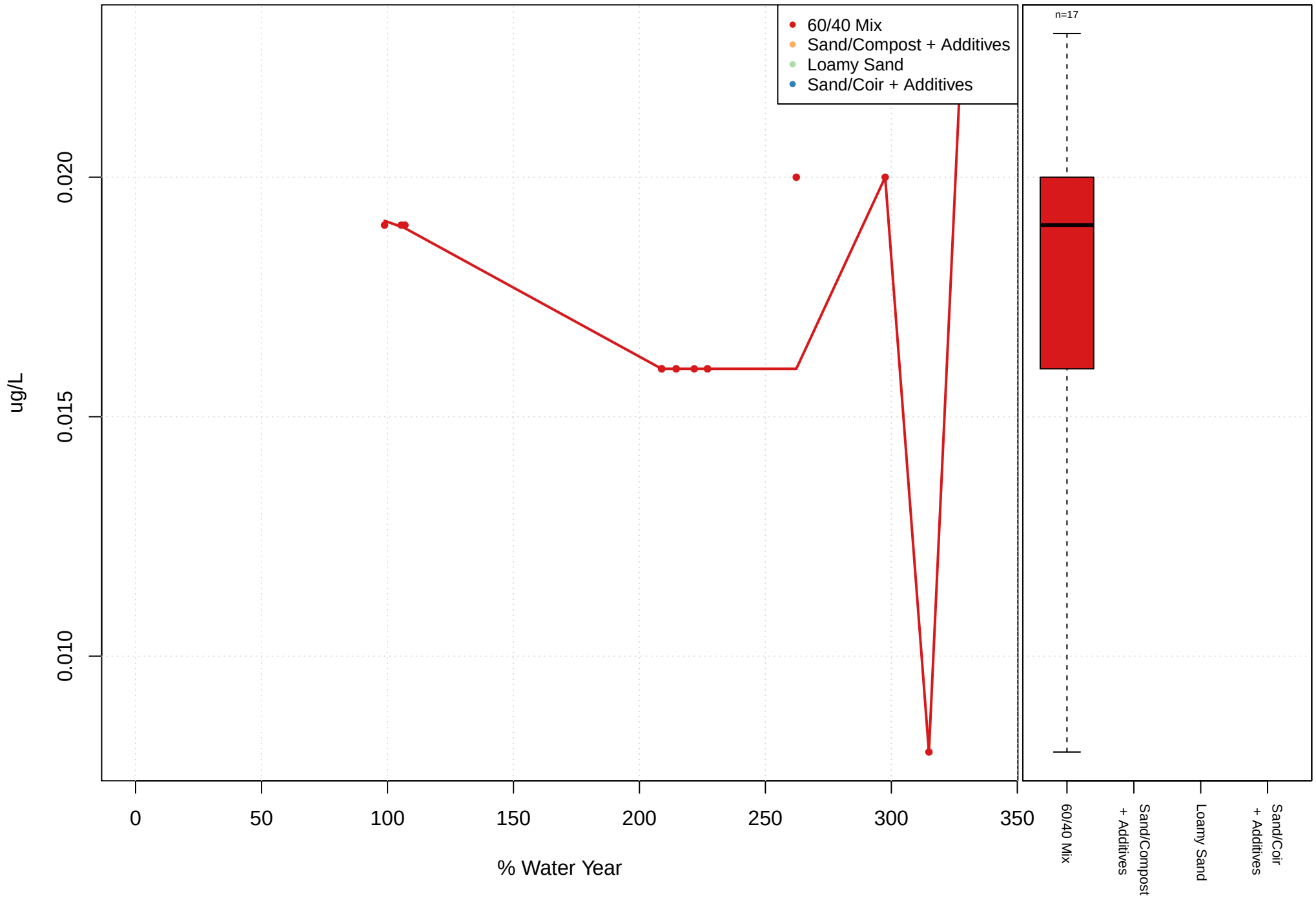
Total Lead


60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
ug/L
0
5
10
15
0
100
200
300
400
% Water Year
n=113
c
n=66
ab
n=40
a
n=65
bc
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

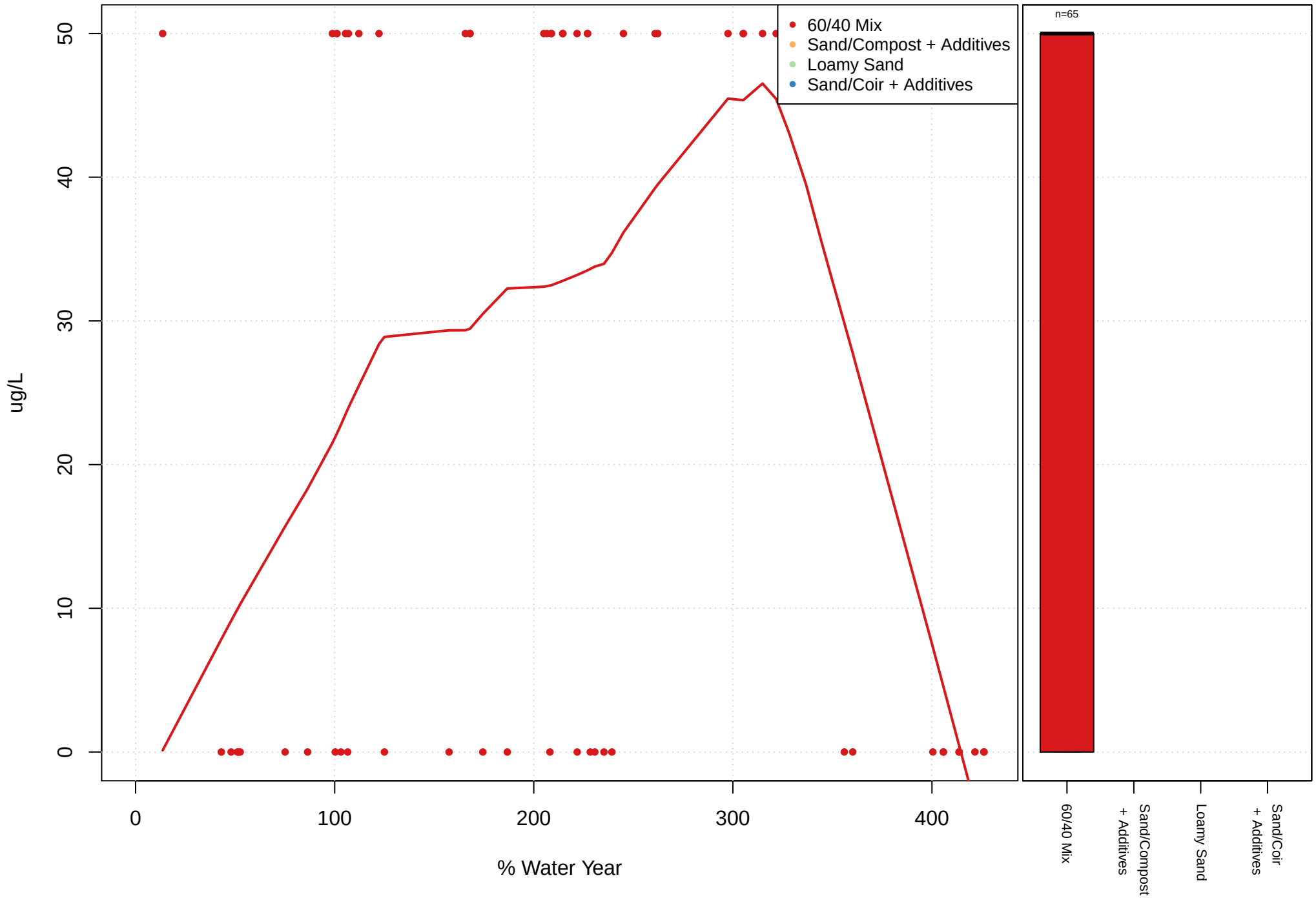
Total Magnesium



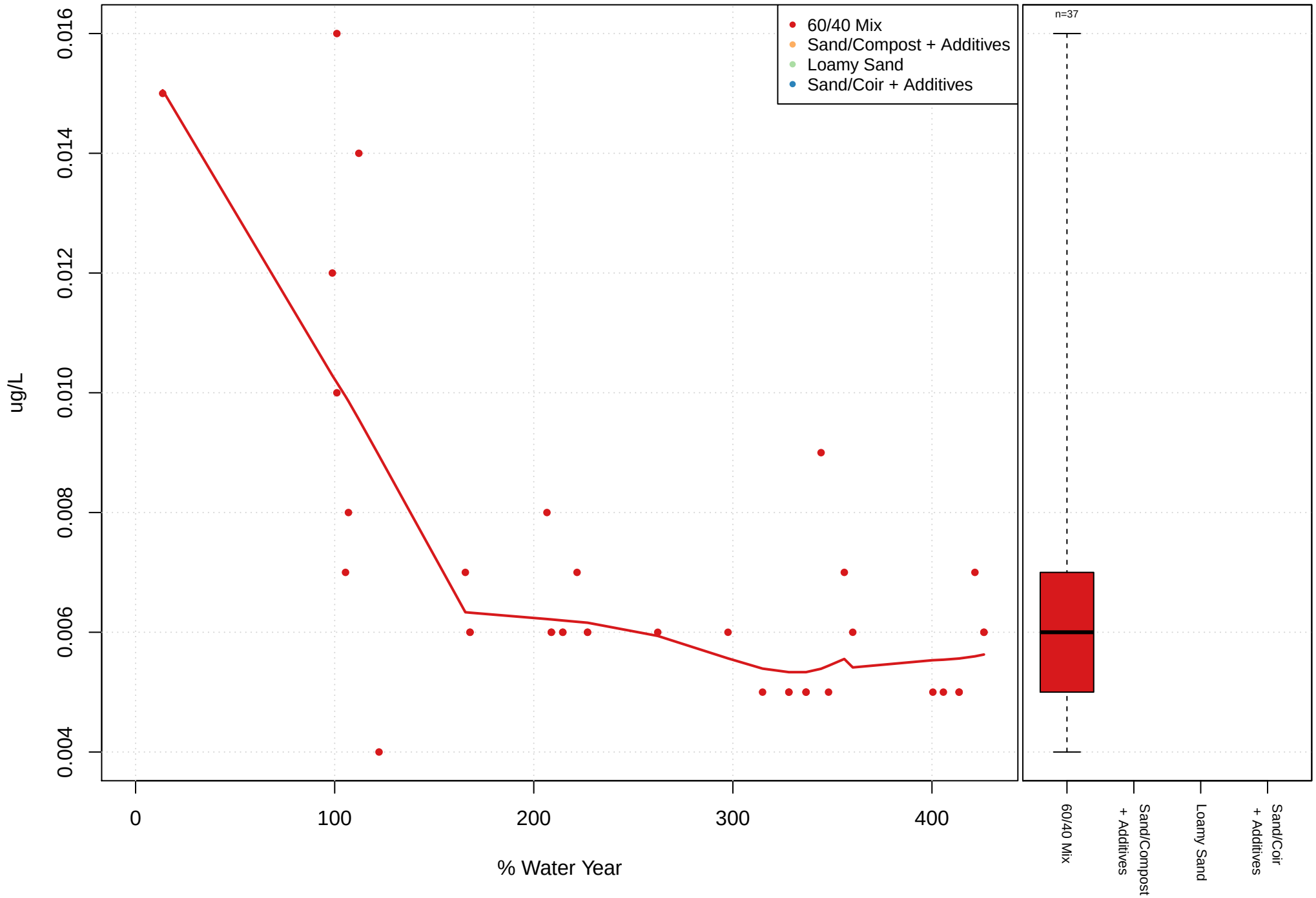
Total Malathion



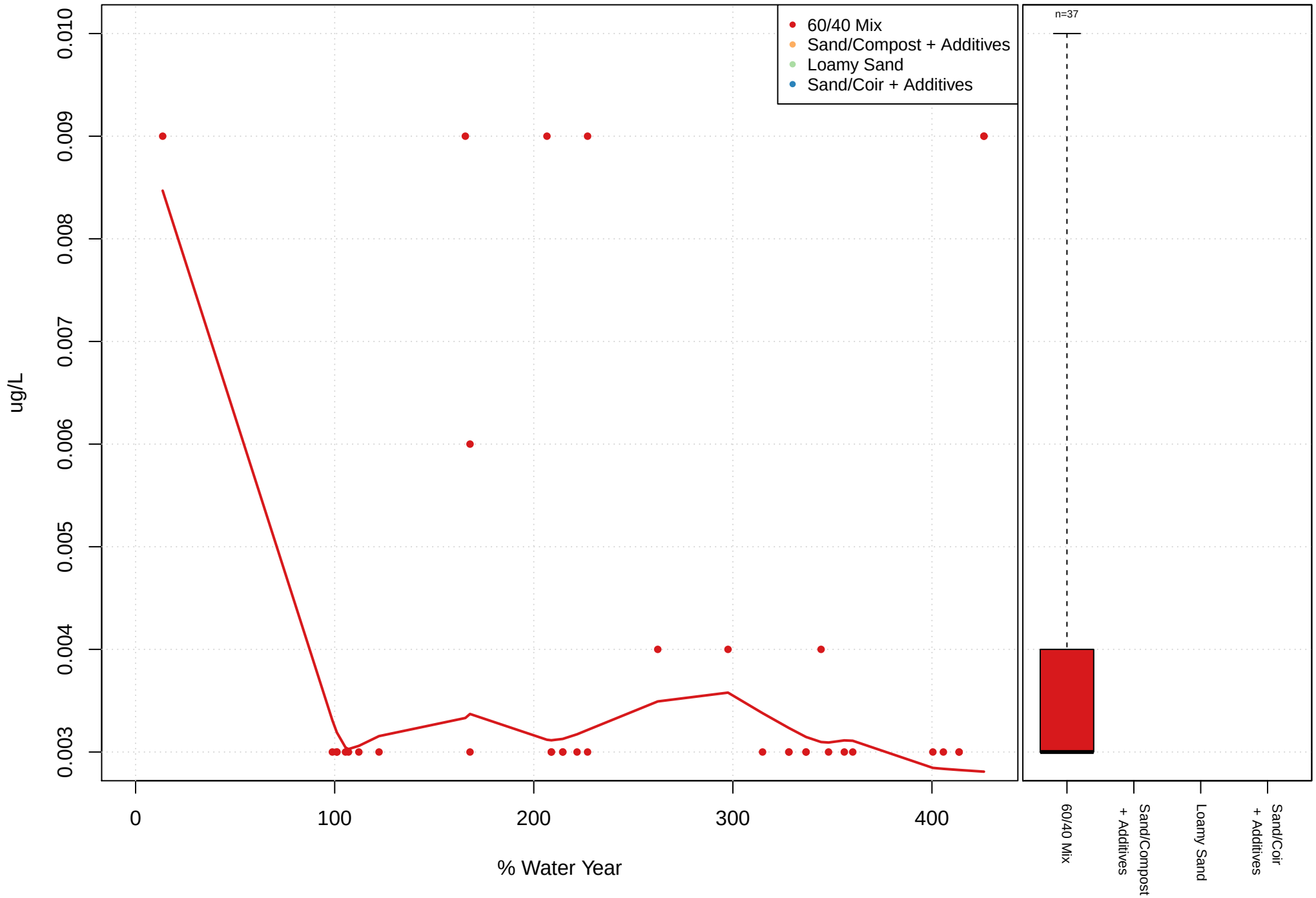
Total Mercury

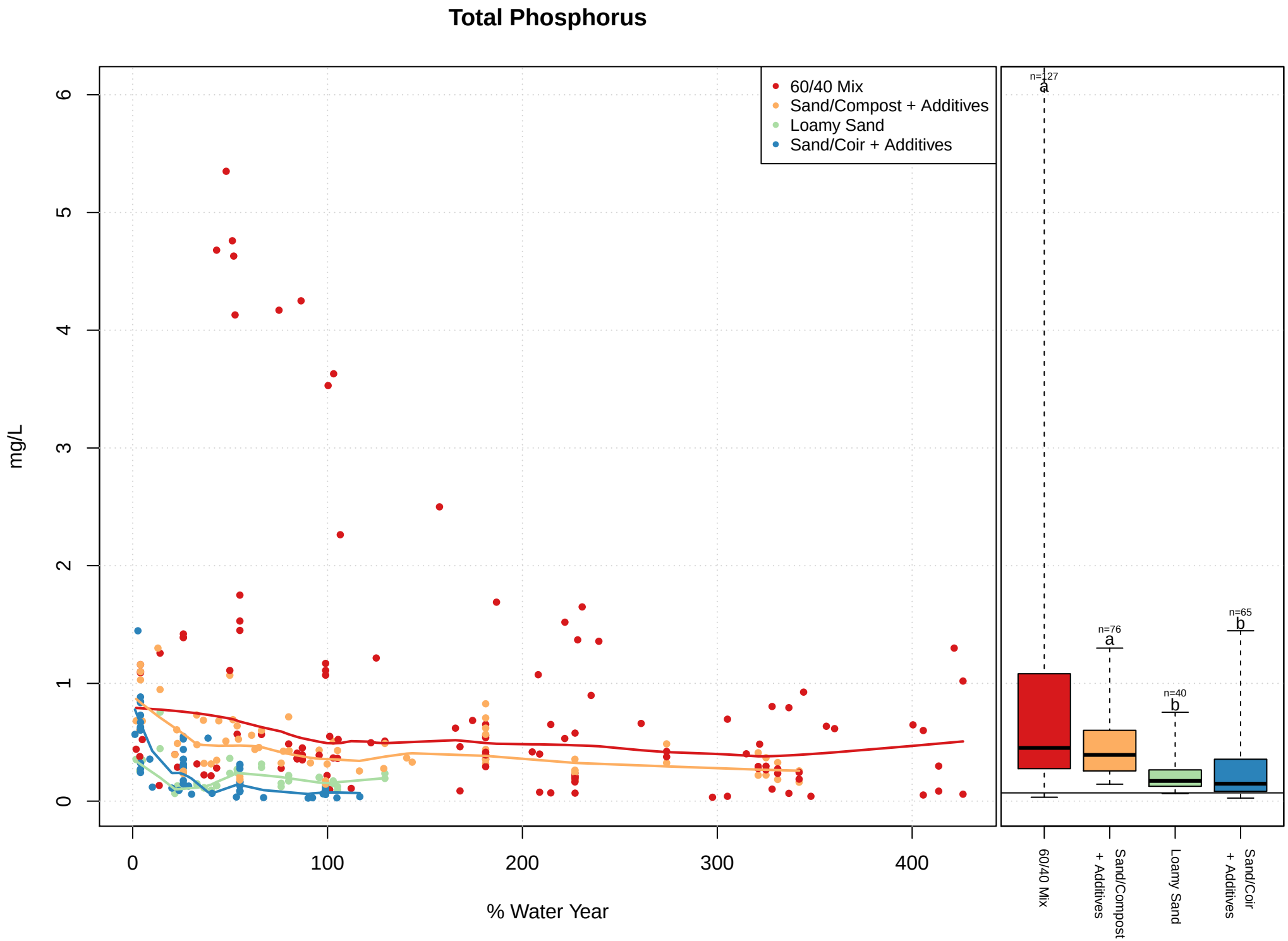


Total Naphthalene

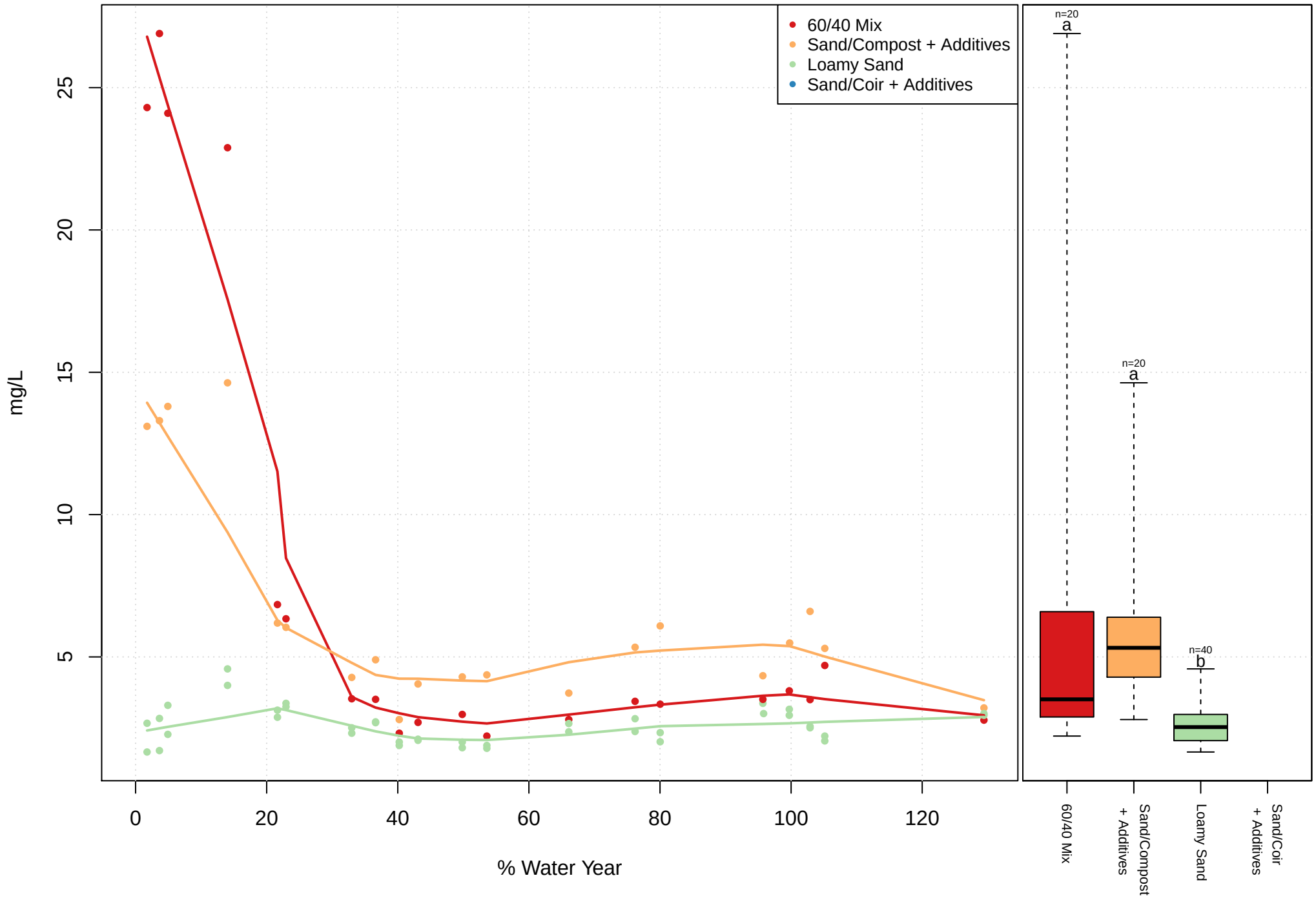


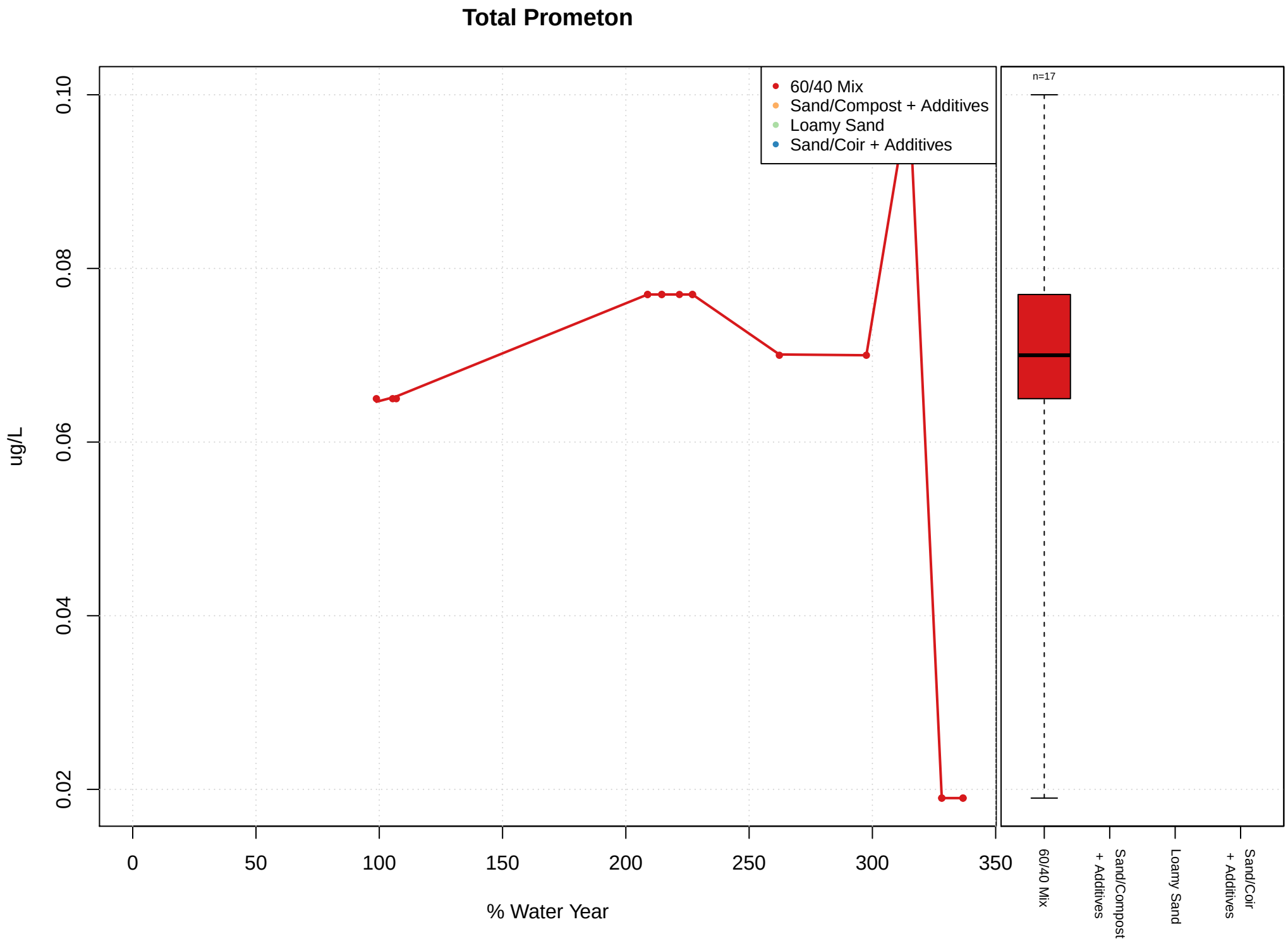
Total Phenanthrene



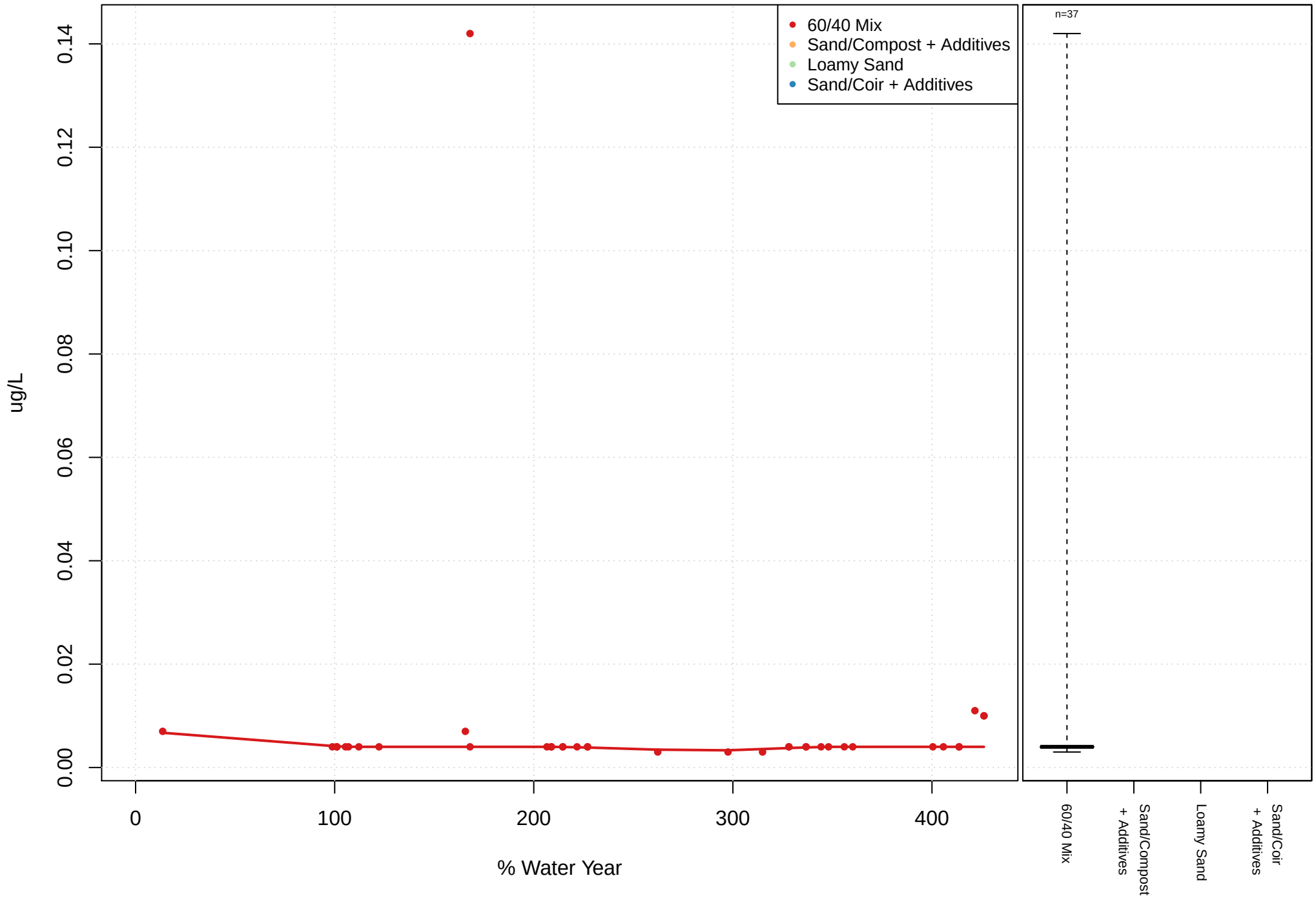

Total Phosphorus
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0
1
2
3
4
5
6
0
100
200
300
400
% Water Year
n=127
a
n=76
a
n=40
b
n=65
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

Total Potassium

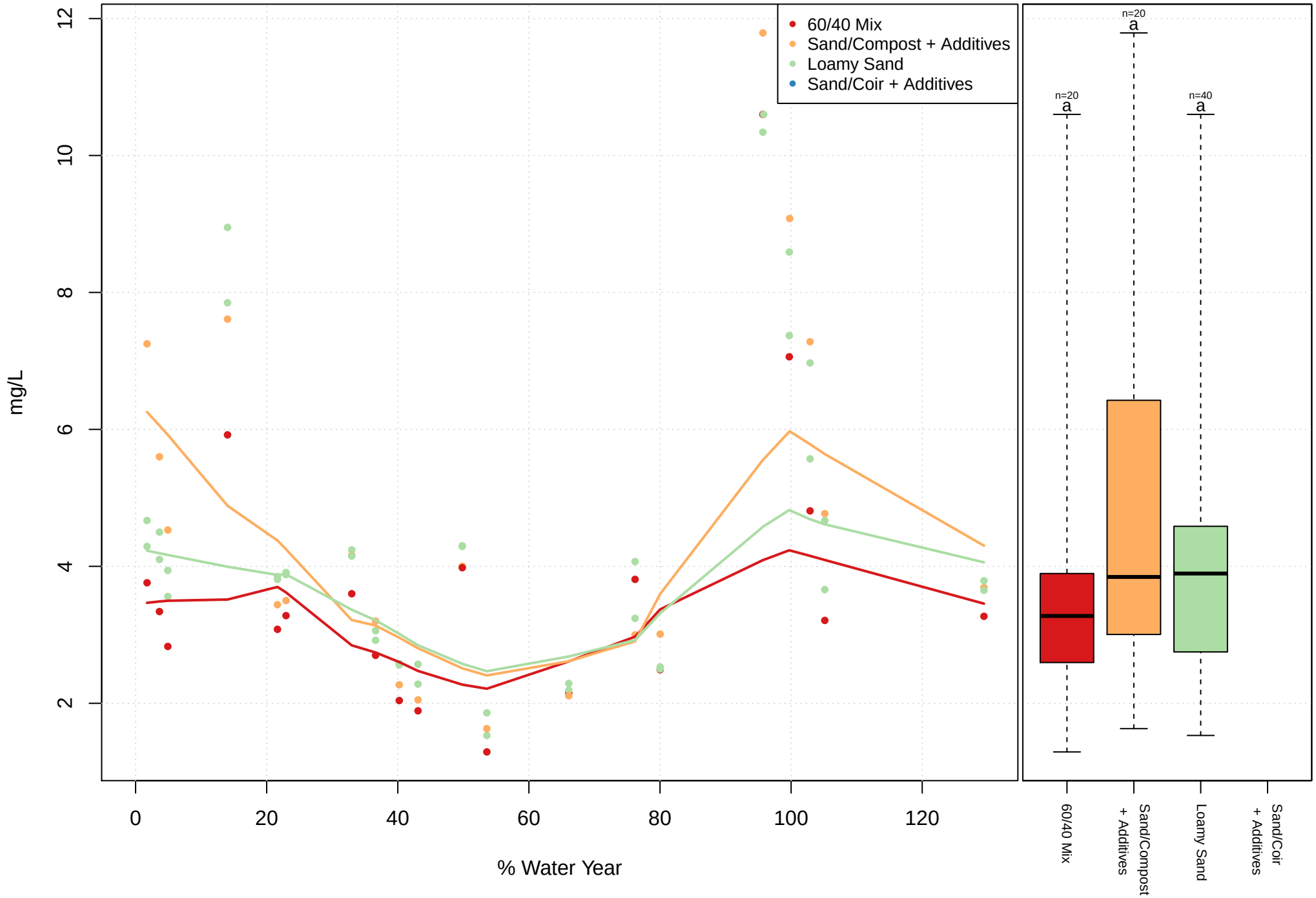



Total Prometon
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
n=17
ug/L
0.02
0.04
0.06
0.08
0.10
0
50
100
150
200
250
300
350
% Water Year
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

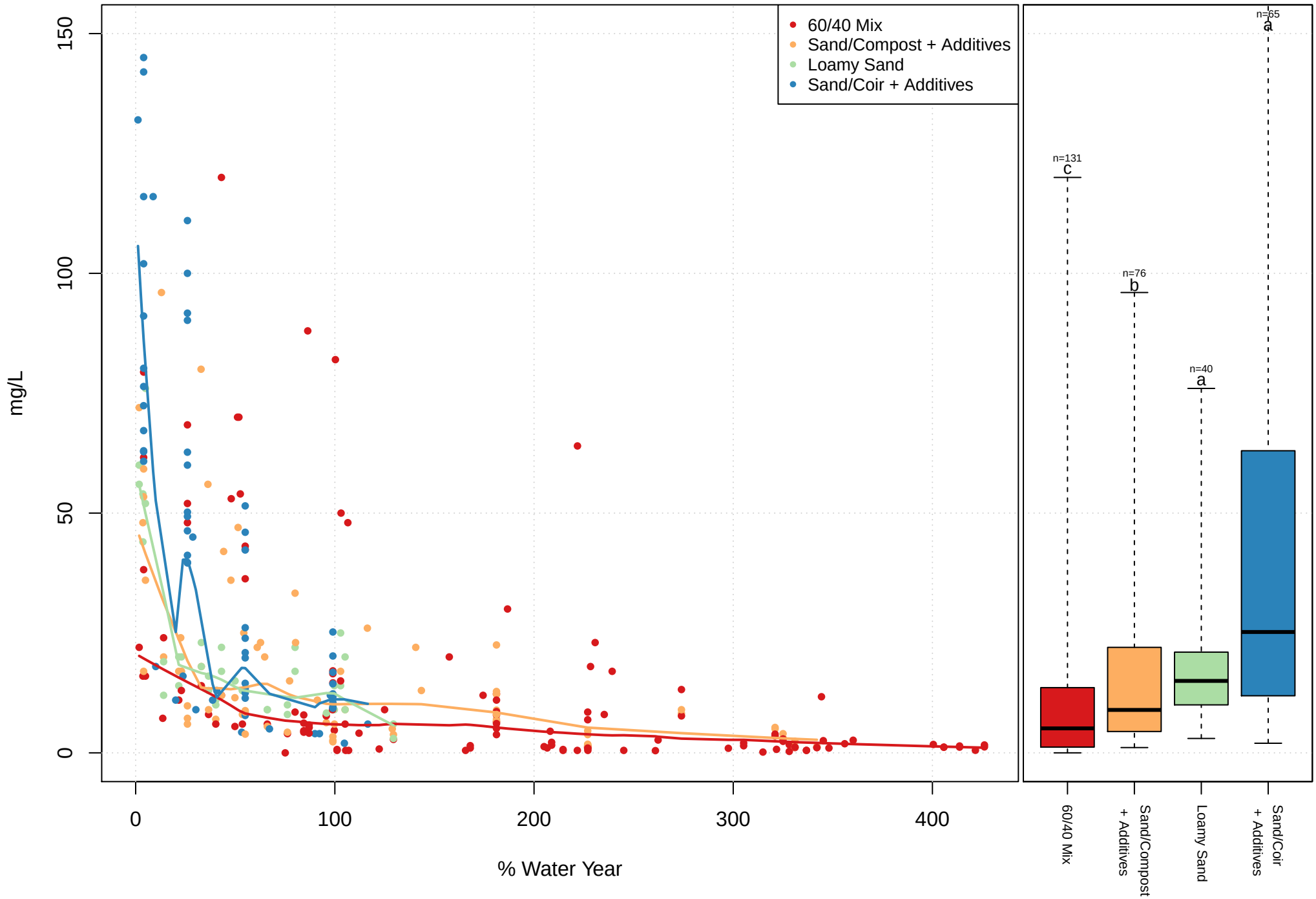
Total Pyrene



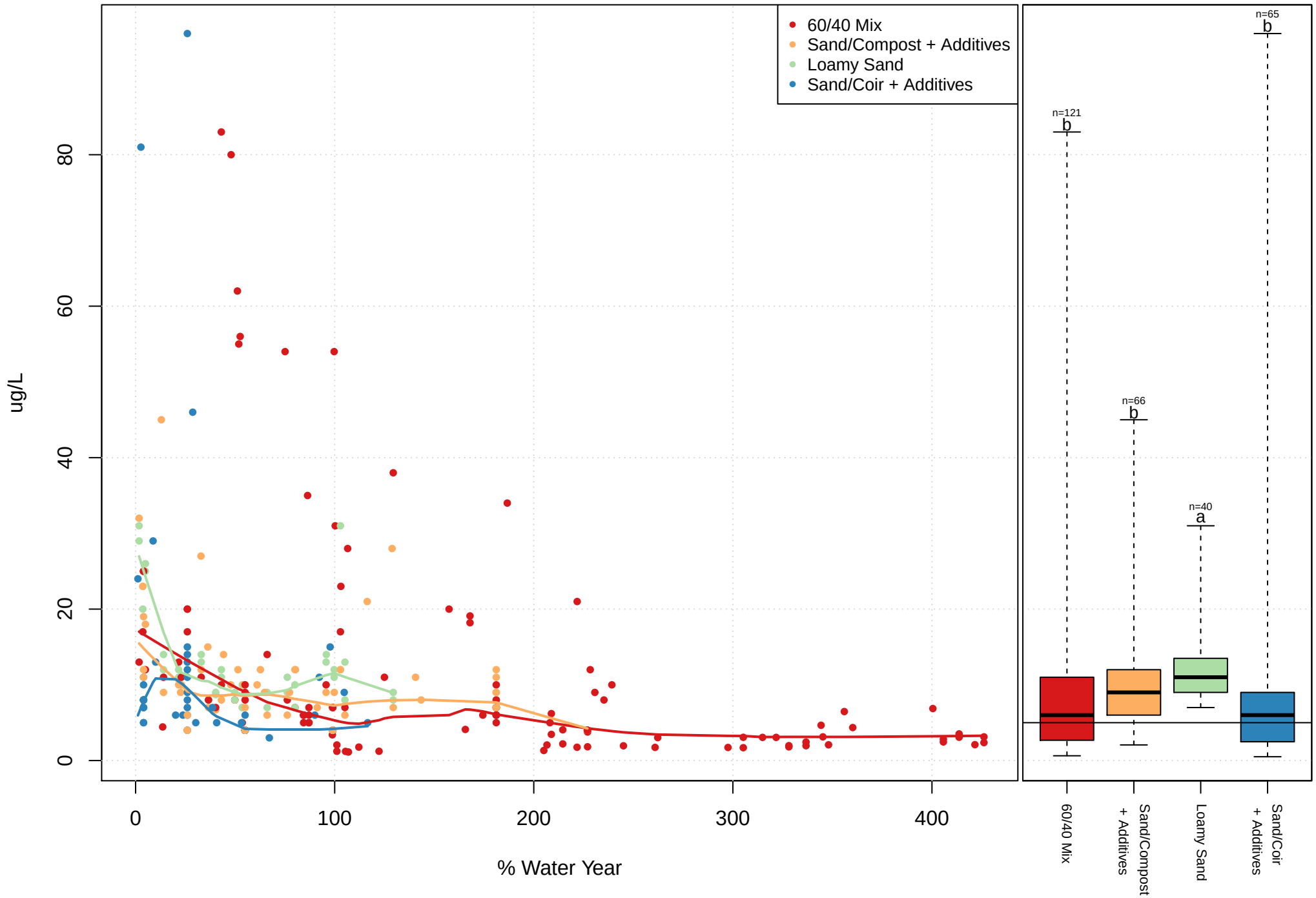
Total Sodium



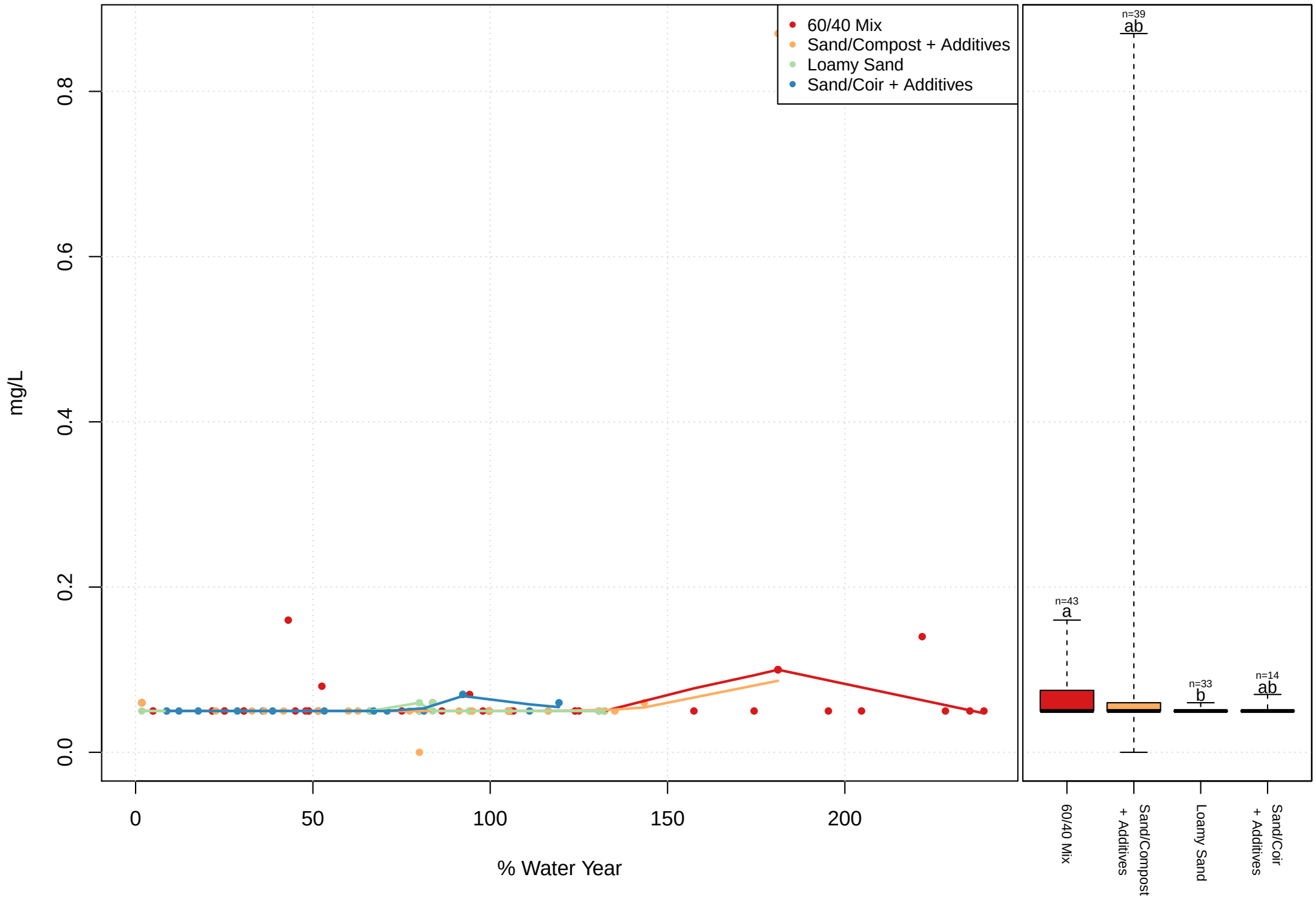
Total Suspended Solids



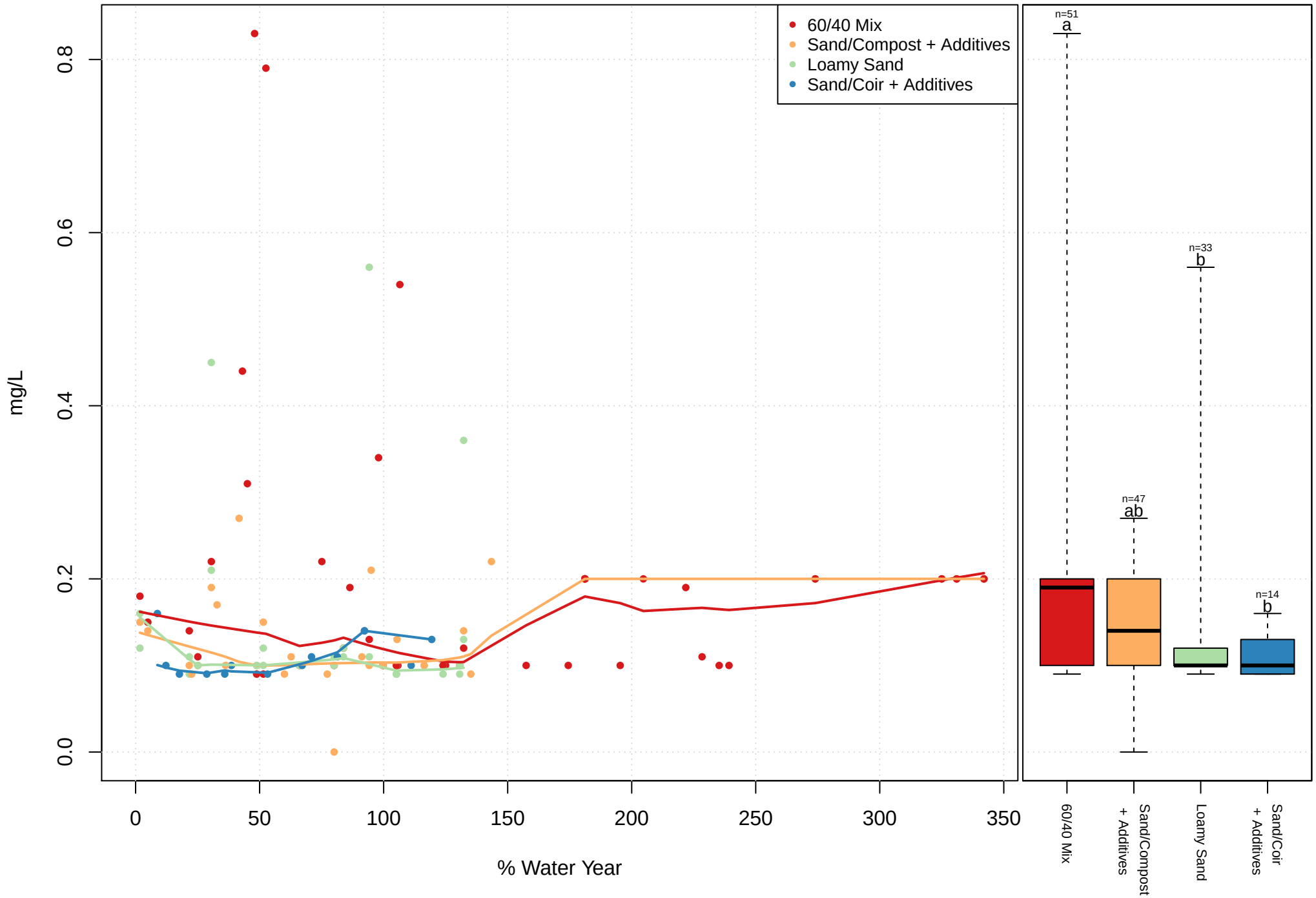
Total Zinc


60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
ug/L
0
20
40
60
80
0
100
200
300
400
% Water Year
n=121
b
n=66
b
n=40
a
n=65
b
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

TPH − Diesel


60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives
mg/L
0.0
0.2
0.4
0.6
0.8
0
50
100
150
200
% Water Year
n=43
a
n=39
ab
n=33
b
n=14
ab
60/40 Mix
Sand/Compost + Additives
Loamy Sand
Sand/Coir + Additives

TPH − Motor Oil



APPENDIX B

Table 14 Rating System Key

Bioretention Media Component Sustainability and Effectiveness

Sustainability and Cost Metrics

Cost

> $100/CY	1
$51–$100/CY	2
$26–$50/CY	3
< $25/CY	4

Origin

Overseas	1
North America	2
Pacific Northwest (PNW)	3
Western Washington	4
Within Puget Sound Watershed	5

Manufacturing Process

Single-use heavy extraction (mining, excavation)	1
Single-use product with high input	2
Byproduct with high energy input	3
Byproduct with low energy input	4
Biological process from renewable feedstock	5