DEVELOPING A PERFORMANCE MODEL
FOR AN INDUSTRIAL STORMWATER FILTER MEDIA

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Abstract

The stormwater runoff from industrial sites is often subject to a higher level of treatment than municipal “non-point” source runoff due to its unusually high concentrations of pollutants. Typically, samples from these sites must be taken quarterly and analyzed for pollutants such as zinc, copper and total suspended solids (TSS). Selecting a treatment option for these industrial sites can be complicated by several environmental factors related to runoff chemistry as well as physical makeup.

The work presented here presents a program of bench-scale and full-scale tests that are used to generalize a model of system performance. Using multivariable regression analysis, a predictive model is identified that can be used to screen applications for appropriate media selection. The results indicate that rule-of-thumb performance predictions such as “percent removal” are likely not accurate enough to be used to confidently select a media. Regression models built from multiple input variables produce a closer correlation and indicate a better predictive model.

Keywords

Stormwater, Industrial, Zinc, Copper, TSS, GAC, Carbon, Peat, Zeolite

Introduction

Although many municipal stormwater quality regulations around the country focus on the removal of suspended solids, there are a growing number of states mandating that areas of special concern be held to a higher standard. The removal of copper and zinc is an important factor in the improvement of aquatic ecology downstream of industrial sites such as factories and shipping ports. The west coast states of California and Washington are leading the way in regulating the runoff from these industrial areas as well as regulating the municipal runoff upstream of ecosystems designated as biologically significant.

The Best Management Practices (BMPs) to control these pollutants range in complexity from simple housekeeping measures to media filtration systems to sophisticated electrochemical removal. Unfortunately, understanding and predicting the performance of these technologies is a difficult task due to the complicated chemistry of stormwater runoff. Site specific variables such as ratio of particulate to dissolved metals or the presence of complexed organic compounds make the selection and sizing of BMPs a complicated and risky endeavor.

To better characterize the performance of a proprietary filter media, this study collected and treated 31 field samples from six different industrial and municipal sites. This test is unique in its scope to have a single media tested under several different field conditions. More typically, runoff from a single site is tested with a range of different media. In another typical test, treatment of pure lab standard or runoff spiked with lab standard is used to evaluate media. By using 100% real site runoff as the independent variable, this test makes it possible to build a performance model to be applied to any site conditions.

This study measures removal efficiency of copper and zinc found in industrial and municipal runoff when treated by a proprietary filter media. This media was designed by Dr. Bob Pitt of the University of Alabama (Pitt, 2002) and consists of carbon, peat and manganese coated zeolite. The data from these tests is then analyzed to create a performance model for this filter media.

Laboratory Methodology

Thirty-one test samples were gathered from the six unique field sites. Approximately 70% of the samples were collected on-site from the point of discharge and 30% came from in-situ demonstration units or installed filter systems. The samples represent three different industrial applications: metal scrap, metal manufacturing and food processing. The fourth application is a municipal discharge of special environmental concern. All the samples were collected in northern California during the fall, winter and spring months.

For samples collected from a discharge culvert, the influent was shipped to Hydro International’s laboratory in Portland, Maine and run through a media test column. This test column is made from 2-inch diameter clear PVC, as shown in Figure 1. The flow enters the column from the bottom and passes through eight inches of treatment media before exiting through the overflow. Pre-treatment and post-treatment samples are taken and analyzed for concentrations of suspended solids, total copper and total zinc to evaluate the effectiveness of the media on these pollutants. Flow rates are measured by the time-to-fill method at the overflow.

Samples collected from in-situ, full-scale filter units were sent directly to the laboratory for processing. Flow rates were measured using a combination of volumetric and flow meter methods.

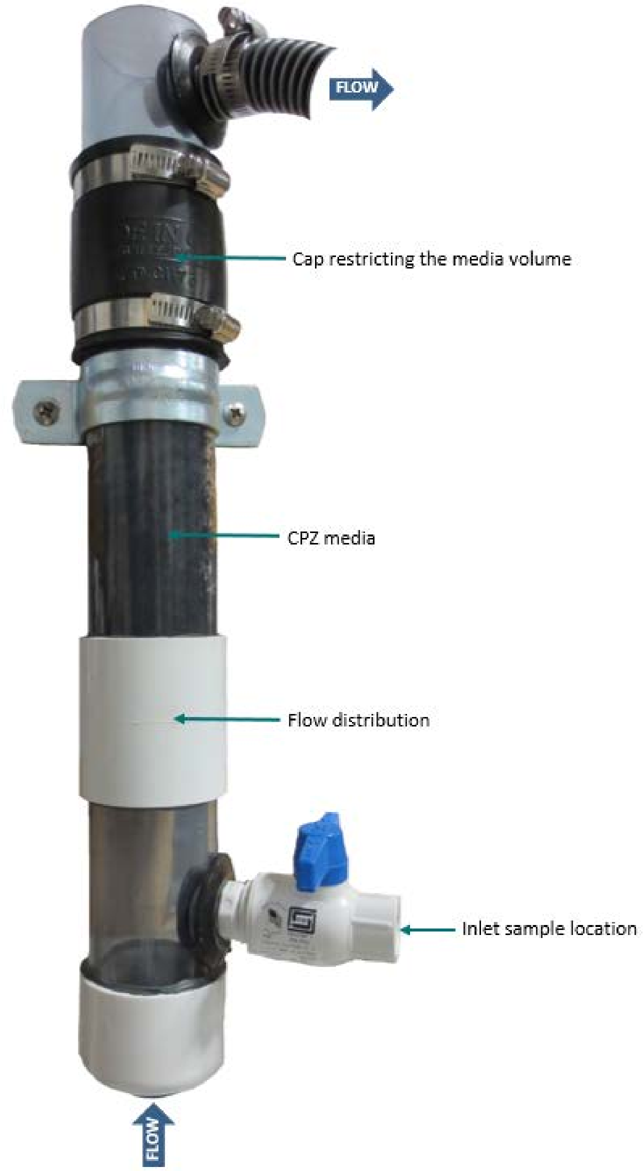

Figure 1. Column test setup for treating runoff collected at point of discharge

The results of these column tests were then analyzed with multi-variable linear regression to produce an empirical model that represents the performance of the system. In the development of the model, two of the samples were discarded. One sample was outside of the typical range of performance being studied and the other sample was contaminated with a paper label that was dissolving in the sample.

In this study, concentrations of copper, zinc and TSS were analyzed due to regulatory focus on these pollutants. In general, the ranges of copper influents (Figure 2a) ranged over an order of magnitude and zinc influents (Figure 2b) ranged over two orders of magnitude. Influent TSS concentrations ranged over an order of magnitude. Loading rate was controlled by the test column pump arrangement and was maintained within one order of magnitude.

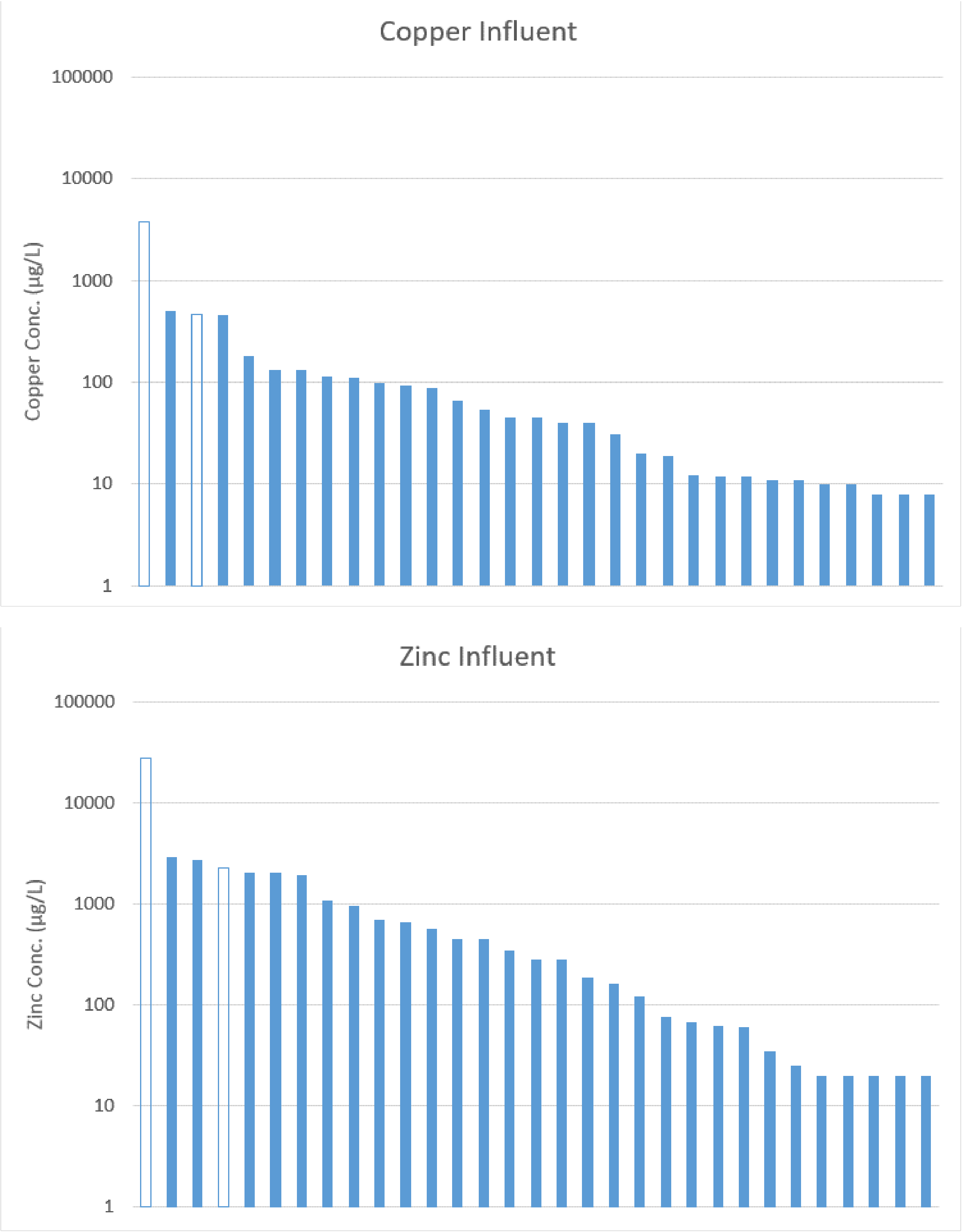

Figure 2a-b. Copper and Zinc influent concentrations sorted in decreasing order. The two samples that were discarded as outliers are shown as outlined bars.

Statistical Model Methodology

The framework for the statistical model development was based on the theoretical understanding of processes involved in removing metals from stormwater. The “total metals” concentration in runoff is typically divided into a particulate fraction that can be physically removed and a dissolved fraction that must be chemically removed. The ratio of these two components changes from site-to-site and from storm-to-storm depending on environmental conditions such as storm antecedent period, or housekeeping practices such as sweeping or vacuuming (Field, 2002).

Physically removing particulate metals from the stormwater is a straining process that can be completed in several different ways ranging from high-pressure micropore filters to sand bed filters. In this study, a bed of filter material is fed in an upward direction to remove the particulate pollutants.

An adsorption process was used to remove dissolved metals from solution. In this process, positively charged metal ions become bonded to negatively charged sites on the surface of the filtration media. Activated carbon, peat and zeolite are all identified as types of adsorption media partly due to their high surface area to volume ratio. It is expected that the effluent concentration of a given pollutant will correlate to the concentration of all competing influent concentrations. This is because some isotherm models of adsorption behavior suggest that removals will be proportional to the available adsorption sites. Additionally, reduced contact time with the media has been shown to negatively affect the adsorption properties of the media. (Cooney 1998)

Based upon this theoretical framework, it is hypothesized that effluent concentration may be able to be predicted given only the influent concentrations of copper, zinc, TSS and filter loading rate. Other environmental variables (for example storm antecedent period, industry type and sample processing method) might show correlation, but should be ignored as outside the fundamentals of metals removal.

Statistical analysis of the multi-variable linear regression models was conducted using the open-source statistics package R. Due to the relatively small data set of 29 points, the risk of model overfit needed to be considered. In an overfit condition, the model developed is excessively complex and describes the noise of the system instead of the underlying relationship. This condition results in poor predictive performance. To avoid overfit, two-factor interactions were included in the model, but three and four factor interactions were discarded in an attempt to avoid spurious correlations. For example, the interaction between Copper and TSS influent concentrations was analyzed, but the three-way interaction between Copper and Zinc and TSS influent concentrations was not. The final linear regression model contained six coefficients.

Five-fold cross validation and confidence intervals were also used to evaluate the extent of overfit. In this technique, the data is randomly split into five sections and one is assigned to be a check against the prediction modeled by the remaining data. This tests the predictive performance of the model by simulating prediction for 20% of the data set.

Results

The entire data set of 29 samples were used for the analysis and a linear regression model was calculated. When the model results are plotted against the actual test results the copper model (Figure 3a) shows an R^2 of 0.9 and the zinc model (Figure 3b) shows an R^2 of 0.7.

In the cross validation charts (Figures 4a-b), each bar and point combination represents one validation prediction. The point is the actual test result while the upper and lower bars indicate the range of predictions that the model estimates with 80% confidence. Because cross validation relies on a random selection of data, some points within the data set were selected more than once and some were not selected at all. The chart shows the results of five validation points repeated five times for a total of 25 validation sets.

The cross validation indicates that the actual test result falls within the 80% confidence band on 21 of the 25 copper samples validated and 18 of the 25 zinc samples validated. For context, the Numerical Action Limits (NAL) in California is also plotted. When compared to these limits as a threshold, none of the cross-validated points predicted a passing result when the actual test result failed.

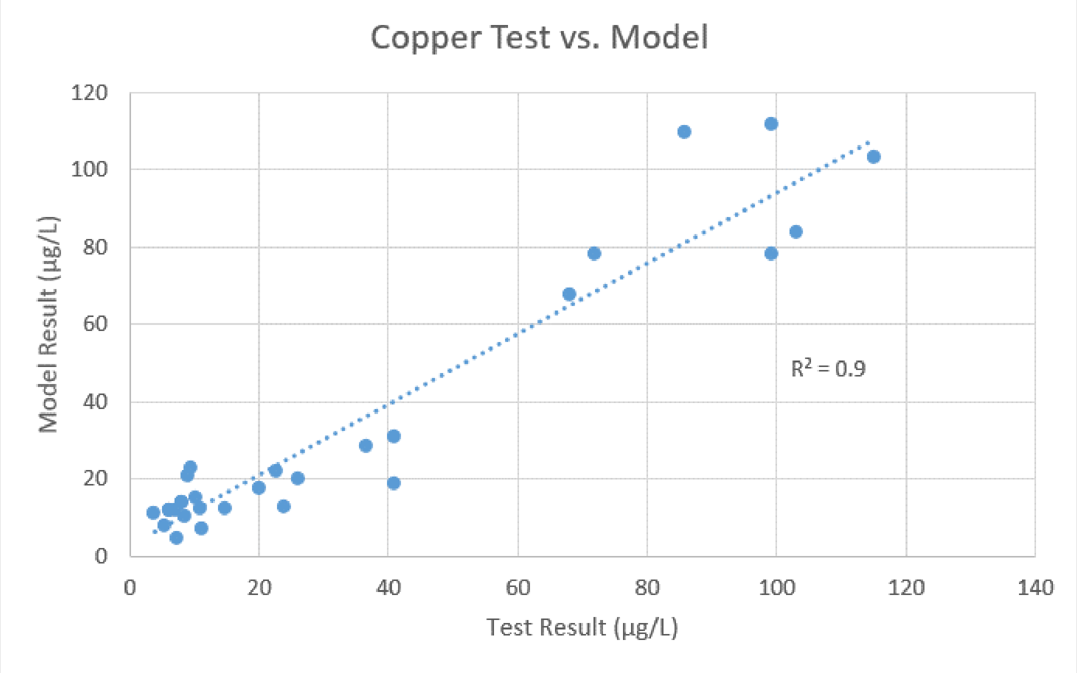

Figure 3a. Copper Effluent Model Results plotted against Copper Effluent Test Results

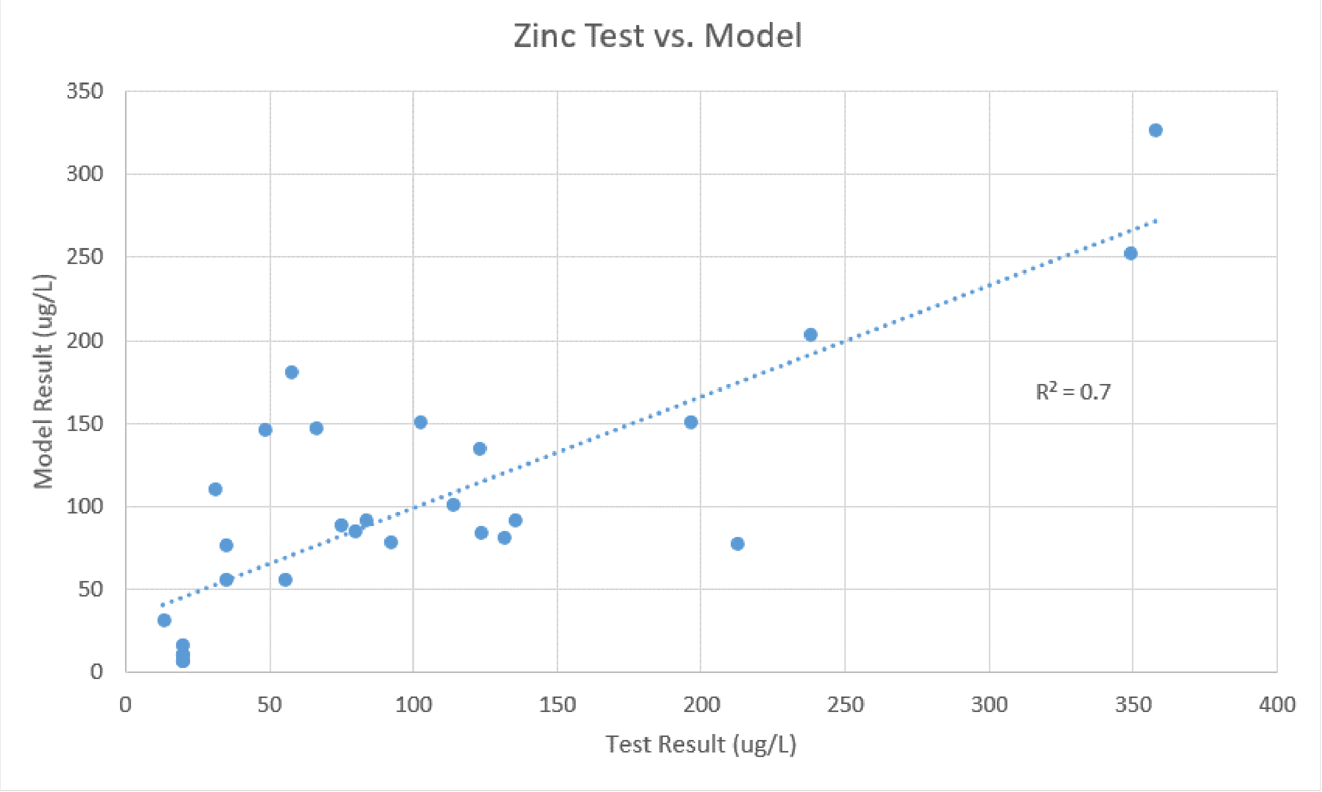

Figure 3b. Zinc Effluent Model Results plotted against Zinc Effluent Test Results

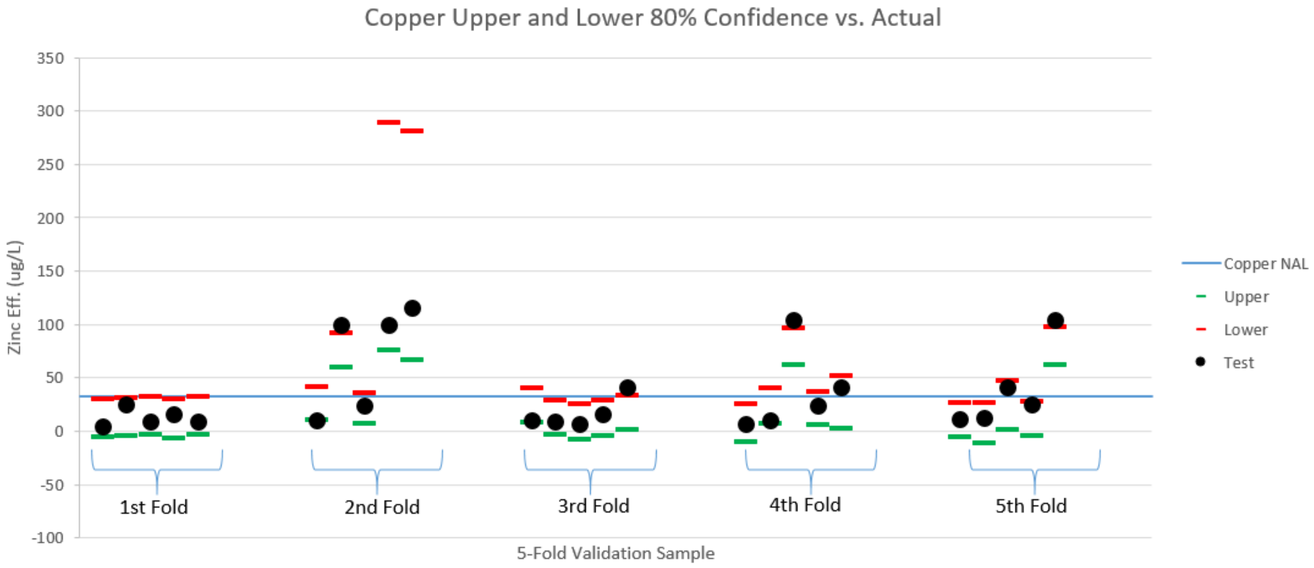

Figure 4a. Copper Test Results against upper and lower 80% confidence bounds using 5-Fold Cross Validation

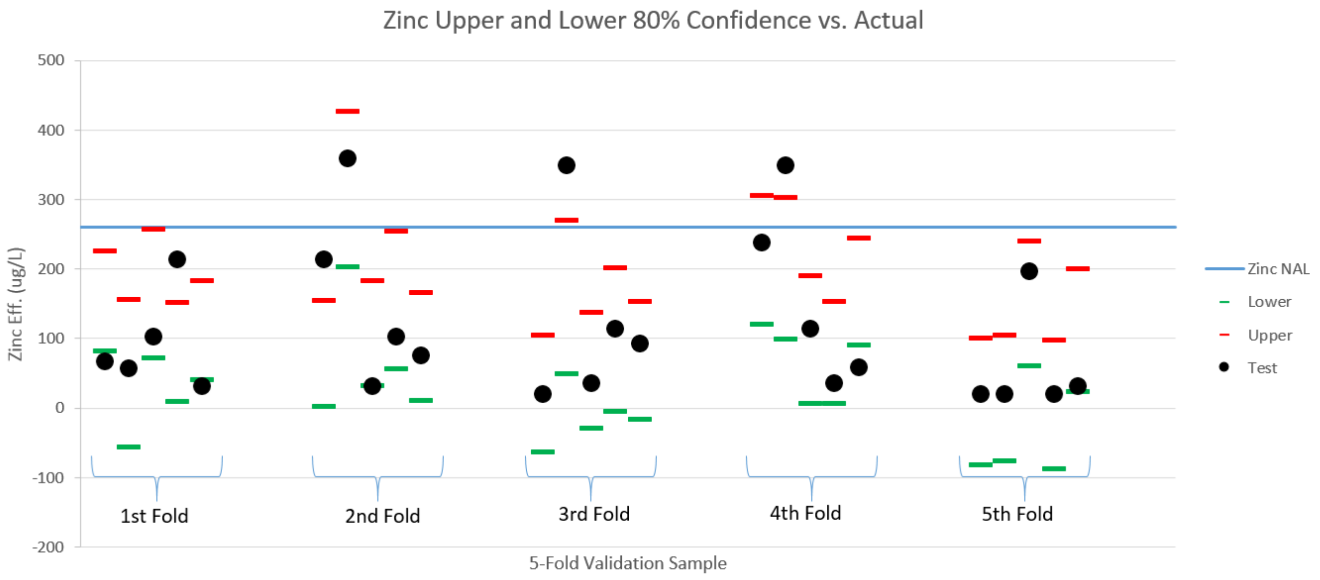

Figure 4b. Zinc Test Results against upper and lower 80% confidence bounds using 5-Fold Cross Validation

Discussion

Because this statistical model is an empirical representation of the system's performance, it's predictions are only valid if they are representative of the training data set. By plotting the 80% confidence interval of the prediction, the model can indicate if the input variables are in a range that is not well represented by the data. Wide confidence intervals, such as those seen in the 2nd Fold of Figure 4a, indicate that the input combination of variables are not within the ranges found in the training data set. Therefore, a wide range of possible effluent concentrations must be considered to predict within 80% confidence. As an example of this, all of the failing test points in the cross validation exercise had 80% confidence bands that exceeded the NAL concentration.

The good correlation between test results and modeled predictions combined with the demonstrated value of the cross-validation indicates that a regression model based on the selected input variables may be appropriate. However, in most cases the projected effluent concentrations for a given site are estimated based on a claimed "percent removal" of a media type. The assumption that "percent removal" will yield an accurate prediction of performance implies that influent concentration gives the best correlation to effluent concentration. As shown in Figure 5 below, some correlation can be seen with influent concentrations, but it is not especially strong. Although a close correlation between influent and effluent concentration may be observed when testing under laboratory conditions, it does not appear to exist when applied to real industrial runoff. As described above, when using an adsorption media like CPZ, zinc, copper and other pollutants compete for the same ion exchange sites and each pollutant can impact the removal of another. Additionally, copper can complex with organic compounds changing the way it is removed from solution.

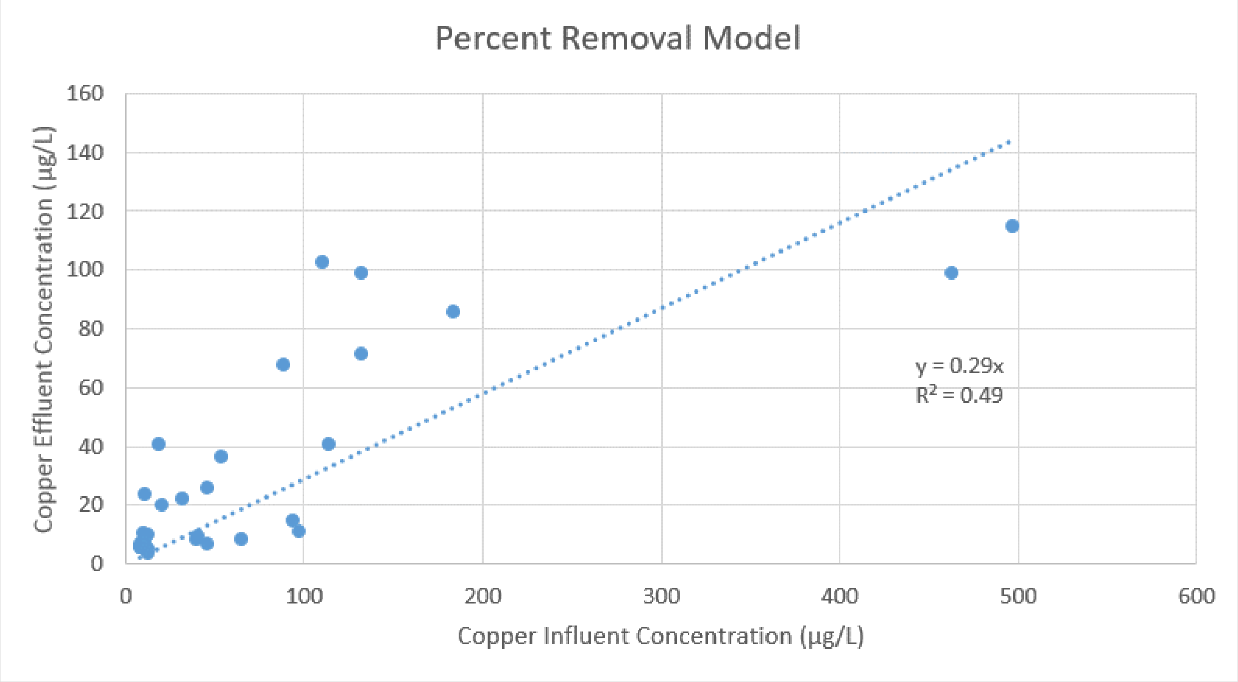

Figure 5a. Copper Effluent Concentrations plotted again Copper Influent Concentrations.

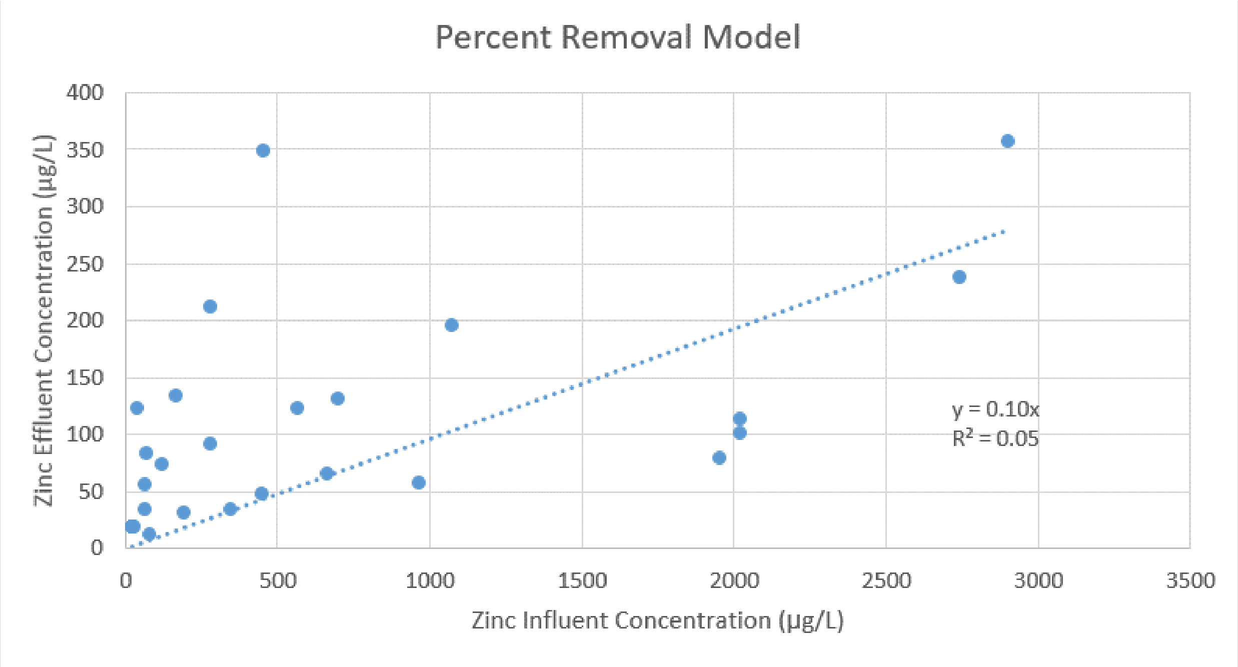

Figure 5b. Zinc Effluent Concentrations plotted again Zinc Influent Concentrations

Conclusions

The empirical model created by this study will continue to be calibrated as more field samples are added to the data set. Ultimately it will be used to more confidently select and size equipment appropriate for a given site. Eliminating the need for costly pilot systems or "adaptive management" programs is a valuable way to plan for the environmental regulatory needs of industry and municipalities. The findings of this study will also be used to further the development of filtration technologies. By better understanding where and when the system works best, it is possible to create new products that can better target unmet needs.

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