# Estimation of Suspended Sediment Concentrations and Loads Using Continuous Turbidity Data

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Luanne Y. Steffy
Aquatic Ecologist
Susquehanna River Basin Commission

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## INTRODUCTION

In 2010, the Susquehanna River Basin Commission (Commission) established the Remote Water Quality Monitoring Network (RWQMN), which includes deployment of water quality data sondes in streams to collect continuous monitoring data for five parameters (temperature, dissolved oxygen, pH, specific conductivity, and turbidity). This well-established network consists of 59 sites throughout the Susquehanna River Basin and affords Commission staff a wealth of continuous monitoring data to leverage into other scientific applications. In this yearlong case study in five test watersheds, the relationship between suspended sediment (SS) and turbidity across a range of flow regimes was examined using continuous turbidity data and some novel approaches to estimating sediment loads.

Sediment loading is a high profile issue within the Susquehanna River Basin, particularly as it relates to the Chesapeake Bay and the maximum sediment holding capacity of Conowingo Pond and other reservoirs. In addition, recent unconventional natural gas (UNG) drilling development within largely rural areas of the northern tier of Pennsylvania has fueled concerns about increasing turbidity and sedimentation. The Middle Susquehanna River Subbasin contains some of the most intense and dense networks of unconventional gas drilling activities within the entire Susquehanna River Basin alongside large expanses of agricultural lands. Both these activities can impact stream sedimentation and make the Middle subbasin an excellent test location for this type of sediment-turbidity study (Figure 1).

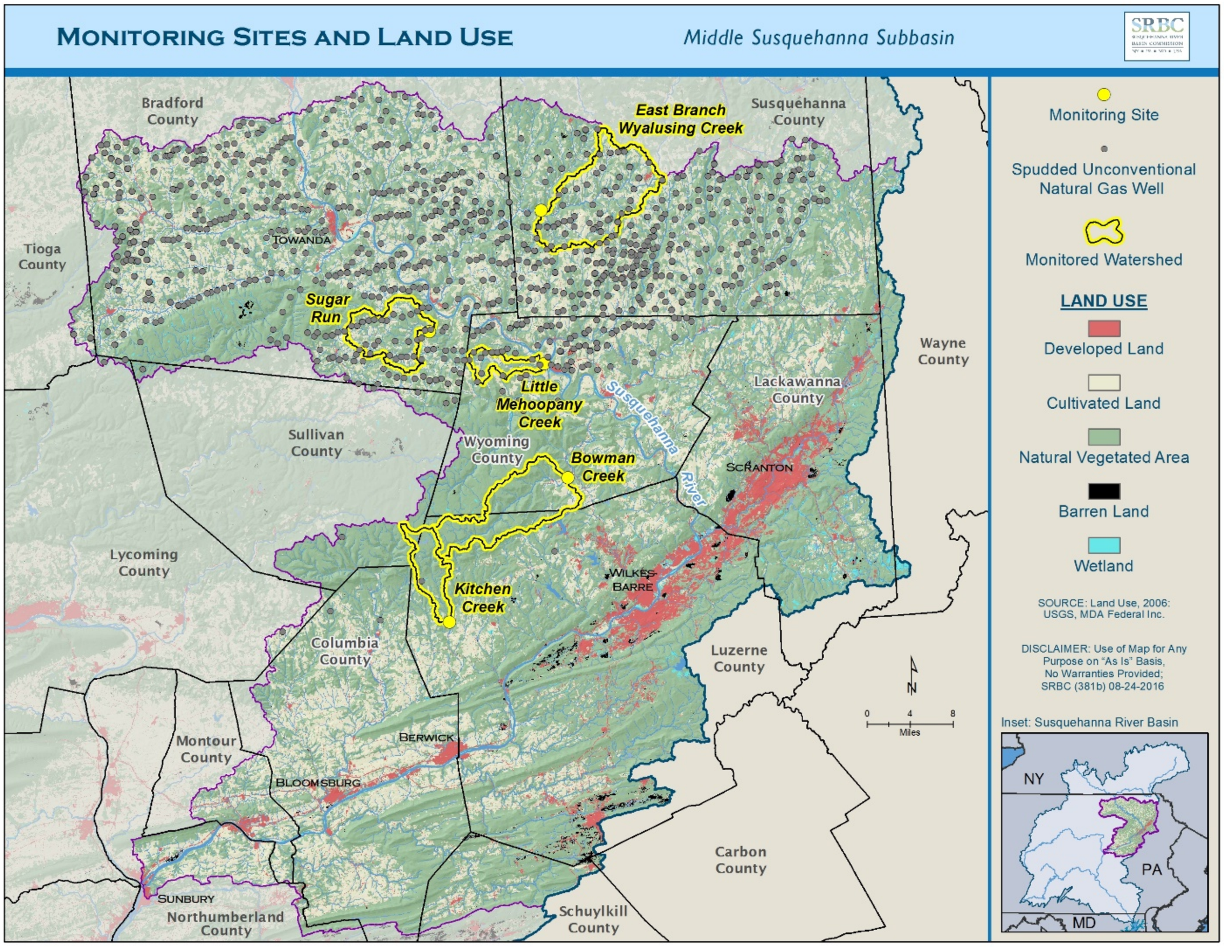


***Figure 1.*** ***Map of Test Watersheds in the Middle Subbasin, with Land Use and UNG Well Locations***

The technique of using in-situ optical sensors to indirectly measure suspended sediment concentrations is not a new idea and has been proposed, used, and presented in numerous scenarios (Gippel, 1995; Uhrich and Bragg, 2003; Pavanelli and Bigi, 2005; Jastram et al., 2009). The Commission is involved in numerous projects that collect discrete suspended sediment samples during baseflow and stormflow conditions in which loads are calculated using continuous flow records. However, sediment loads coming from smaller systems are largely unknown and are difficult to estimate without rigorous field data collection. This work explores the utility of using continuous turbidity data as a surrogate for suspended sediment at five case study sites, all of which are ungaged and drain less than 60 square miles and are mostly forested watersheds (Table 1).

Short-term project goals for each site included the following: correlate suspended sediment and turbidity, create usable stage versus discharge rating curves for each site, provide a means to estimate sediment loading using continuous turbidity and stage readings, and calculate yields for each watershed. Longer-term goals include improving confidence in continuous turbidity data, further exploring the relationship between sediment and phosphorus and expanding results of this work to include broader applicability across the Basin.

***Table 1. Watershed Characteristics of Five Test Streams***

| | drainage area (sqm) | % forest | % agriculture | % developed | gas wells/sqm (thru 6/2014) |
|---|---|---|---|---|---|
| **Little Mehoopany Creek (LMehoop)** | 11 | 68 | 26 | 3.8 | 2.18 |
| **Kitchen Creek (Kitchen)** | 20 | 84 | 10 | 3.2 | 0.05 |
| **Sugar Run (SugarRun)** | 33 | 65 | 30 | 4.3 | 1.45 |
| **Bowman Creek (Bowman)** | 54 | 90 | 7 | 1.9 | 0.02 |
| **East Branch Wyalusing Creek (EBWY)** | 50 | 50 | 45 | 5.0 | 3.22 |

## METHODS

Continuous turbidity data were collected at 15-minute intervals using a 6600 series YSI data sonde at each site as part of the Commission's RWQMN project. Real-time data collection has been ongoing at each of the five test sites since at least 2012 and sonde maintenance and data correction were completed as directed by the standard protocol for that project (SRBC, 2015). In early 2015, pressure transducers were installed in conjunction with the previously established RWQMN set up, to report level height of water based on pressure.

Twice monthly for the 2015 calendar year, stream discharge measurements and suspended sediment samples were completed at each of the five test sites. The instantaneous flow measurements were paired with recorded water level readings taken by pressure transducers to create a site-specific rating curve for each site. Average daily flow (ADF) records were estimated using the linear regression equation from the rating curve relationship. The goal in rating curve development was to include the widest range of flow magnitudes as possible and create a power curve relationship. In cases where rating curve predicted flows exceeded the range of the observed flows, flows were estimated using reference gages to avoid biases resulting from extrapolation outside of observed measurements. Optimal reference gage relationships were identified for each site using Baseline Streamflow Estimator (BaSE) software (Stuckey et al., 2012) followed by an examination of best fit correlation between methods (Markowitz, 2015). ADF values outside the predictive range of the rating curve were estimated by either 1) using linear regression equations developed from field measured flows at the ungaged locations and concurrent ADF values at nearby unregulated USGS gaging stations, or 2) by multiplying the ratio of the ungaged drainage area and USGS gaging station drainage area by the USGS gage ADF value. In creating a daily flow record for 2015, reference gage derived flows were used for days when on-site rating curve predicted flows that exceeded the range of measured flows or when pressure transducer data were not available. Where mean daily turbidity values were recorded as negative due to equipment malfunction or calibration uncertainties, a conservative value of 0 turbidity was used as a daily mean for that day. Sediment yields were calculated as US pounds per acre (lbs/acre) for each site based on the 14 month total loading to create a comparable unit of measure across watersheds. Loads were calculated by multiplying the volume of flow by the measured concentration of the constituent and area reported as mass in a given time period. Daily suspended sediment loads were calculated using the estimated daily SS concentrations and the average daily flow records and then aggregated by month (Figure 5).

The R software package loadflex was used to estimate daily SS concentrations and monthly/annual SS loads using both ADF and turbidity data as covariates (Appling et al., 2015). Two methods were used to estimate SS loading; the first method used only ADF data and discrete sediment samples. The second method used average daily turbidity data to estimate average daily sediment concentrations, and then each daily sediment concentration was paired with average daily flow to calculate a daily load.

A minimum of one storm was intensively sampled using ISCO autosamplers on a discretely sampled 30-60 minute time interval over a 12-24 hour period. Linear regression was used to determine the relationship between the natural log of instantaneous sediment concentrations and turbidity measurements during runoff events.

# RESULTS

## Turbidity Method

*Calculation of Sediment Loads*

During the 14-month period of January 2015 – February 2016, the continuous turbidity profile for each of the five streams was unique (Figure 2). Average daily turbidity at all locations was generally low, as is expected in small forested watersheds, but was punctuated with brief spikes of high turbidity from rain events. The magnitude of these spikes differed greatly between watersheds, despite their relatively close proximity. The two smallest watersheds, Kitchen Creek and Little Mehoopany Creek, rarely had an average daily turbidity above 50 NTU, which is likely a function of the flashiness of stormflows through smaller systems combined with a high percentage of forested land cover. While 15 minute readings were much higher than 50 NTU, the daily average rarely was.

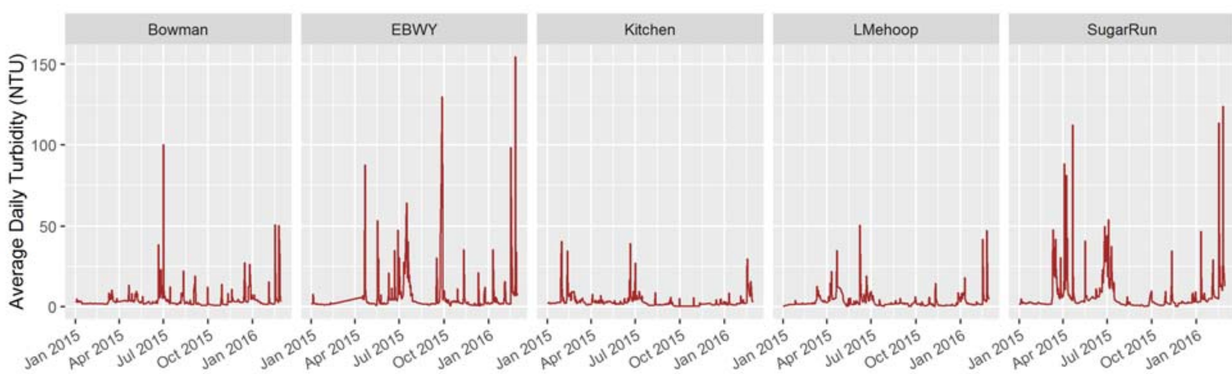


***Figure 2. Continuous Average Daily Turbidity Profile for All Sites, January 2015-February 2016***

The relationship between the natural log of instantaneous sediment concentrations and turbidity measurements was used to determine the estimated daily sediment concentration throughout the study period (Figure 3). A prediction interval was also calculated around the data, which can vary widely depending on the site-specific relationship between sediment and turbidity, especially at high values.

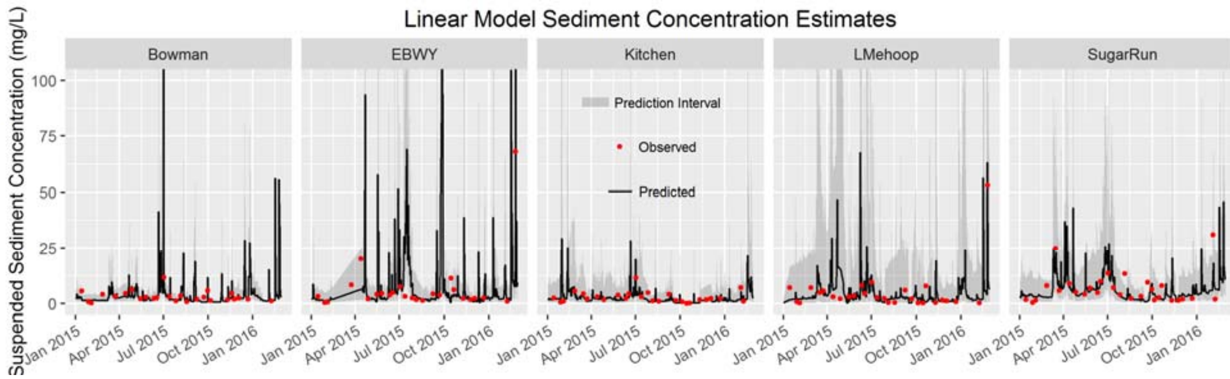


***Figure 3. Estimated Daily Suspended Sediment Concentrations for All Sites, January 2015-February 2016***

For each of the five sampling stations, a continuous ADF record was compiled using stage-discharge rating curves developed specifically for each stream location. When stage height predicted flows outside of the extent of the rating curve, reference gage based flow data were used for those days. As with turbidity, ADF varied greatly between sites (Figure 4). Not surprisingly, the two largest watersheds, Bowman Creek and East Branch Wyalusing Creek, had the highest magnitude of recorded average daily flows.

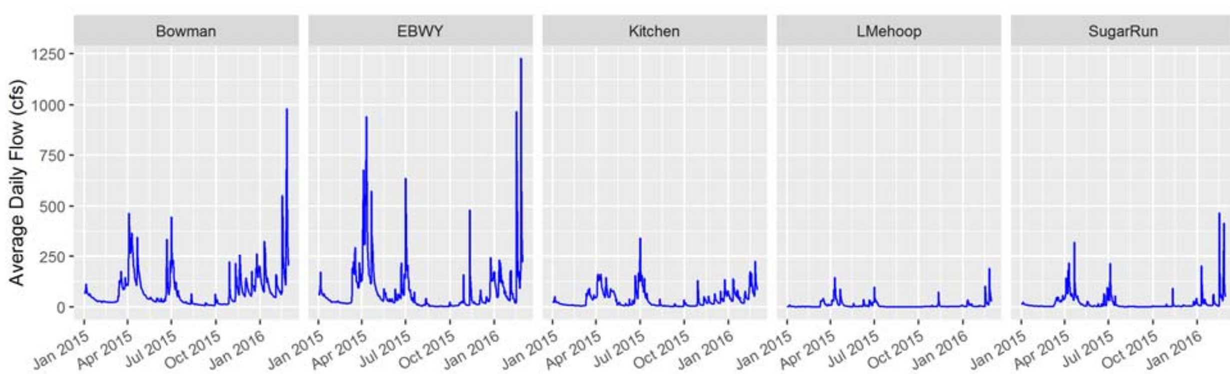


***Figure 4. Continuous Average Daily Flow Record for All Sites, January 2015-February 2016***

Daily suspended sediment loads were calculated using the estimated daily SS concentrations and the average daily flow records and then aggregated by month (Figure 5). This loading model is based on the relationship between SS and flow and error bars indicate upper limit of prediction interval. Notable observations include temporal trends across watersheds which vary widely in magnitude of sediment loading. For the 14 month study period, SS loads ranged from 140 tons in Little Mehoopany Creek to more than 1,700 tons of sediment at East Branch Wyalusing Creek.

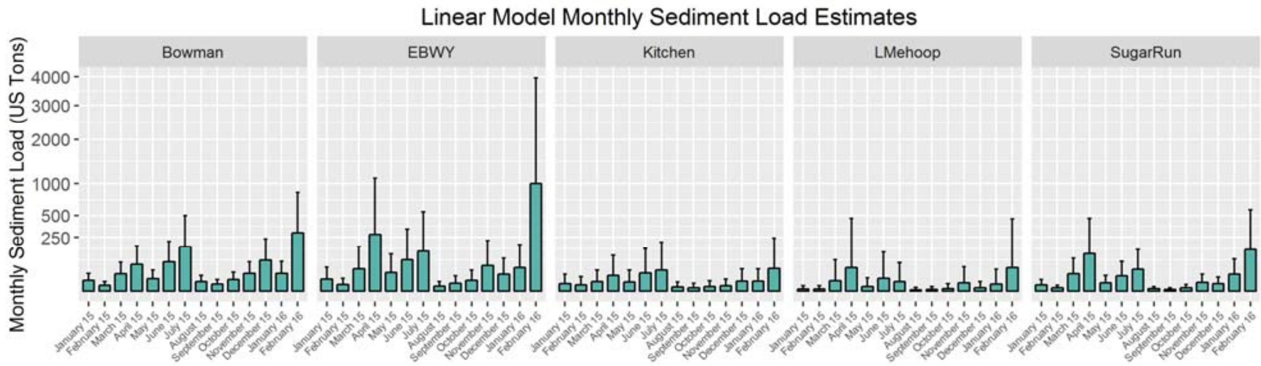


***Figure 5.*** ***Monthly Suspended Sediment Loading Estimates for All Sites, January 2015-February 2016 (Y-axis is shown in square root scale is order to allow a wide range of values to be visible.)***

In order to compare the amount of sediment being transported between watersheds, loading estimates were divided by watershed size to calculate a yield, in tons per acre (Figure 6). The estimates of SS yield allow for more in-depth standardized analysis across sites and create a normalized unit for regression analysis. Yields were estimated based on SS estimations and streamflow and the error bars indicate the upper limit of the confidence interval.

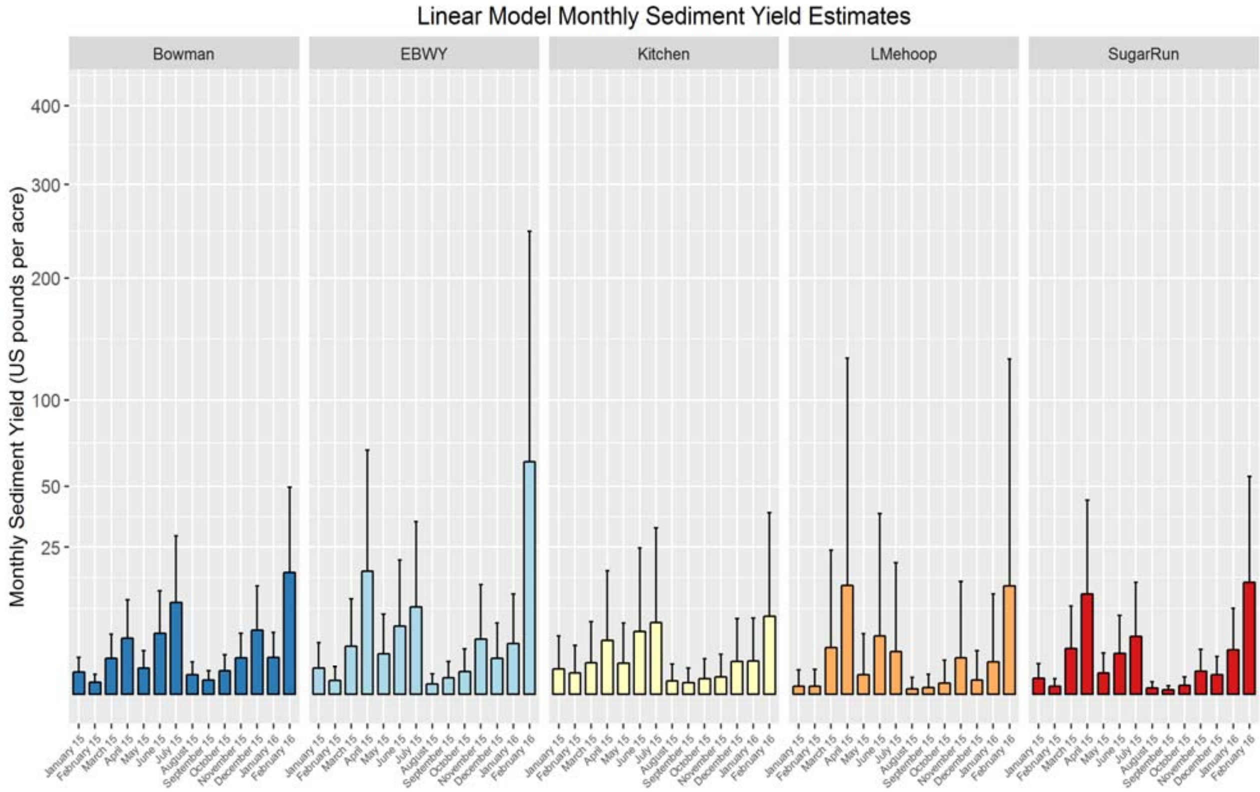


***Figure 6. Monthly Suspended Sediment Yield Estimates for All Sites, January 2015- February 2016 (Y-axis is shown in square root scale is order to allow a wide range of values to be visible.)***

Monthly yields vary across sites, but a general pattern of which months had the highest yields through the study period is consistent. Unlike sediment loading, the largest yields are not always in the largest watersheds in a given month. For example, in April 2015, Little Mehoopany Creek had a monthly yield of 48 tons/acre while Kitchen Creek, which is double the size, had a yield of 22 tons/acre. Annual differences in weather are also reflected in this dataset, as January and February 2016 generally had higher yields than the same months in 2015. A milder winter with little snow and less ice accretion on streams seems to promote higher sediment loads during those winter 2016 months as precipitation comes as rain instead of snow. Also notable are the considerable sediment yields, even in months when flows are consistently lower, such as October and November.

*Relationships Between Land Use and Suspended Sediment Yields*

Natural watershed characteristics such as slope, annual precipitation, depth to bedrock, percent glacial geology, drainage quality, and predominant soil type across all five watersheds were relatively similar given their spatial proximity. However, anthropogenic watershed characteristics such as land use and well density vary widely among watersheds. Regression analysis revealed notable relationships between percent forest, percent developed and percent agriculture and suspended sediment yield for the study period (Figure 7). UNG well drilling is prevalent in the Middle Susquehanna River Subbasin, so well density was calculated for each watershed to evaluate potential correlation with SS yields. However, there is a strong positive correlation between percent agriculture and UNG gas well density (Pearson $r$ = 0.96, P < 0.001), which produces similar regression analysis results. It is likely that the agricultural land use is more influential in driving the sediment loading than is the density of UNG wells.

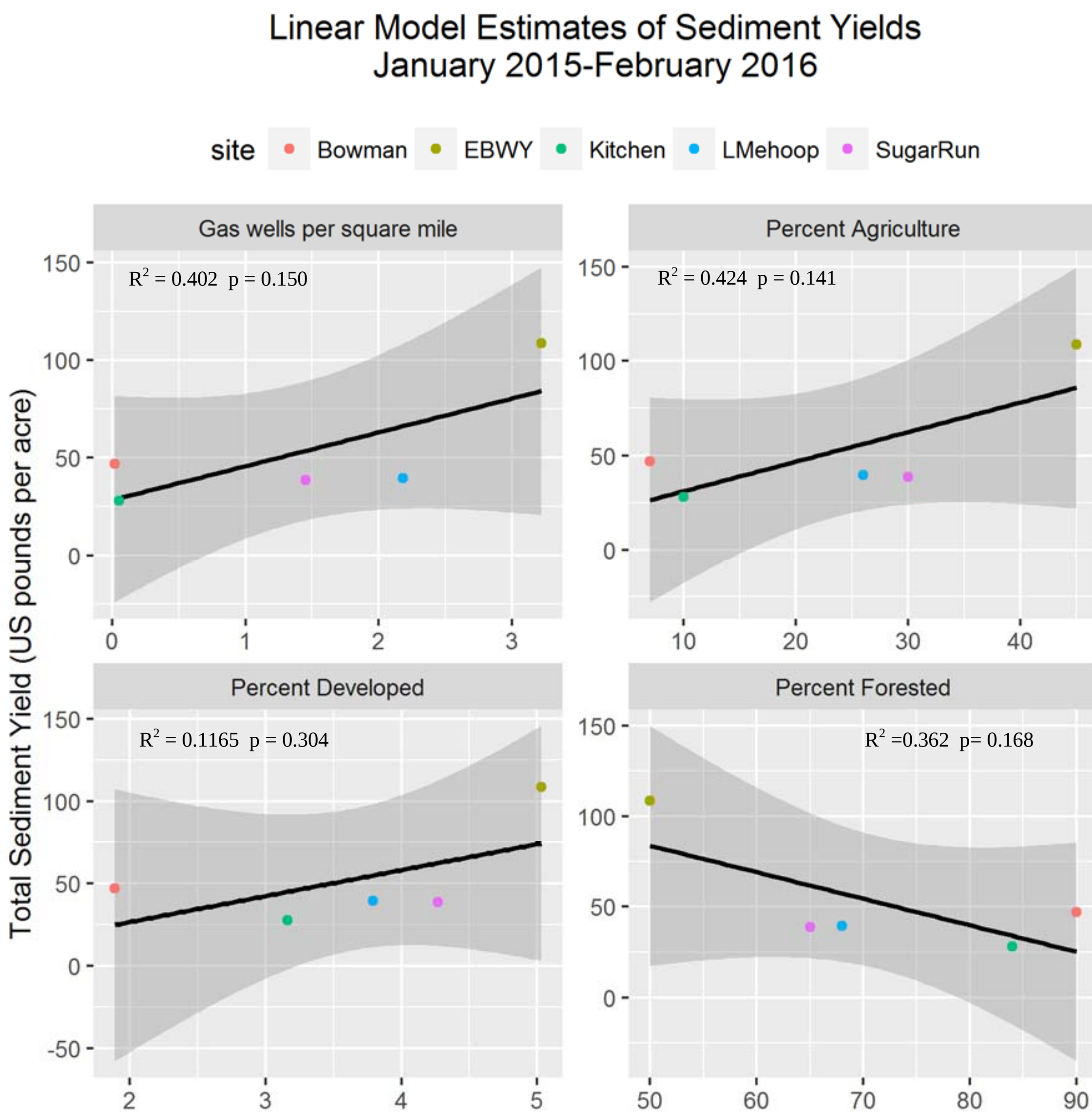


***Figure 7. Regression Analysis between Sediment Yield and Landscape Variable***

*Impacts of Storm Events*

Storm events carry the majority of SS in streams (Wolman & Miller, 1960; Webb & Walling, 1982). With increasing rainfall intensity (both amount and rate) more sediment is delivered from upslope watersheds to receiving streams and transported within streams. One storm was sampled in all watersheds, with two storms sampled in Bowman Creek. Data from this study demonstrate that even relatively small storms can account for a majority of the monthly loading for a given stream. These data from runoff events showed a very strong linear correlation between turbidity and suspended sediment (Table 2). The high frequency data collected during storm events allowed for a closer examination of how modeled SS aligns with turbidity, flow and observed SS concentrations. A consistent pattern of turbidity peaking just prior to peak flow events was observed at all sites. Monthly plots of sediment loading for each stream location, visually demonstrate the proportion of a specific month's sediment load that can be accounted for by a single high flow event (Figure 8).

***Table 2. Summary of High Frequency Data Collected During Storms at Each Site***

| Date of Storm | $R^2$ of sediment vs turbidity | p-value | Storm load (US tons) | max flow (cfs) | max turbidity (NTU) | % of monthly SS load |
|---|---|---|---|---|---|---|
| **BOWMAN CREEK** | | | | | | |
| **9/30/2015** | 0.933 | <0.001 | 3.35 | 109 | 22 | 58 |
| **11/19-20/2015** | 0.953 | < 0.001 | 15.60 | 440 | 37 | 75 |
| **EAST BRANCH WYALUSING CREEK** | | | | | | |
| **2/25-26/2016** | 0.959 | < 0.001 | 1022* | 1648 | 1143 | 102* |
| **KITCHEN CREEK** | | | | | | |
| **2/4-5/2016** | 0.951 | <0.001 | 2.04 | 136 | 22 | 4.5 |
| **LITTLE MEHOOPANY CREEK** | | | | | | |
| **2/24-25/2016** | 0.988 | <0.001 | 143* | 255 | 935 | 317* |
| **SUGAR RUN** | | | | | | |
| **2/4/2016** | 0.528 | <0.001 | 8.12 | 248 | 73 | 5.3 |

*High frequency data collection resulted in a higher calculated sediment load for this storm than was estimated for the entire month of February using average daily values for both sediment and flow.

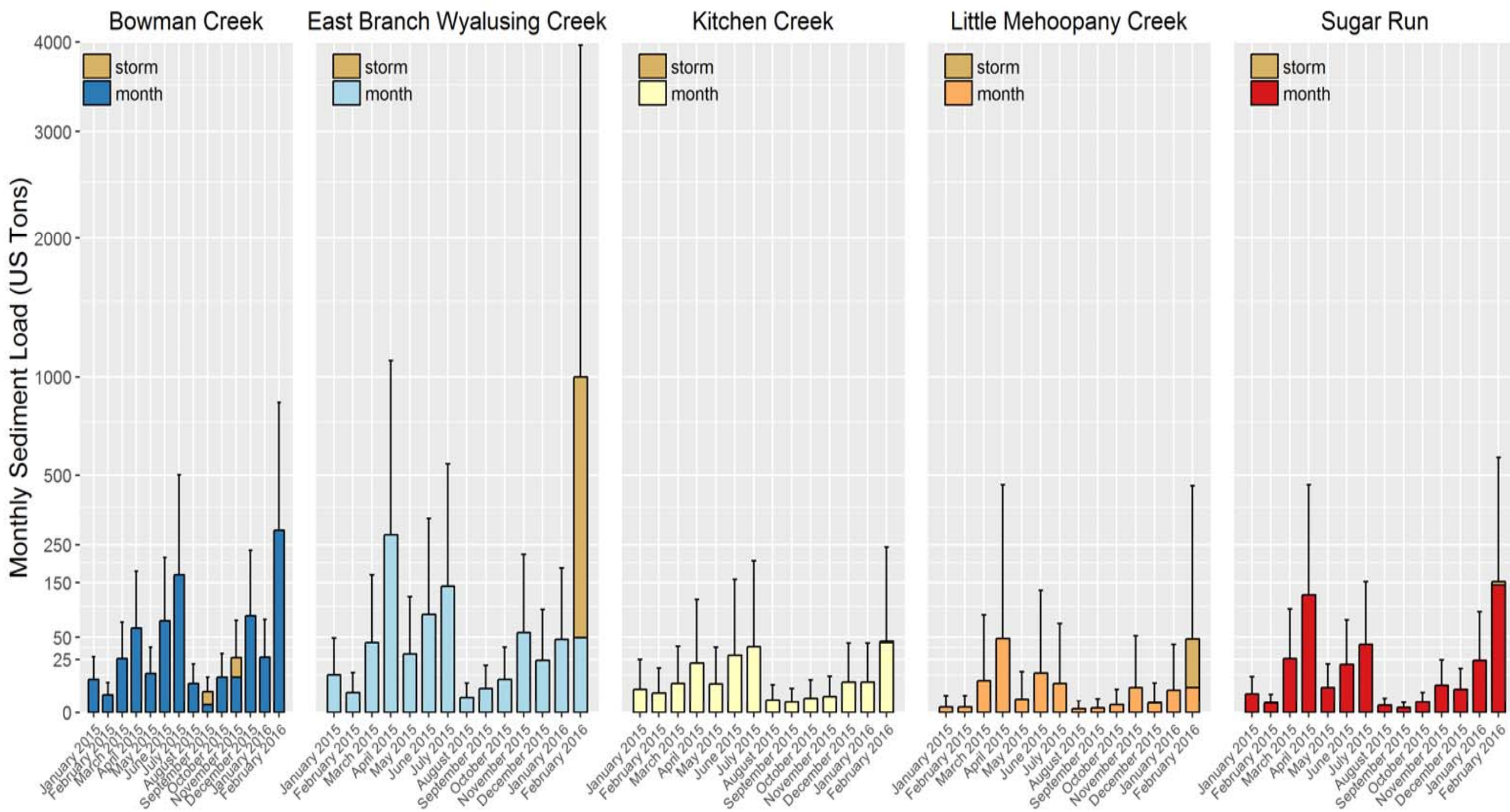


***Figure 8. Monthly Sediment Loads for All Five Sites, Showing Storm Contribution (Y-axis is shown on a square root scale to allow a wide range of values to be visible.)***

## Flow Method Comparison

Traditional methods of computing sediment loads were often based on a linear regression model that uses only discrete SS samples and flow records. For comparison, sediment load estimations were also computed using this Flow Method as a way to compare the calculated sediment loads for each method. The Flow Method does not take turbidity data into account in any manner.

For four of the five sites, the Flow Method resulted in considerably different results than the Turbidity Method in estimating the total amount of SS loading (Figure 9). The Flow Method underestimates loadings in Bowman, EBWY, and Sugar Run. Interestingly, the Flow Method over-predicts SS loading at Kitchen Creek. Kitchen Creek is notably clear and for the 14-month study period, the average daily turbidity was 3.1 NTU.

All sites showed a different temporal pattern when comparing the two methods (Figure 10, example presented is from Bowman Creek). The Flow Method, predictably, estimated sediment loading to be highest during the spring time when flows are naturally higher. In contrast, the Turbidity Method incorporated the influence of smaller runoff events where flow may not increase much but where turbidity can be 10-20 times normal baseflow conditions. These sorts of lower flow but higher turbidity conditions most often occurred in summer and early fall during the study period. Even when flows are higher, turbidity remains relatively low. While Figure 10 illustrates just one example, these differences in temporal trends when using different methods are apparent at all sites.

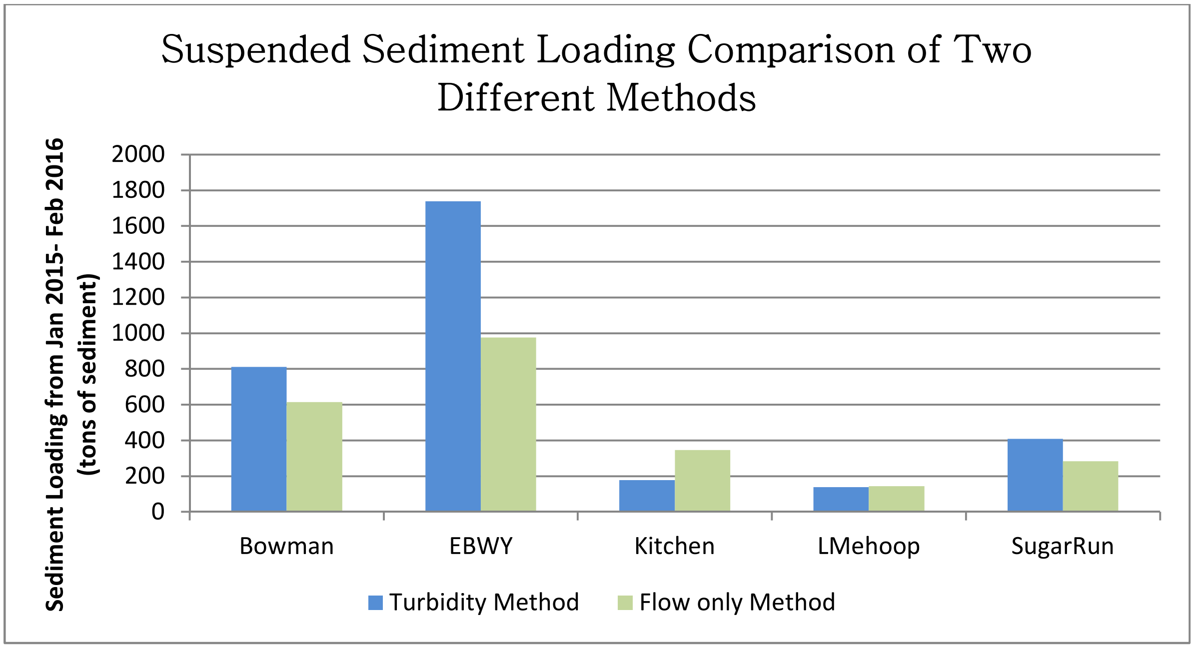


*Figure 9.* ***Comparison of Sediment Loading with Turbidity and Flow Only Methods***

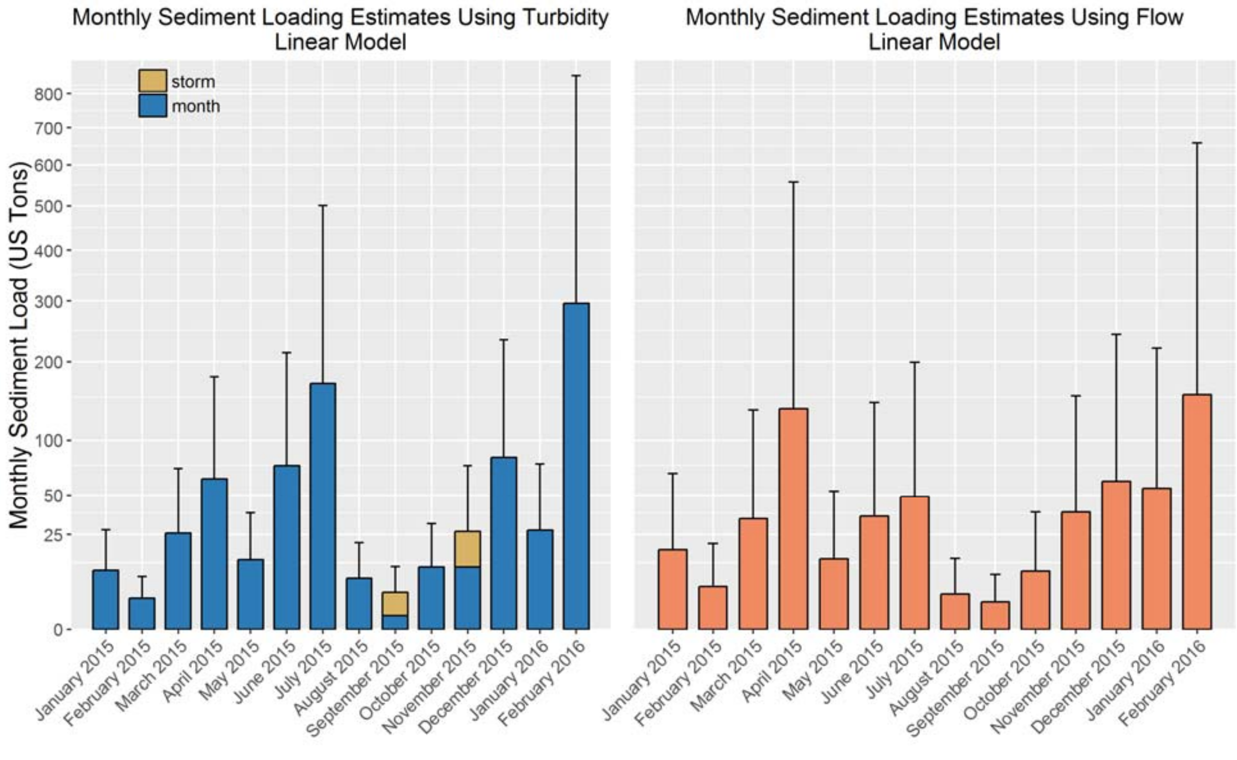


***Figure 10. Comparison of Monthly Loads Using Two Different Methods of Estimation, Bowman Creek***

As a result of all sites being located in the same general geographic area, their natural watershed characteristics varied minimally. The major differences between watersheds were drainage area size, and anthropogenically driven variables such as land use, including UNG well development. By using yield (tons/acre) as a standardized unit of measurement, the impact of drainage area was removed, leaving land use as the driving factor behind differences in sediment yields. Even with only five data points, the positive correlations between increased sediment yields and increased development and agricultural land uses are evident. In contrast, the negative relationships between lower sediment yields in watersheds with higher percent forest cover are also observable.

The importance of site-specific flow measurements became very clear during this analysis. Because of the differences in local rainfall pattern, timing in how rainfall is delivered to specific streams and drainage size differences, turbidity tracked flow much more closely with on-site flow measurements compared to estimated flows derived from reference gages. The use of on-site gaging is especially critical when estimating sediment loads during high flow events, which is when a majority of the sediment loading occurs. In order to most accurately estimate sediment loads for a given storm, accurate pairing of turbidity and flow peaks are crucial. Pairing highest turbidities recorded on-site with an off-site flow record can result in considerable underestimation of sediment loads (Figure 11).

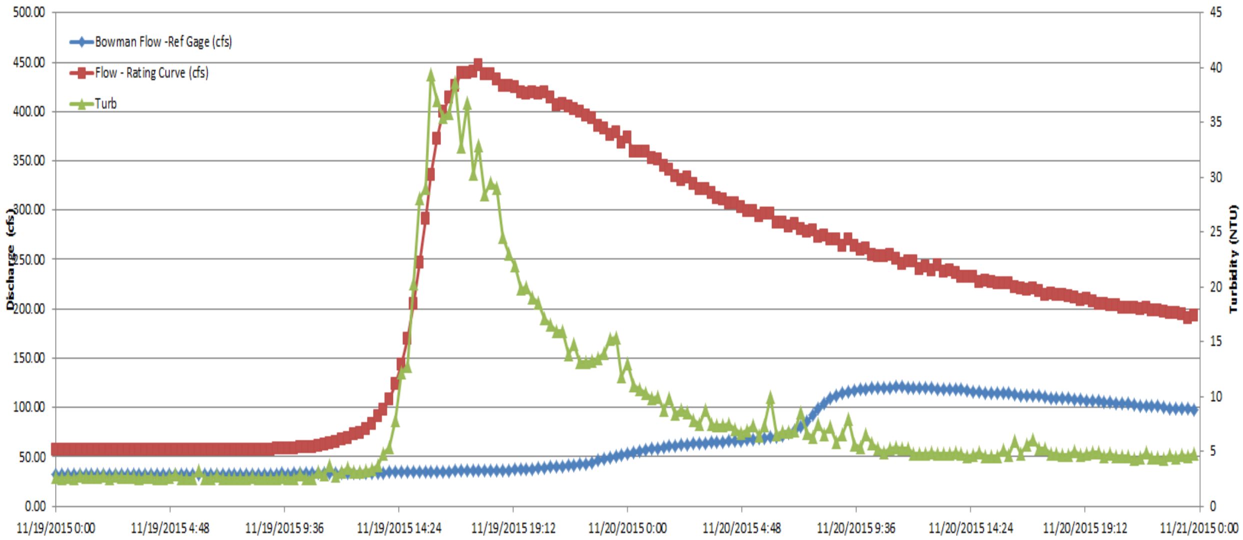


***Figure 11.*** ***Example of Timing Discrepancies for High Resolution Storm Data using On-site Rating Curve Flow Records versus Reference Gage Derived Flow Records, Bowman Creek, November 2015 (The blue line represents predicted flow record over the period of elevated flows from the storm based on the recorded flow data at the reference gage for this site. The red line represents the actual flow record based on flow data derived from stage height data taken at the site during the storm. The green line shows the continuous turbidity data recorded by the data sonde.)***

Estimating the contributions of storms was an important component of this study, as most of the sediment loading happens as a result of rain runoff from the landscape. Because sediment data were collected at close intervals (30-60 minutes), storms could be modelled using 15-minute turbidity and flow data as opposed to the average daily turbidity and ADF used in the general monthly analysis. At three of the sites, the storms captured were relatively small and many ADF and turbidity values over the study period were higher than the modeled storm.

However, at Little Mehoopany Creek and East Branch Wyalusing Creek, the same late February 2016 storm was captured and at both sites it represented the highest ADF and turbidity recorded in the entire study period (Figure 12). As a result, the fine scale resolution that was used to model these storms provided estimates for that two-day storm that exceeded the monthly estimates, which only use daily resolution.

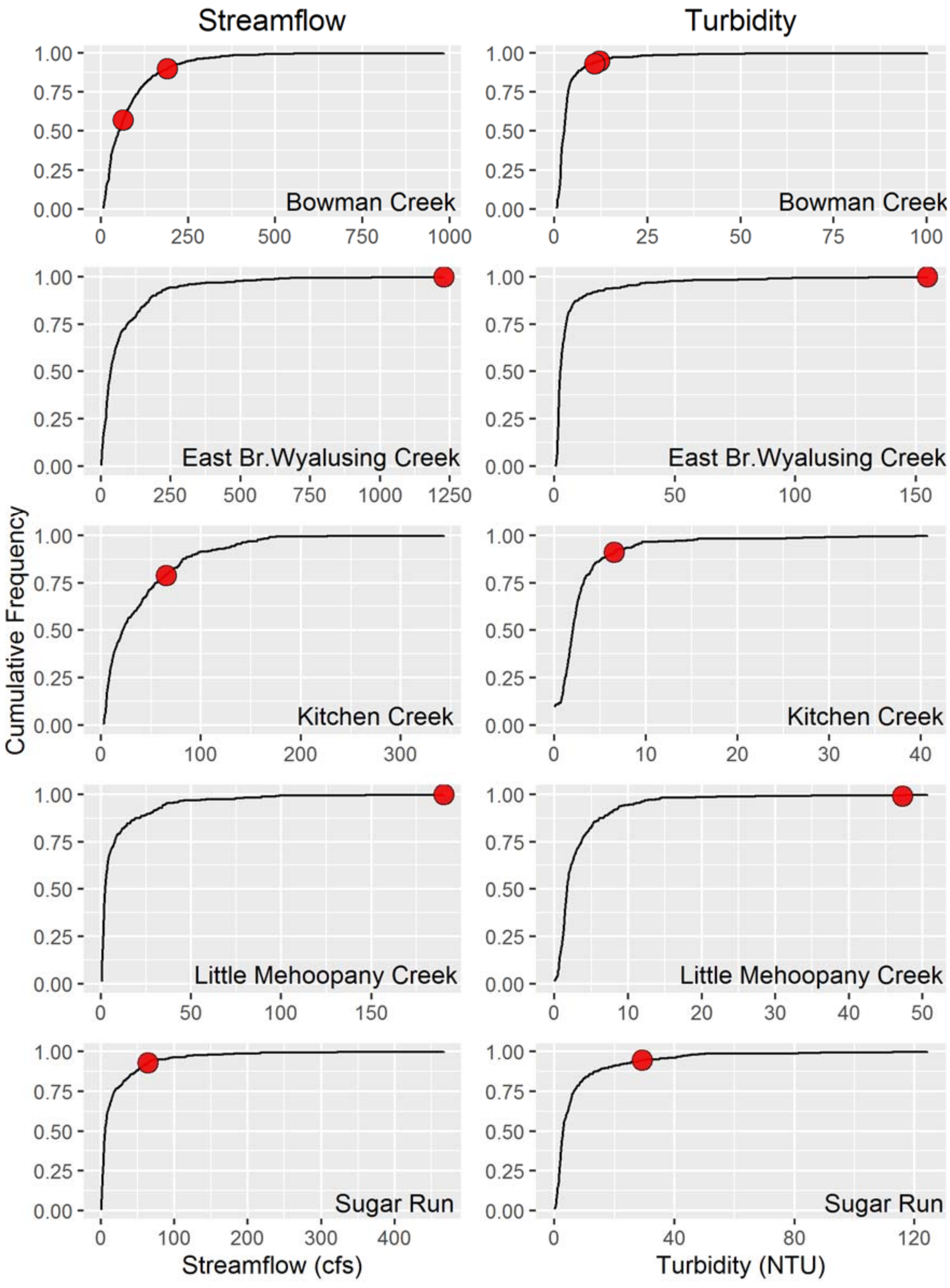


***Figure 12. Cumulative Frequency Plot Indicating Streamflow and Turbidity During Modeled Storm***

## CONCLUSIONS

Our results indicate that sediment loading can be accurately estimated in small ungaged streams in the Middle Susquehanna River Subbasin by continuously monitoring turbidity and streamflow, with little additional effort necessary to collect discrete suspended sediment samples on-site. Ranges in the magnitude of turbidity and flows varied throughout the study period, but similar general relationships were observed across all sites. Land use within the watershed showed a strong relationship with sediment yields. Watersheds with a greater proportion of forested land use had lower yields (lbs/acre), while as development and agricultural land use increased, so did sediment yields.

Turbidity is not the perfect surrogate, however. The relationship of turbidity with SS can be highly variable especially at low values (Figure 13), which underscores the importance of capturing a large range of paired SS and turbidity values. Turbidity data are noisy and prone to exclusion during data correction, but using turbidity profiles in addition to flow data better reflects instream conditions. Using turbidity to estimate SS concentrations acknowledges that variations in sediment concentration may be highly variable during similar hydrologic conditions based on precipitation intensity, seasonality, and upstream land use. We anticipate testing these methods in watersheds in other regions of the Susquehanna River Basin.

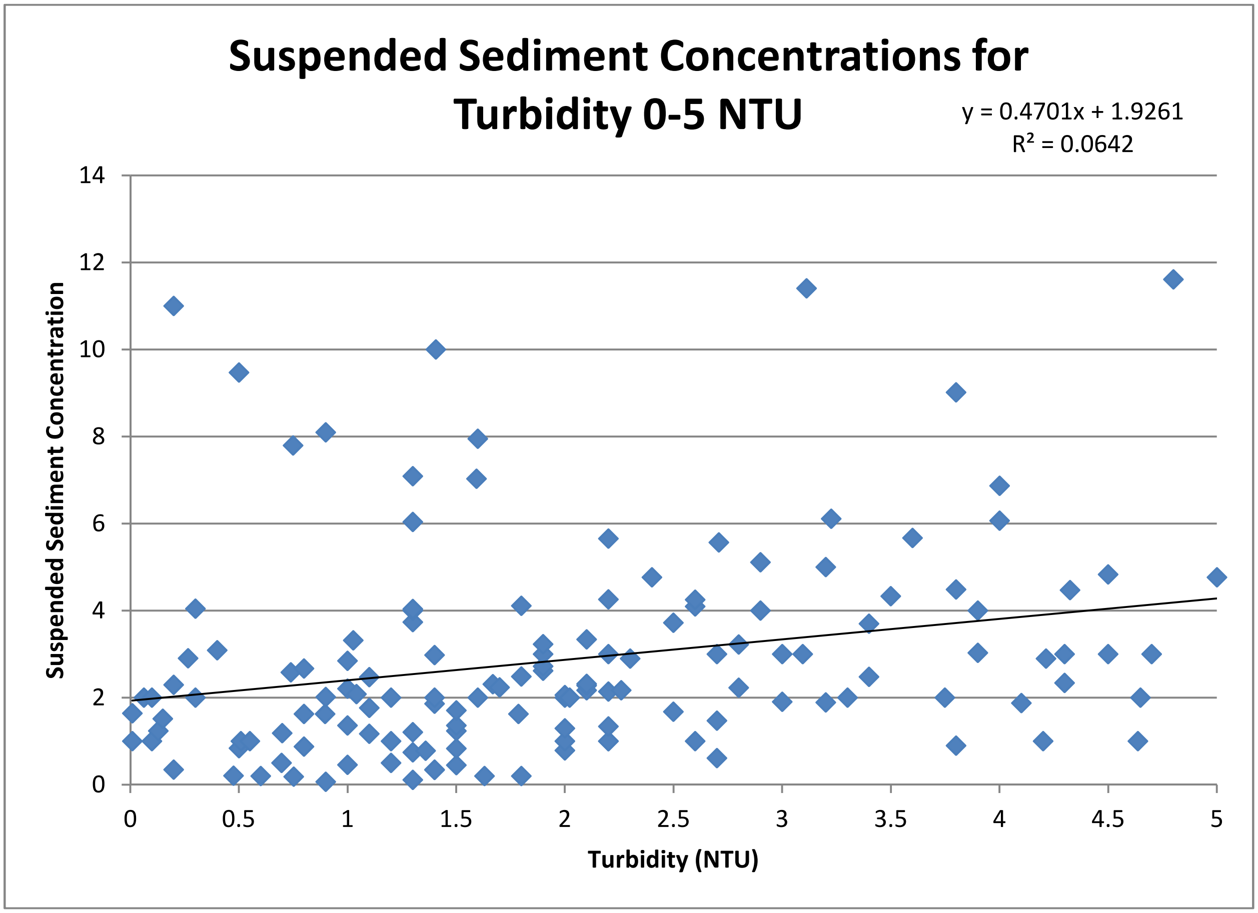


***Figure 13. Sediment –Turbidity Relationship for Turbidity Values < 5 NTU***

## LESSONS LEARNED

- The best possible turbidity data come from diligent maintenance of turbidity probes;
- There exists a very noisy relationship between sediment and turbidity at < 5 NTU;
- On-site rating curve development yields much more accurate results compared to reference gage-based flow records;
- High paired turbidity and SS observations are essential so linear model not driven by only one high value;
- High flow does not always equate to high SS and low flow does always equate to low SS;
- Turbidity values frequently peaked prior to the arrival of peak flows and

- Turbidity is not the perfect surrogate, but using turbidity is advantageous over methods that rely only on flow.

## APPLICATIONS

These methods can be easily transferred to any stream location where continuous turbidity data are available. Varying levels of effort and cost can be applied depending on the desired goals of a particular project. Discrete sediment samples should be taken on at least a monthly basis, in order to capture temporal variability. In addition, high flow events should be targeted, ideally one in the spring and one in the summer/fall. As with any model estimation, the more data that are incorporated into the model, the more accurate and robust the estimates will be. However, the range and type of data collected are as important as the number of samples taken. On-site flow records proved to be critically important in improving the precision of the SS loading estimates. In the absence of a USGS gage, using stage-discharge rating curves created from pressure transducers paired with instantaneous flow measurements over a wide variety of flow regimes is ideal. However, when project objectives are more for screening purposes or where on-site rating curve development is cost prohibitive, continuous flow records can be approximated from existing USGS gage data.

## FURTHER RESEARCH OPPORTUNITIES

It is possible that the sediment – turbidity relationships of streams in other geographic settings will not behave as similarly as the five sites in this study did. Continuous turbidity data are already being recorded at all 59 RWQMN stations within the Basin. If paired sediment and turbidity data from each station can be compiled, characterized, and analyzed, one or more models could be created to estimate sediment loads and yields across broad geographic areas with little new data collection necessary.

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