Continuous Water Quality Trends Adjusted for Seasonality and Streamflow in the Susquehanna River Basin

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EXECUTIVE SUMMARY

In 2010, the Susquehanna River Basin Commission established a real-time, continuous remote water quality monitoring network (RWQMN) to monitor headwater streams for potential impacts from natural gas drilling and other activities in the Basin. The unconventional natural gas (UNG) industry was rapidly expanding in the Susquehanna River Basin and the majority of the activity was located near headwater streams. Continuous water quality parameters collected at each site included pH, specific conductance, water temperature, dissolved oxygen, and turbidity. Fluctuations of these parameters may be, in part, due to the natural range of variability, changes in land use/land cover including agriculture, urban, and forest cover, potential impacts from natural gas drilling, or changes in climate and the hydrologic regime.

At the conclusion of 2015, 53 of the 59 monitoring stations had a range of 36 to 72 months of data which was sufficient to begin preliminary trend analysis. Longer periods of record and/or more intensive sampling frequency generally provide a greater sensitivity to detect changes in water quality parameters. There is potential that observed, statistically significant trends depicted from a limited time period may be more-representative of the variability in time-series data rather than a long term monotonic trend. Statistical trend analysis can be used to examine trends and evaluate the rate of change, but does not provide insight in attributing a trend to a particular cause. For this reason, streamflow and seasonality need to be accounted for in order to determine if water quality is changing over time and if those changes can be attributable to anthropogenic activities. Instantaneous streamflow data were not available for 49 out of 53 of the RWQMN site locations; therefore, average daily flow records for each ungaged RWQMN station were estimated using field measured streamflows and United States Geological Survey (USGS) reference gage data. The drainage area ratio (Emerson et al., 2005) and streamflow correlation methods (Hirsch, 1979) were used to provide an estimated long-term record of daily mean streamflow at these sites. The specific method used for each site depended on the highest correlation coefficient observed between the two methods and the number of streamflow measurements acquired in the field at each site.

Seasonal Mann-Kendall tests and Locally Weighted Scatterplot Smoothing (LOWESS) were used to account for streamflow and seasonality in the water quality trends. Significant water quality trends ($\alpha \leq 0.05$) were noted for 57 individual parameters (22 percent) at 40 stations (75 percent). Twenty-four of the stations experienced increasing specific conductance trends, although 10 of the watersheds illustrating these trends have not experienced natural gas activity. The presence of actively fractured wells coincided with 14 out of 24 stations where increasing specific conductance trends were observed. When comparing watershed characteristics of stations with increasing specific conductance trends to those with no observable trends, no significant differences ($\alpha \leq 0.05$) between the two groups were observed. As such, it was determined that the land use composition in each watershed, density of natural gas wells, and watershed size are not driving specific conductance water quality trends. The stations trending upward are located in both shale and sandstone geology and throughout two Level III ecoregions. Ecoregions are areas with similar climate, geology, and soils; typically water chemistry and aquatic biology are similar within streams in an ecoregion.

Ten stations were found to exhibit significant dissolved oxygen and pH water quality trends. Dissolved oxygen increased at eight stations, which can be beneficial, particularly for macroinvertebrate populations and coldwater species such as trout. A decreasing trend for pH was identified for nine stations. The optimal pH range is between 6-9 (on a range of 0-14); therefore, a decreasing trend can be both beneficial and adverse. There were five stations with significant water temperature trends observed: two with decreasing temperatures and three with increasing temperatures. Turbidity concentrations were decreasing at four stations and increasing at three stations.

It is important to consider that these water quality trends were determined using a limited dataset (three-six years of continuous data) and predominantly estimated streamflow conditions. Future plans include revisiting the water quality trends when 10 years of data are available and also evaluating the magnitude of change. Biological conditions at the stations experiencing water quality trends will also be assessed to determine if changes in water quality are being reflected in stream biota.

INTRODUCTION

In 2010, the Susquehanna River Basin Commission (Commission) established a real-time, continuous water quality monitoring network called the Remote Water Quality Monitoring Network (RWQMN) (http://mdw.srbc.net/remotewaterquality/). The initial purpose of the network was to monitor small headwater streams for potential impacts from natural gas drilling (85 percent of the Susquehanna River Basin is underlain with natural gas shales). Since 2008, unconventional natural gas extraction by means of hydraulic fracturing (fracking) has greatly increased throughout the Basin from over 600 wells being fractured by the end of 2010 to over 3600 wells being fractured by the end of 2015 (Pennsylvania Department of Environmental Protection, 2015). Out of 59 RWQMN stations, actively fractured wells were identified in 39 RWQMN watersheds; the remainder of the watersheds have not experienced natural gas activity. The applicability of the continuous, real-time monitoring network is also not only limited to the impacts of natural gas drilling. Additional activities, captured by land use/land cover changes were considered as explanatory variables influencing increases or decreases in water quality trends. The RWQMN allows the Commission and other agencies/groups to determine if water quality conditions are changing over time, monitor impacts from various activities in the watersheds, and gain an overall, better understanding of water quality conditions in headwater streams.

The RWQMN includes high-frequency, continuous monitoring stations that measure pH, specific conductance (conductance), water temperature, dissolved oxygen (DO) and turbidity. The continuous monitoring network has been in place for six years (2010-2015), which has resulted in a sufficient amount of data to begin preliminary trend analysis. In looking for trends in water quality, it is important to recognize limitations of analyzing trends with short monitoring periods and small sample sizes. Longer periods of record and/or more intensive sampling frequency generally provide a greater sensitivity to detect smaller changes. Five years of monthly data is typically the minimum required for monotonic trend (continuous rate of change, increasing or decreasing) analysis and at least two years of monthly data is required for step trend (abrupt shift up or down) analysis (Hirsch 1988). Fifty-three stations had a minimum of three years of continuous data needed to analyze for water quality trends (Figure 1) (Appendix A). Although the range of RWQMN data satisfies statistical requirements for detecting trends, there is potential that observed, statistically significant trends depicted from a limited time period may be more-representative of the variability in time-series data rather than a long term monotonic trends.

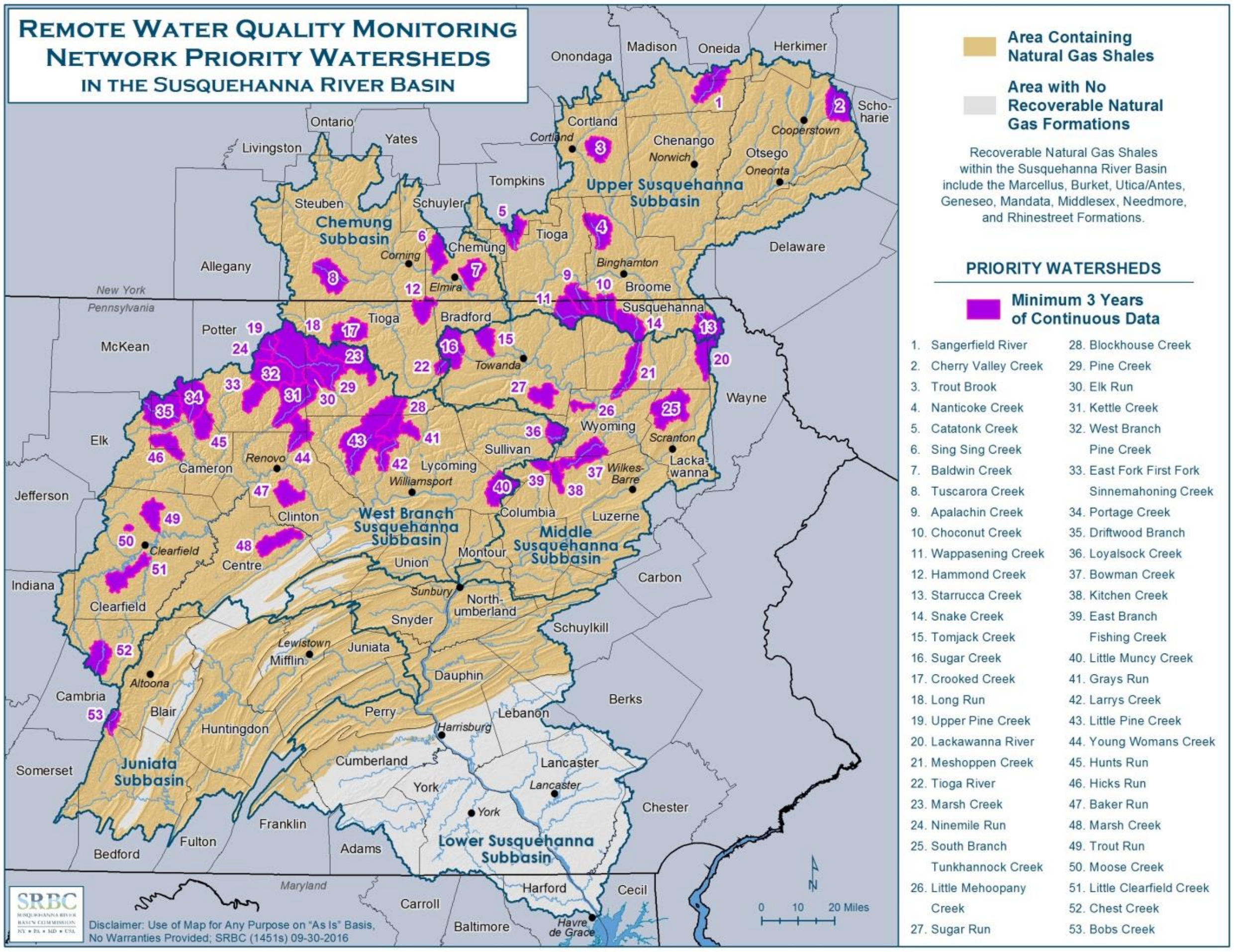

Figure 1. *RWQMN Stations with a Minimum of 36 Months of Continuous Data*

Statistical trend analysis can be used to examine trends and evaluate the rate of change, but does not provide insight in attributing a trend to a particular cause. Other than local geology and anthropogenic activities, streamflow and seasonality tend to influence fluctuations in water quality. Often, a combination of antecedent ground conditions and intense precipitation events can lead to greater streamflows capable of scouring streambeds and banks and entraining suspended sediments, which may cause potential increases in turbidity, pH, and water temperature. Conversely, during periods of little to no precipitation, groundwater influxes to streams and higher air temperatures may lead to increases in conductivity and lower DO levels. Therefore, streamflow and seasonality need to be accounted for in order to determine if water quality is changing over time and if those changes can be attributable to other external factors such as land cover/land use changes and hydrofracking activities. Locally Weighted Scatterplot

Smoothing (LOWESS) was used to smooth water quality measurements against streamflow in order to remove the impact of streamflow on water quality measurements. A seasonal Mann-Kendall test was performed on the residuals from LOWESS and the results represent water quality trends that exclude influences from streamflow and seasonality. The Mann-Kendall test (Mann, 1945; Kendall, 1975) is a non-parametric statistical test used for detecting upward or downward trends over a period of record.

DATA COLLECTION METHODS

Continuous Water Quality Data

Continuous pH, conductance, water temperature, DO, and turbidity data were collected at 5-minute intervals using a YSI, Inc. 6600 series data sonde from January 2010 to November 2015. In November 2015, the interval was changed to 15 minutes at stations utilizing cellular telemetry. The collection interval was not changed at stations using satellite telemetry because the data reported represent a 4-hour average; the discrete data are not reported. There are 33 stations transmitting data via cellular telemetry, 14 stations using satellite telemetry, and six stations transmitted data through satellite telemetry until mid-2015 when cellular telemetry became available in the watersheds. Appendix A indicates which stations utilize each telemetry source.

Once the data were received in-house, they were stored in an Aquarius Time-Series database. The Aquarius software was used to remove suspect data and correct water quality data from equipment fouling or drift (SRBC, 2016). Once the data were corrected to SRBC standards, Aquarius software was used to determine monthly mean values for each parameter at every station. These monthly mean values were used in the seasonal Mann-Kendall tests to determine water quality trends.

The five water quality parameters collected on a continuous basis influence the aquatic communities able to be sustained in waterbodies. Conductance is the measure of how well water can conduct electricity. Conductance increases as more ions are added to the water and/or as the ions become more mobile. Geology and soils influence conductance, however, changes in conductance are caused by human impacts in a watershed. Within the Susquehanna River Basin, these impacts may include abandoned mine drainage, agricultural runoff, urban runoff, and unconventional natural gas (UNG) fracking fluid spills or leaks. Aquatic life is impacted when conductance values reach 300 µS/cm in Central Appalachian streams (USEPA, 2011).

pH is the measure of a waterbody's acidity or alkalinity. Pennsylvania's water quality standard for pH is 6 – 9. A pH value outside of water quality standards can have an adverse impact on aquatic life. While some streams can have naturally acidic conditions, acidic conditions are more often related to human influences. Acid rain and acid mine drainage can significantly lower pH values. Streams with low pH will begin to release metals into the stream and streams with high pH values allow for excessive algal growth, both of which are detrimental to the stream health. Other human influences, agricultural and urban runoff, can increase pH causing basic conditions.

Dissolved oxygen (DO) in a waterbody is an important component in its ability to support aquatic life. Rapidly moving water with riffles and plunge pools will have higher levels of dissolved oxygen compared to slower moving, pooled water bodies. Cooler water temperatures will also increase the amount of dissolved oxygen in a water body. The Pennsylvania water quality standard for DO varies with the designated use of the waterbody. In order to meet water quality standards, the minimum DO level is 5 mg/l. Optimal DO levels for smaller streams is 9 mg/l; when DO drops below 3 mg/l, it is difficult for any aquatic organism to survive.

Turbidity is the amount of particulate matter suspended in the water column and can be caused by sediment, microscopic organisms, or organic/inorganic compounds. Turbidity will typically increase in a waterbody during higher flows caused by rainfall and snow melt. Overland runoff carries sediment loads to the stream and higher flows can cause streambank erosion and re-suspension of materials from the substrate.

Increased and prolonged periods of turbidity increase sedimentation in a waterbody and have inverse impacts on aquatic organisms. Turbidity can lower the DO level of a waterbody and as the sediment settles on the substrate, valuable habitat is lost for aquatic organisms. High levels of turbidity also make it difficult for water suppliers to treat drinking water.

Discrete Water Quality Data

Discrete water quality samples (Table 1) have been collected at the stations intermittently from the time the stations were installed until 2012. Since the beginning of 2012, discrete samples have been collected on a seasonal basis, with four samples collected each year. The discrete samples are collected to help understand what is driving the continuous water quality parameters. The discrete water quality results were not used in the trends analysis.

Table 1. Discrete Water Quality Parameters

Parameter	Parameter
Acidity	Lithium
Alkalinity	Magnesium
Alkalinity, Bicarbonate	Manganese
Alkalinity, Carbonate	Nitrate
Aluminum	pH
Barium	Phosphorus
Bromide	Potassium
Calcium	Sodium
Carbon Dioxide	Specific Conductance
Chloride	Strontium
Gross Alpha	Sulfate
Gross Beta	Total Dissolved Solids
Iron	Total Organic Carbon

Biological Data

Macroinvertebrates are often used to indicate the biological health of a stream. Macroinvertebrates have been collected at each station since 2011; if the monitoring station was installed after 2011, macroinvertebrate sampling started the year of installation. They are collected using the Pennsylvania Department of Environmental Protection (PADEP) Freestone Streams collection method and subsampled to a 200 count (PADEP, 2013). The taxa in the subsample are identified and scored through several individual metrics; these metrics are combined to determine the Index of Biotic Integrity (IBI) score. The IBI score is a scale of 0-100 and higher scores indicate better water quality.

STREAMFLOW ESTIMATION METHODS

Average daily flow time series were estimated for 49 ungaged RWQMN stations using field measured streamflows collected at RWQMN site locations and concurrent USGS discharge data at 30 separate reference gage locations. USGS reference gages were identified using the Pennsylvania Baseline Streamflow Estimator (BaSE) tool which uses map correlation and interpolation techniques to provide suggestions of appropriate reference stream gages for ungaged locations (Stuckey, 2012). Reference stream gages selected for this analysis were minimally altered by regulation, diversions, mining, and other anthropogenic activities, and had at least 10 years of continuous record. Regulation was defined as having upstream reservoirs that control at least 10 percent of the contributing drainage area at the stream gage.

Methods that have been used to estimate streamflow for ungaged sites include regional regression (Thomas and Benson, 1970; Bingham, 1986; Vogel et al., 1999; Sanborn and Bledsoe, 2006), rainfall-runoff models (Liu and Gupta, 2007; Wagener and Montanari, 2011), baseflow or streamflow correlation (Hirsch, 1982; Stedinger and Thomas. Jr., 1985; Reilly and Kroll, 2003; Zhang and Kroll, 2007), and the drainage area ratio method (Hirsch, 1979; Emerson et al., 2005). Hirsch (1982) states that the selection of an appropriate method depends on the relevant time step of analysis and the benefits of increased accuracy in estimation of outcomes in comparison to the cost of applying a more complex method. For these reasons, average daily streamflow was estimated and evaluated for 49 stations using the drainage area ratio and streamflow correlation methods.

The drainage area ratio method is commonly used to estimate streamflow and flow duration curves at ungaged assessment points (Emerson et al., 2005). The method is based on the assumption that the streamflow for a site of interest can be estimated by multiplying the ratio of the drainage area for the site of interest, and the drainage area for a nearby stream gage, by the streamflow for the nearby stream gage (Equation 1). Hirsch (1979) noted that the drainage area ratio method works relatively well if streams have similar flow characteristics. Similarly, this method is most valid in situations where watersheds are of similar size, have similar land use and soil types, and experience similar precipitation patterns. Ries and Friesz (2000) indicated that the drainage area ratio method is generally as accurate as, or more accurate than, regression estimates when the drainage area ratio for an ungaged site is between 0.3 and 3 times the size of the reference gage watershed.

$$Q_{ungaged} = \frac{DA_{ungaged}}{DA_{gaged}} x Q_{gaged}$$ Equation 1

where
Qungaged: Flow at the ungaged location
Qgaged: Flow at surrogate USGS gage station
DAungaged: Drainage area of the ungaged location
DAgaged: Drainage area at surrogate USGS gage station

The streamflow correlation method can be used to provide an estimated long-term record of daily mean streamflow or long-term estimates of streamflow statistics at sites with limited data; this is completed by exploiting the correlation between flows at the site and concurrent flows at some nearby long-term gage (Riggs, 1972; Matalas and Jacobs, 1964; Hirsch, 1979). The underlying assumption for using regression to extend or augment the streamflow record is that the population of streamflows at the two sites (long-term stream gage station and partial record stations) have similar properties in terms of the shapes of the distributions of flows, serial correlations of flows, and seasonal variations (Vogel and Stedinger, 1985). When using this method, limitations may exist when predicting high flows as individual flow values at the RWQMN or USGS gage location may be affected by local temporal variations in the timing and duration of precipitation, infiltration, and runoff, differently. To avoid large potential separations in flow values between sites due to storm events, average daily streamflow (ADF) values were used at the USGS reference gage rather than 15 minute timeseries data for streamflow correlation analyses.

If the relationship between flows at the partial record site and concurrent reference gage flows do not appear to be linear, gaged and partial record streamflow measurements can be logarithm-base 10 (log-10) transformed. Streamflow data for record extension purposes are often log-10 transformed to mitigate scaling effects and the issues involving low (negative) predicted flow values (USEPA, 2009). The transformed data are typically plotted with the reference gage data as the independent variable and the partial record data as the dependent variable (Equation 2). Based upon the linear regression equation, the predicted log-10 streamflow can then be retransformed by exponentiation to convert the estimates into their original units of measurement, cubic feet per second.

$$\hat{Y} = bX + a$$ Equation 2

where
$\hat{Y}$: Predicted values of Y
b: Slope, rate of increase/decrease of Y for each unit increase in X
a: Y-intercept

For this study, four of the RWQMN sites were located at active USGS stations and therefore streamflow estimation techniques were not required. Of the 49 remaining sites, five had less than 10 independent flow measurements acquired in the field and were not considered for regression analyses. Similar correlation coefficients calculated from predicted and measured values were observed for the DA ratio and regression methods. The specific method used to estimate daily streamflow values at each station was determined based on the highest correlation coefficient observed between the two methods. The DA ratio method was used to estimate streamflow at 32 sites and the regression method was used for 17 sites. Results from these estimation approaches, including individual regression equations, correlation coefficients, and drainage area ratios can be observed in Appendix B. An example of a predicted daily streamflow record from USGS gage information can be viewed in Figure 2.

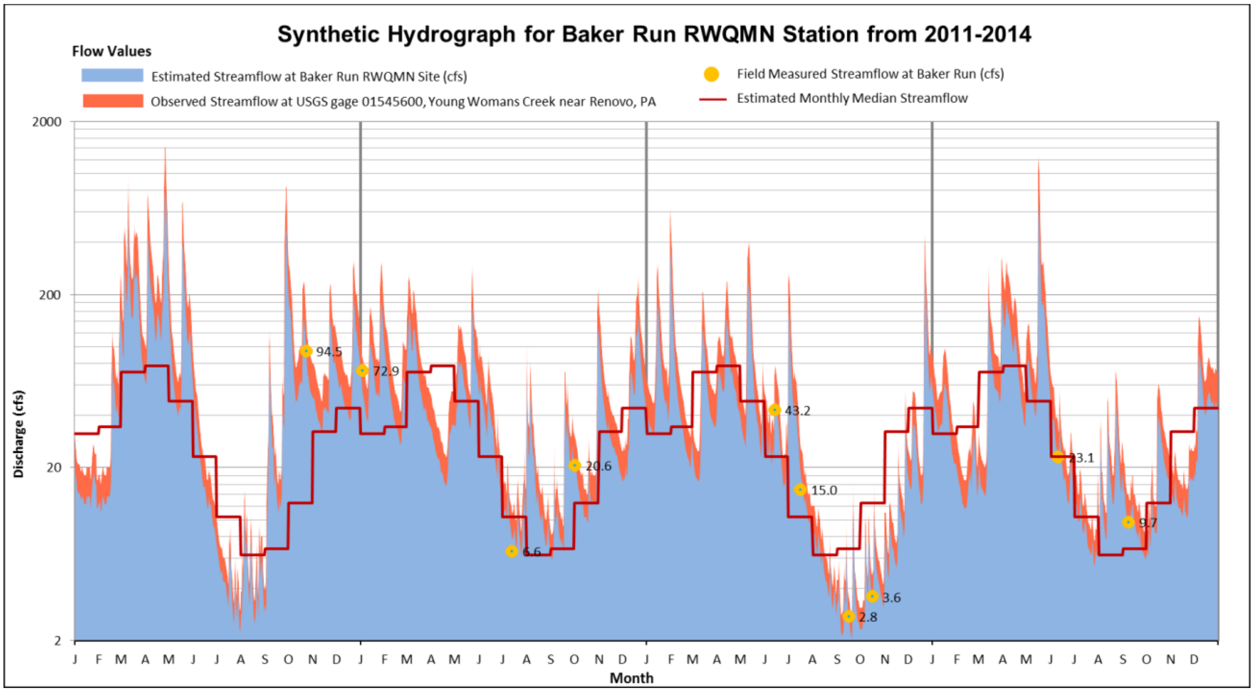

Figure 2. Daily Streamflow Estimated for Baker Run Using a Log-base 10 Regression Equation Derived from Paired Field Measured Streamflow at the Ungaged RWQMN Station and USGS Recorded Streamflow at Young Womans Creek

TREND TEST METHODS

Trend tests were used to determine if water quality measurements (pH, specific conductance, temperature, DO, and turbidity) were increasing or decreasing over time. Two important variables, seasonality and streamflow, need to be accounted for in the data before a final test can determine if there are water quality trends. Streamflow can either dilute or concentrate solutes in the water column, which impacts the observed water quality measurements. In addition, seasonal impacts such as groundwater and biological activity can influence the concentration of water quality parameters.

There are several trend test methods that can be utilized to determine water quality trends – parametric, nonparametric, and mixed. Based on the volume of data being analyzed, it was not feasible to test for normality, therefore, a nonparametric approach was selected to determine water quality trends at the RWQMN stations (Helsel and Hirsch, 1992; Hirsch et al., 1982). The nonparametric test selected was a seasonal Mann-Kendall. A seasonal Mann-Kendall trend test indicates if there are positive or negative monotonic trends in the parameters over time.

Seasonal Mann-Kendall trend tests were used to account for the impact of seasons and LOWESS were used to account for the impact of streamflow. LOWESS is a curve fitting process used (Cleveland, 1979; Hirsch et al., 1991) on raw data in order to remove the impact of a variable (streamflow) from the nonlinear relationships (Helsel and Hirsch, 1992). With this method, streamflow may not be removed entirely as the water quality parameters may respond differently to the timing and duration of precipitation events and infiltration and runoff rates, which may not be directly observable with estimated average daily flow values. The response of a water quality parameter to streamflow may show a lag due to antecedent groundwater conditions and the time between effective rainfall and direct runoff. In an attempt to address this limitation, the Mann-Kendall test was performed on average monthly values of streamflow normalized, daily mean concentrations of each water quality parameter. By calculating results for each month individually, the Mann-Kendall test accounts for seasonality as monthly data are only compared to the same month from year to year. Once the test statistics are determined for each month, the results are summed to yield an overall test statistic. A seasonal Mann-Kendall trend test was then performed on the residuals from the LOWESS smoothing to determine positive or negative water quality trends at each of the RWQMN stations.

For stations with observed increasing conductance trends, a two-way ANOVA was performed on various watershed characteristics of each station in Minitab to determine if anthropogenic activities appear to be influencing the presence of water quality trends. Watershed characteristics considered for this analysis included land use, well density, and drainage area.

WATER QUALITY RESULTS

Water quality conditions for streams can change over time. These changes can be beneficial (i.e., an increase in forested stream buffers could lower the stream temperature) or have adverse impacts (i.e., conductance increases due to human activities in a watershed). Results from the seasonal Mann-Kendall tests indicated 57 individual trending parameters ($\alpha \leq 0.05$ significance) (Table 2) at 40 of the RWQMN stations (Table 3). Trends were observed in each of the five parameters at various stations; however, significant conductance trends were more prevalent than any other parameter.

Table 2. Number of Water Quality Trends Using Seasonal Mann-Kendall ($\alpha \leq 0.05$)

Parameter	**Increasing**	**Decreasing**
Specific Conductance	24	1
pH	1	9
Dissolved Oxygen	8	2
Temperature	3	2
Turbidity	3	4

Specific Conductance

A total of 25 sites exhibited a water quality trend for conductance: 24 of those sites showed increasing trends, and one site showed a decreasing trend. A trend analysis only considers data within a site and does not compare sites; in order to determine if stations with increasing conductance were unique compared to those showing no trends or decreasing conductance, several different watershed characteristics were evaluated. Characteristics used for this analysis include natural gas well density, natural gas hydraulically fractured well density, percent agriculture, percent forested, percent developed, and watershed size. The stations with increasing trends are underlain with both shale and sandstone geology and are located throughout both the North Central Appalachian and Northern Appalachian Upland & Plateau level III ecoregions.

A two-way ANOVA was used to determine if stations with an increase in conductance had significantly different ($\alpha \leq 0.05$) watershed characteristics compared to those watersheds with no trends or a decrease in conductance. The resulting data showed no significant difference of watershed characteristics between stations with increasing or decreasing trends (Table 4) and stations with no observable trend. Box plots in Figure 3 indicate the range, median, and quartile ranges of the stations grouped as trending for conductance and not trending for conductance.

Table 3. Seasonal Mann-Kendall p-values for Water Quality Trends (α ≤ 0.05) (N.S. = not significant)

Station	**SpCond p-value**	**SpCond Direction**	**DO p-value**	**DO Direction**	**pH p-value**	**pH Direction**	**Temp p-Value**	**Temp Direction**	**Turb p-value**	**Turb Direction**
Apalachin Creek	0.020	Increase	N.S.		N.S.		N.S.		0.018	Decrease
Baker Run	N.S.		N.S.		0.010	Decrease	N.S.		N.S.	
Baldwin Creek	0.000	Increase	N.S.		N.S.		N.S.		N.S.	
Blockhouse Creek	0.048	Increase	N.S.		0.001	Decrease	N.S.		N.S.	
Bobs Creek	N.S.		N.S.		0.017	Decrease	N.S.		N.S.	
Bowman Creek	0.002	Increase	N.S.		N.S.		N.S.		N.S.	
Catatonk Creek	N.S.		0.001	Decrease	N.S.		0.018	Increase	N.S.	
Cherry Valley Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Chest Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Choconut Creek	N.S.		0.021	Decrease	N.S.		N.S.		N.S.	
Crooked Creek	0.024	Increase	0.040	Increase	N.S.		0.011	Decrease	N.S.	
Driftwood Branch	0.005	Increase	N.S.		N.S.		N.S.		N.S.	
East Fork Sinnemahoning	N.S.		N.S.		N.S.		N.S.		N.S.	
East Branch Fishing Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Elk Run	N.S.		N.S.		N.S.		0.045	Increase	N.S.	
Grays Run	N.S.		N.S.		N.S.		N.S.		N.S.	
Hammond Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Hicks Run	0.048	Increase	N.S.		0.006	Increase	N.S.		N.S.	
Hunts Run	N.S.		N.S.		N.S.		N.S.		0.000	Increase
Kettle Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Kitchen Creek	0.004	Increase	N.S.		N.S.		N.S.		N.S.	
Lackawanna River	N.S.		N.S.		0.024	Decrease	N.S.		N.S.	
Larrys Creek	0.035	Increase	N.S.		N.S.		N.S.		N.S.	
Little Clearfield Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Little Mehoopany Creek	0.000	Increase	N.S.		N.S.		N.S.		N.S.	
Little Muncy Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Little Pine Creek	N.S.		0.002	Increase	N.S.		N.S.		N.S.	

Station	SpCond p-value	SpCond Direction	DO p-value	DO Direction	pH p-value	pH Direction	Temp p-Value	Temp Direction	Turb p-value	Turb Direction
Long Run	0.041	Increase	N.S.		N.S.		N.S.		N.S.	
Loyalsock Creek	0.001	Increase	N.S.		N.S.		N.S.		N.S.	
Marsh Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Marsh Creek – Tioga	0.000	Increase	N.S.		N.S.		N.S.		N.S.	
Meshoppen Creek	N.S.		N.S.		0.001	Decrease	N.S.		0.022	Decrease
Moose Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Nanticoke Creek	0.018	Increase	N.S.		N.S.		N.S.		0.012	Decrease
Ninemile Run	N.S.		N.S.		N.S.		0.001	Decrease	N.S.	
Pine Creek	N.S.		N.S.		N.S.		N.S.		N.S.	
Portage Creek	0.042	Increase	0.001	Increase	N.S.		N.S.		0.002	Increase
Sangerfield River	N.S.		N.S.		N.S.		N.S.		N.S.	
South Branch Tunkhannock Creek	0.000	Increase	0.017	Increase	N.S.		N.S.		N.S.	
Sing Sing Creek	0.010	Increase	0.000	Increase	0.032	Decrease	0.030	Increase	N.S.	
Snake Creek	0.002	Increase	N.S.		N.S.		N.S.		N.S.	
Starrucca Creek	N.S.		0.015	Increase	0.003	Decrease	N.S.		N.S.	
Sugar Creek	0.001	Increase	N.S.		N.S.		N.S.		N.S.	
Sugar Run	0.000	Increase	N.S.		N.S.		N.S.		N.S.	
Tioga River	0.016	Increase	N.S.		N.S.		N.S.		N.S.	
Tomjack Creek	0.003	Increase	0.003	Increase	N.S.		N.S.		N.S.	
Trout Brook	N.S.		N.S		0.022	Decrease	N.S.		N.S.	
Trout Run	N.S.		N.S.		N.S.		N.S.		N.S.	
Tuscarora Creek	0.000	Increase	N.S.		N.S.		N.S.		N.S.	
Upper Pine Creek	N.S.		N.S.		0.001	Decrease	N.S.		N.S.	
Wappasening Creek	0.017	Increase	N.S.		N.S.		N.S.		0.025	Decrease
West Branch Pine Creek	0.012	Decrease	0.002	Increase	N.S.		N.S.		N.S.	
Young Womans Creek	N.S.		N.S.		N.S.		N.S.		0.037	Increase

Table 4. Two-way ANOVA p-values for Watershed Characteristics at Trending and Non-trending Stations

Watershed Characteristic	p-value	Range of stations with increasing trends	Range of stations with no trends
Percent Agriculture Land Use	0.067	1% – 55%	0% – 51%
Percent Developed Land Use	0.144	0 – 9.6%	0 – 3.7%
Percent Forested Land Use	0.110	42% – 93%	35% – 99%
Drainage Area	0.553	11 – 83 mi^2	3 – 385 mi^2
Well Density	0.812	0.0 – 3.86 $wells/mi^2$	0.0 – 3.69 $wells/mi^2$
Fracked Well Density	0.416	0.0 – 2.48 $wells/mi^2$	0.0 – 3.04 $wells/mi^2$

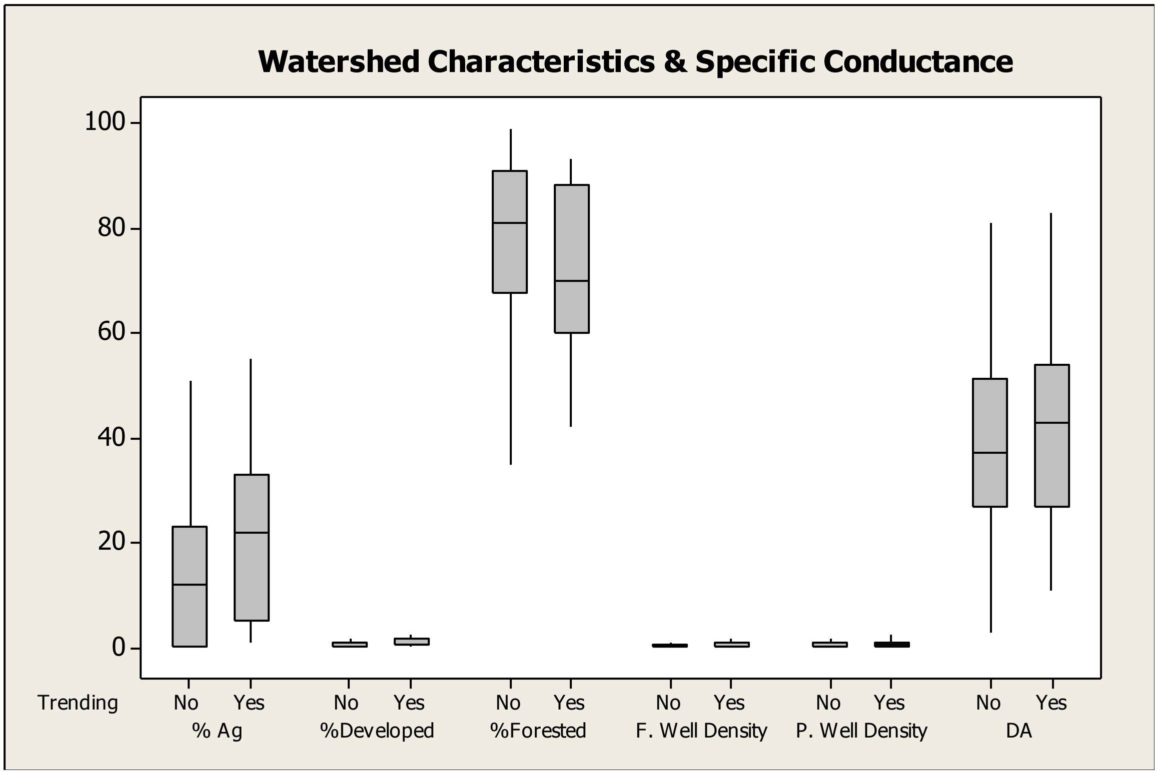

Figure 3. Box Plot of Watershed Characteristics for Trending and Non-trending Stations

The UNG industry experienced a substantial increase in the number of fracked wells from 2010 to 2015. Figure 4 shows the cumulative number of UNG wells in the Susquehanna River Basin during that time period. An environmental concern with UNG is spills or leaks of fracking fluids which typically illustrates high conductance values. Annual flow-adjusted conductance values were determined for all stations experiencing an increasing trend. The conductance values were plotted against the cumulative number of fracked wells in each watershed to see if the rises in conductance correlated to the rise in the number of wells.

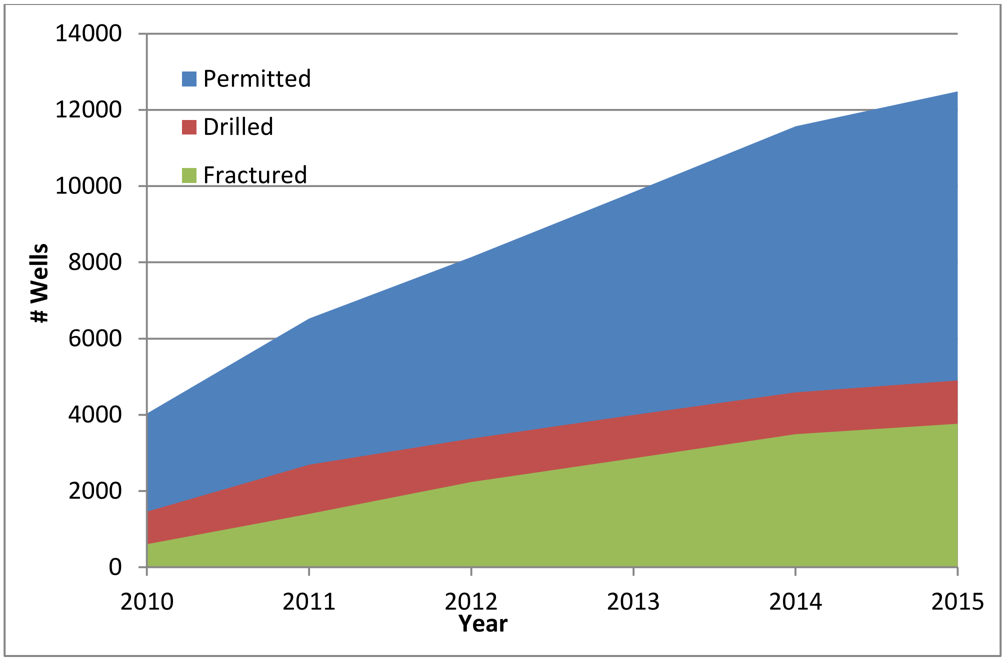

Figure 4. Cumulative Number of UNG Wells in the Susquehanna River Basin from 2010 to 2015

Correlating annual conductance values to the number of wells at stations trending upward for conductance resulted in inconclusive evidence for the presence of fractured wells influencing conductance trends. A wide range of natural gas and non-gas related development scenarios were observed in watersheds with increasing conductance trends (Figures 5–10). For Little Mehoopany Creek and Driftwood Branch, conductance appeared to be following an increase in fracked wells (Figures 5 and 6); others including Kitchen Creek and Portage Creek showed conductance increasing as the number of wells hydraulically fractured in the watershed leveled off (Figures 7 and 8). Several watersheds including Long Run and Baldwin Creek did not experience any natural gas activity during the sampling period and yet experienced upward conductance trends (Figures 9 and 10). A total of ten of the 24 stations with increasing conductance did not have any UNG fractured wells through 2015.

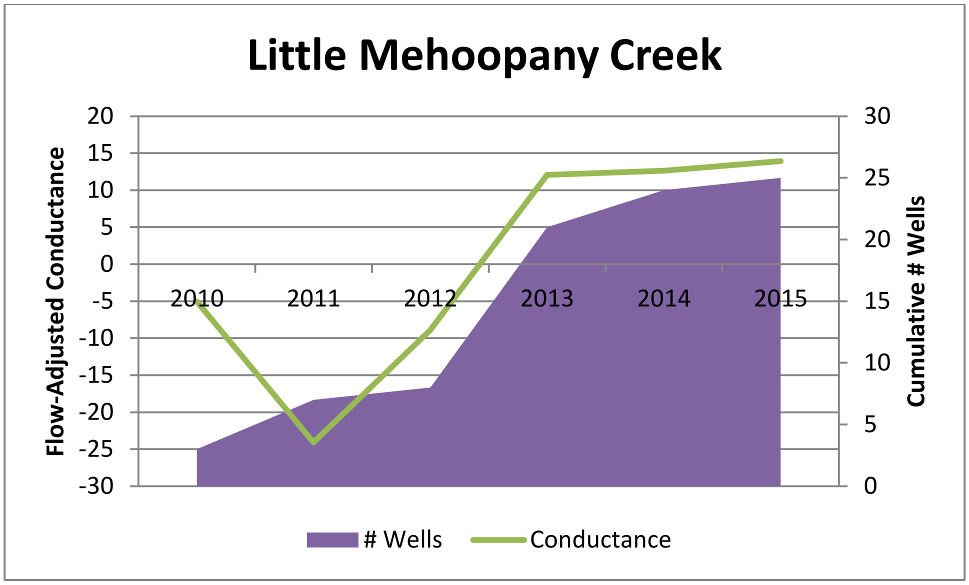

Figure 5. *Little Mehoopany Creek – Increasing Conductance; Increase in Wells*

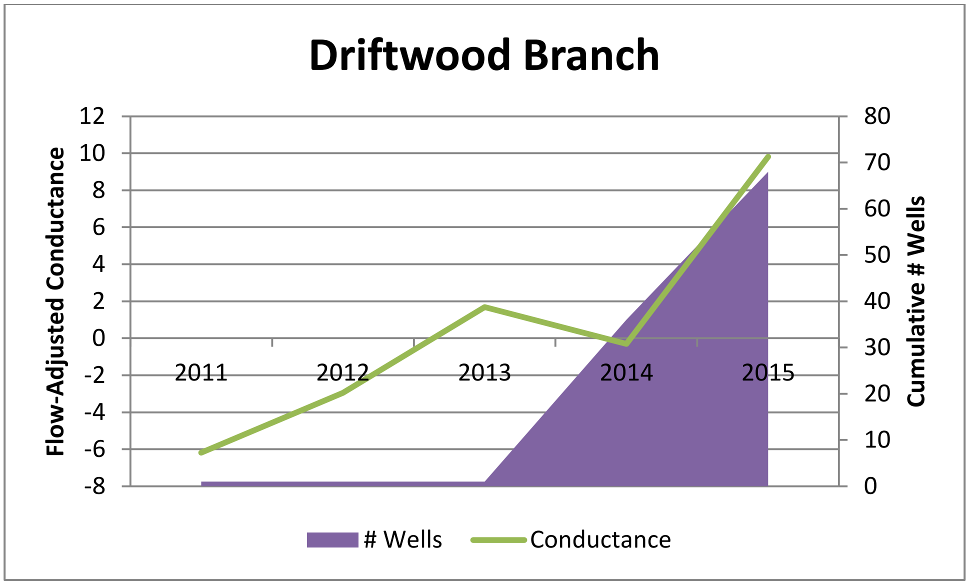

Figure 6. *Driftwood Branch – Increasing Conductance; Increase in Wells*

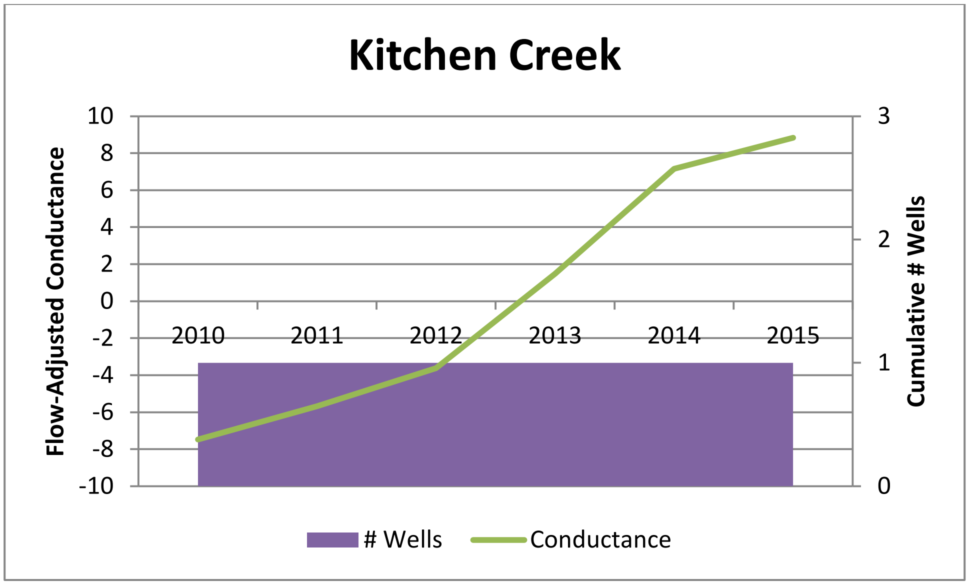

Figure 7. *Kitchen Creek – Increasing Conductance; No Increase in Wells*

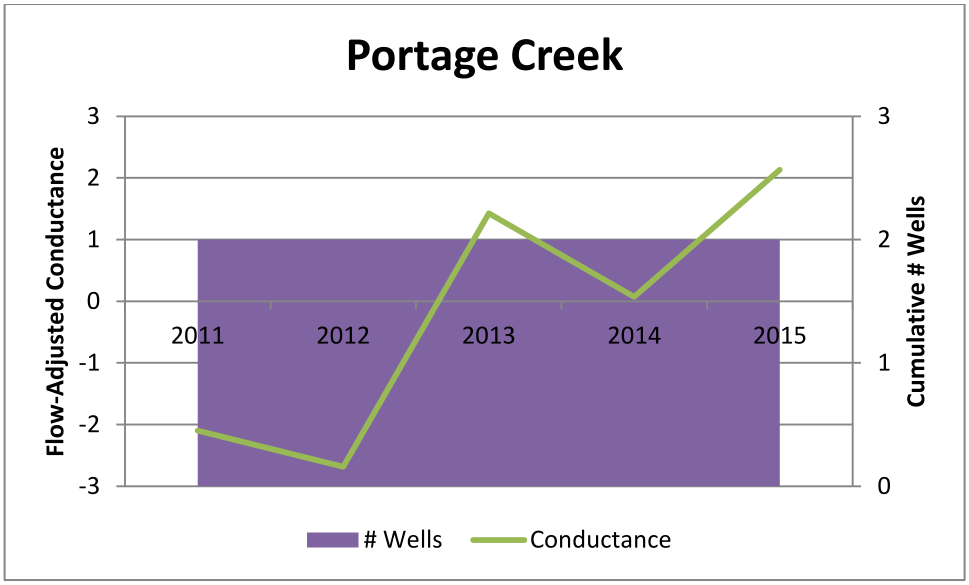

Figure 8. *Portage Creek – Increasing Conductance; No Increase in Wells*

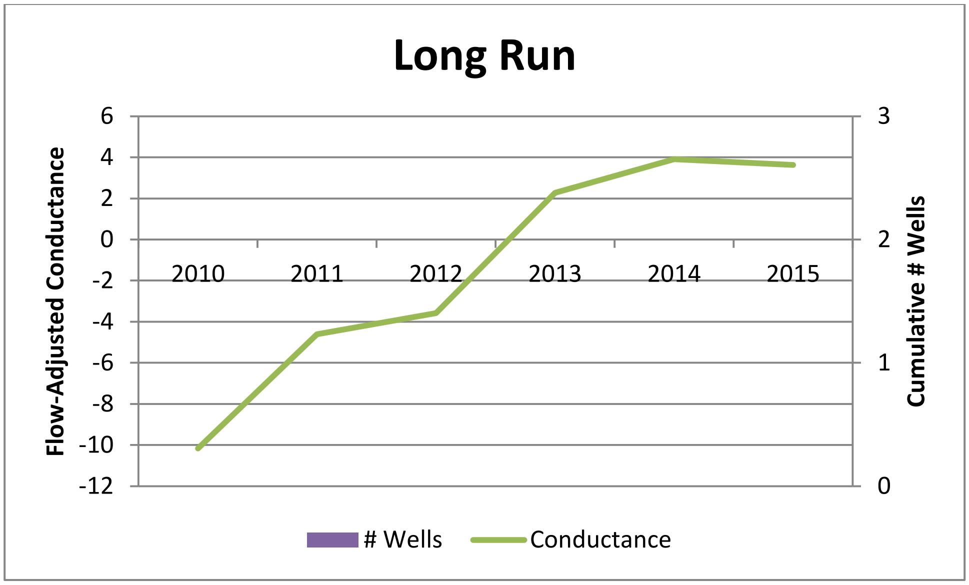

Figure 9. Long Run – Increasing Conductance with No Fracked Wells

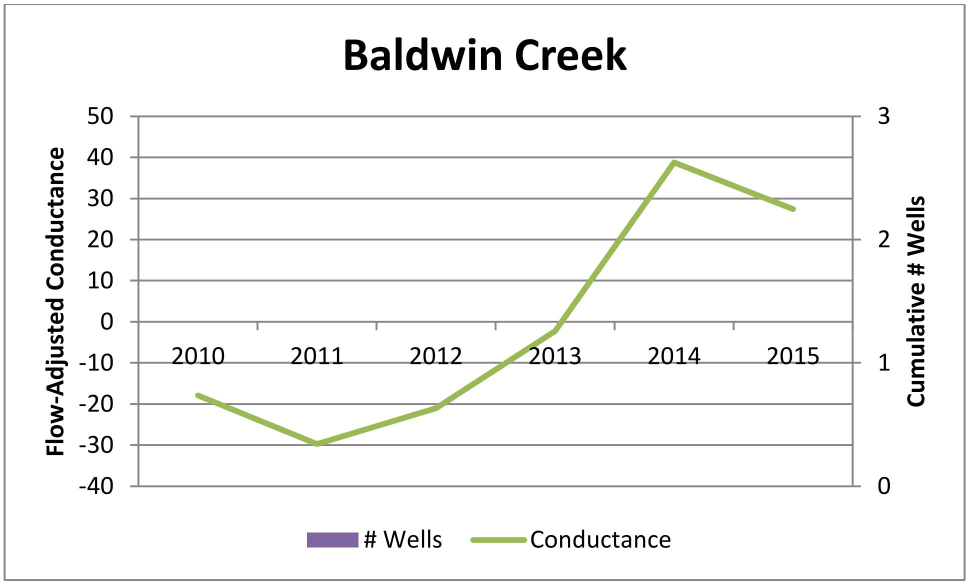

Figure 10. Baldwin Creek – Increasing Conductance with No Fracked Wells

For stations with no observable conductance trends, the same mixed results noted above were apparent. There were stations with no fracked wells, stations with the same number of wells over the study period, and stations with an increasing number of wells over time that showed no conductance trends. These inconclusive results make it difficult to discern any impact of UNG wells on surface water conductance values.

Ion Loads and Specific Conductance

Conductance values increase with the addition of ions to the waterbody; therefore, discrete sample loads of chloride, magnesium, sodium, and calcium were calculated to see if the loads of these ions were increasing as conductance was increasing over time. The estimated daily ion load was calculated using the average annual ion concentration and average annual discharge. Because discrete samples were targeted by season and not discharge, the average daily discharge was derived from the methods described in the Flow Methods section above.

$$\text{Ion Load} = \text{Flow (mgd)} \times \text{Ion (mg/l)} \times 8.345 \qquad \text{Equation 3}$$

The results from the ion discrete sample loads were not able to indicate which ion(s) was increasing in the waterbody to cause rising conductance values. Figure 11 shows the estimated average daily chloride load by year. The r^2 values ranged from 0.006 to 0.941; however, there were mixed results. Several of the most significant results indicated higher conductance values correlated with lower chloride loads, which is the opposite of what would be expected particularly if hydrofracking fluid was detected. The limited ion dataset, and the fact that the discrete samples were not collected across all flow regimes, limited the ability to determine which ion(s) were increasing.

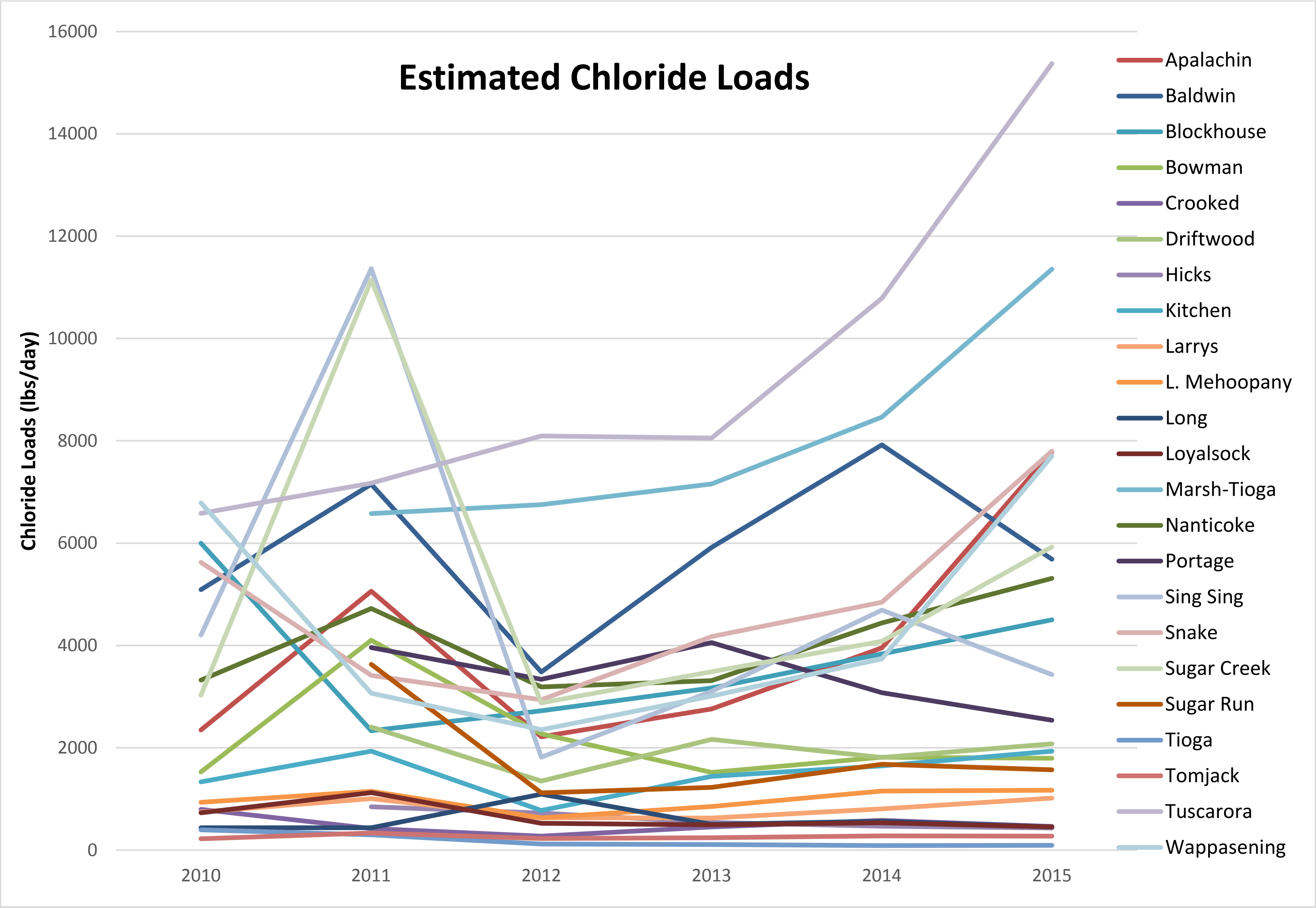

Figure 11. ***Estimated Daily Chloride Loads at Stations with Increasing Conductance***

Macroinvertebrates and Specific Conductance

Macroinvertebrate IBI scores were compared by year for all stations with increasing conductance values (Appendix C) to see if the scores reflected the increase in conductance. As conductance increases in a system, IBI scores are assumed to decrease. In 2011, macroinvertebrates were collected shortly after high flow events, which is expected to decrease macroinvertebrate populations in the sample as a function of streambed scour from flooding; results from 2011 were excluded for this reason. In later years, samples collected after extended periods of low flow and macroinvertebrate communities were markedly different than 2011 (Hintz and Steffy, 2015). Figure 12 shows mixed results for six stations with a hydraulically fractured well density greater than 1.0 wells/mi^2 and increasing conductance trends. IBI scores have remained about the same for some stations, have steadily risen for others, and fluctuated at other stations; no stations show a steady decline in IBI score.

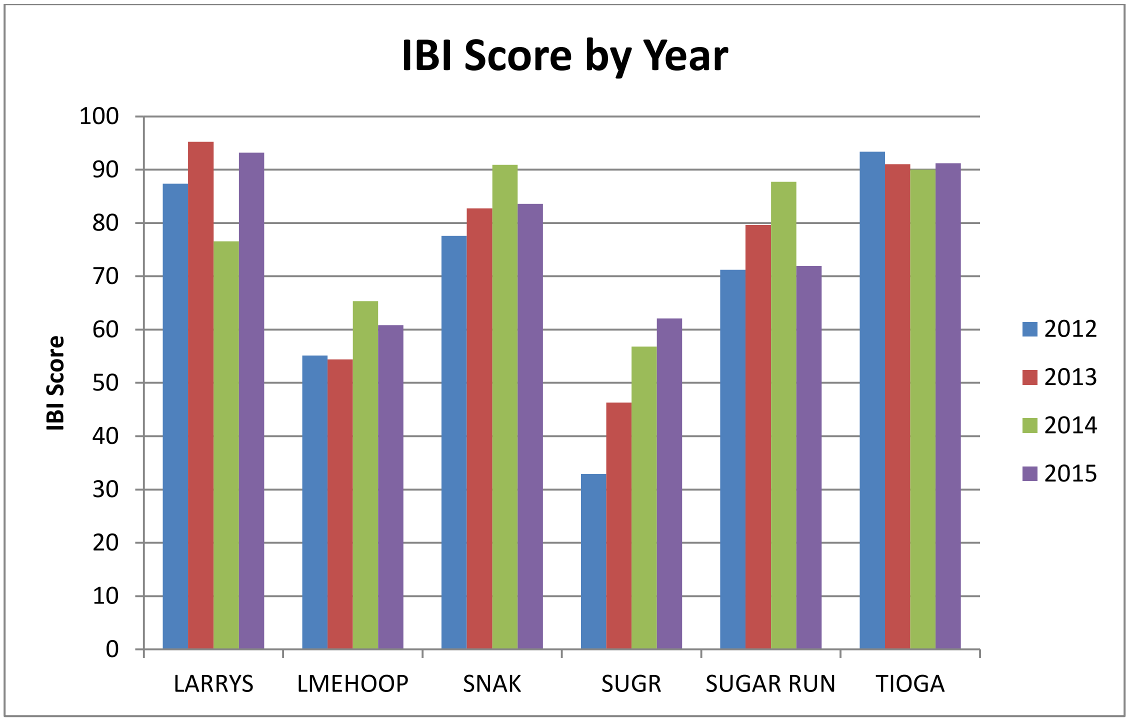

Figure 12. IBI Scores by Year at Stations with a Hydraulically Fractured Well Density Greater than 1.0 Wells/mi^2

pH

There were 10 stations that experienced significant pH trends; nine stations illustrated decreasing pH levels and one station illustrated an increase in pH. With optimal conditions for pH being in the middle of the pH range (0-14), a decrease or increase can be either beneficial or adverse. For example, if runoff is reduced in a stream with elevated pH levels from agriculture, less nutrients would enter the stream and the result would be less algal growth. Less algal growth can lower the pH which is a beneficial decreasing trend in pH. However, if acid mine drainage is introduced to a system, an adverse decreasing pH trend would likely be observed. Table 5 indicates the percentage of data points at each data that was outside of the water quality standard for pH (between 6 and 9). Blockhouse Creek, Lackawanna River, Meshoppen Creek, Starrucca Creek, and Trout Brook exhibited a decreasing pH trend, but pH values within these streams commonly exceed 9 during periods of low flow and warm temperatures (Table 5). Lowering the pH in these systems would benefit aquatic life and improve stream heath.

Baker Run had a decreasing pH trend and the watershed already has an acidic pH. The average pH at Baker Run during the sampling period was 6.47, and the pH was below 6 for five percent of the sampling period. Baker Run has 19 fractured wells located in the headwaters of the stream; fluids used to hydraulically fracture wells have low pH values. If these fluids reached the surface water through spills or leaks, the stream pH would decline. Baker Run is not experiencing an increasing conductance trend as would be expected if fluids were reaching the stream. Therefore, it is not possible to attribute the trend to hydraulically fractured wells in the watershed. A steadily decreasing pH in the watershed over the long-term could be concerning, especially if pH levels continue to trend below water quality standards.

Table 5. Mean, Minimum, and Maximum pH Data for Stations with pH Trends

Watershed	Mean pH	Min pH	Max pH	Percentage of data points outside of standards (<6.0/>9.0)
Baker Run	6.47	5.26	7.19	5/0
Blockhouse Creek	7.48	4.05	11	0.1/0.9
Bobs Creek	7.11	6.19	8.43	0/0
Lackawanna River	7.13	5.96	10.01	0/2
Meshoppen Creek	7.61	4.49	9.76	0/1.2
Sing Sing Creek	7.76	6.34	8.60	0/0
Starrucca Creek	7.44	5.08	9.65	0/1.5
Trout Brook	7.76	6.65	9.39	0/1.2
Upper Pine Creek	7.08	5.87	8.25	0/0
Hicks Run*	6.96	5.95	8.21	0.1/0

*Increasing pH trend; all other stations have a decreasing trend

Dissolved Oxygen

Ten of the 53 stations experienced trends in dissolved oxygen. Catatonk and Choconut Creeks demonstrated decreasing DO levels, while Crooked Creek, Little Pine Creek, Portage Creek, South Branch Tunkhannock Creek, Sing Sing Creek, Starrucca Creek, Tomjack Creek, and West Branch Pine Creek demonstrated increasing DO concentrations. There were three stations with both temperature and DO trends. The temperature at Catatonk Creek was increasing, which would contribute to the decrease in DO; in contrast, the temperature at Crooked Creek was decreasing, contributing to the increase in DO. Sing Sing Creek was experiencing an increase in temperature, which should signal a decrease in DO; however, DO was increasing at the site.

Temperature

Only five of the 53 stations had temperature trends. Decreasing temperature trends were observed at Crooked Creek and Ninemile Run, while temperature was increasing at Catatonk Creek, Elk Run, and Sing Sing Creek. With such a low percentage of stations experiencing a temperature trend, it was not possible to distinguish a difference between the stations with increasing temperature trends, decreasing temperature trends, and those without a trend.

Turbidity

Seven stations experienced turbidity trends. The four stations with decreasing turbidity trends have a minimum of four and a half years of continuous data, and include Apalachin Creek, Meshoppen Creek, Nanticoke Creek, and Wappasening Creek. They are comprised of a range of 26 to 48 percent agriculture and 48 to 70 percent forested lands. The hydraulically fractured well density ranged from 0 to 3.04 wells/mi^2, which represented the lowest and highest well densities. Decreasing turbidity trends could be attributed to several things: best management practices on agricultural land, decreased runoff from dirt roads, or changes in land use.

Hunts Run, Portage Creek, and Young Womans Creek are heavily forested watersheds (> 90 percent) with few human influences and are experiencing increasing turbidity trends. Young Womans Creek has the second lowest mean turbidity value (2.01 NTU) of all the stations; Hunts Run has the fifth lowest value (2.64 NTU) and Portage Creek has the tenth lowest value (3.73 NTU). These undeveloped watersheds have very few sources of sediment; increases in sediment from activities within the watershed would be more easily noticeable than a watershed that already has large sources of sediment.

CONCLUSIONS

The Susquehanna River Basin Commission began continuous water quality monitoring in early 2010 in headwater streams in the northern half of the Susquehanna River Basin. Parameters continuously monitored include specific conductance (conductance), pH, dissolved oxygen, water temperature, and turbidity. At the conclusion of 2015, the Commission had compiled enough data (minimum of 36 months) at 53 stations to begin assessing water quality trends. At least one water quality trend was observed at 40 individual stations, with a total of 57 water quality trends being observed (Table 6).

Table 6. Water Quality Trends by Parameter

Parameter	Increasing	Decreasing
Specific Conductance	23	1
pH	1	9
Dissolved Oxygen	8	2
Temperature	3	2
Turbidity	3	4

More trends were observed for specific conductance than any of the other four parameters. For this reason, the stations with specific conductance trends were a major focus of analysis. Less than 20 percent of stations with increasing conductance trends also experienced trends in dissolved oxygen, temperature, or turbidity, making it difficult to analyze for the cause of the trend. Several preliminary findings were noted for stations with specific conductance trends:

- Watershed characteristics (watershed size, land use, natural gas well density, etc.) for stations with increasing conductance were not statistically different from those at stations with no observable trends.
- Over time, the increase in conductance did not correlate to the presence of natural gas wells since similar increasing conductance trends were also observed in watersheds with no natural gas development. Although there is a possibility that conductance could be linked to natural gas development in these watersheds, the correlation between the two is inconclusive, especially without identifying the source of increased conductance in watersheds that lack well development.
- Increases in concentrations of ions commonly found in hydraulically fractured fluids (including chloride, sodium, magnesium, and calcium) were not consistently correlated to increases in conductance.
- There were no significant changes to the aquatic biological community, as indicated by macroinvertebrate IBI scores, as a function of increased conductance trends.

NEXT STEPS

To date, the Commission's remote water quality monitoring network has not detected discernible impacts on the quality of the Basin's water resources as a result of natural gas development, but continued vigilance is warranted. The Commission's next steps include selecting a subset of stations with increasing conductance trends to further investigate the cause of increasing conductance. Potential site-specific investigations of these watersheds may include conducting detailed aerial image analyses to detect any changes in land cover that may be influencing water quality trends and/or implementing a nested sampling approach to isolate tributaries and potential point-sources.

Water quality trends will be re-examined when there are 10 years of continuous data at each station. The extended timeframe will allow for more robust analysis of the data, and also allow additional supplemental data, such as discrete water chemistry samples, to be collected in each watershed. In addition to revisiting the trends, any changes to water quality conditions will also be evaluated against the aquatic biological community data collected within the monitored watersheds.

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APPENDIX A

Period of Data Collection and Telemetry Source by Station

Site	**Stream Name**	**Site ID[1]**	**Period of Data Collection**
*Apalachin Creek near Apalachin, NY	Apalachin Creek	9	12/14/2010 – 12/31/2015
+Baker Run near Glen Union, PA	Baker Run	47	9/19/2011 – 12/31/2015
*Baldwin Creek near Loman, NY	Baldwin Creek	7	12/7/2010 – 12/31/2015
*Blockhouse Creek near English Center, PA	Blockhouse Creek	28	6/4/2010 – 12/31/2015
+Bobs Creek near Pavia, PA	Bobs Creek	53	3/30/2010 – 12/31/2015
*Bowman Creek near Noxen, PA	Bowman Creek	37	4/1/2010 – 12/31/2015
*Upper Catatonk Creek near Spencer, NY	Catatonk Creek	5	12/16/2010 – 12/31/2015
+Cherry Valley Creek near Middlefield, NY	Cherry Valley Creek	2	12/2/2010 – 12/31/2015
*Chest Creek near Patton, PA	Chest Creek	52	9/21/2010 – 12/31/2015
*Choconut Creek near Vestal Center, NY	Choconut Creek	10	1/27/2010 – 12/31/2015
+Upper Crooked Creek near Keeneyville, PA	Crooked Creek	17	6/16/2010 – 12/31/2015
*Driftwood Branch near Lockwood, PA	Driftwood Branch	35	5/19/2011 – 12/31/2015
+East Branch Fishing Creek near Jamison City, PA	East Branch Fishing Creek	39	3/27/2012 – 12/31/2015
+East Fork Sinnemahoning Creek near Logue, PA	East Fork First Fork Sinnemahoning Creek	33	5/25/2011 – 12/31/2015
+Elk Run near Watrous, PA	Elk Run	30	6/23/2010 – 12/31/2015
*Grays Run near Gray, PA	Grays Run	41	5/5/2011 – 12/31/2015
*Hammond Creek near Millerton, PA	Hammond Creek	12	1/27/2010 – 12/31/2015
+Hicks Run near Hicks Run, PA	Hicks Run	46	6/16/2011 – 12/31/2015
*Hunts Run near Cameron, PA	Hunts Run	45	10/16/2012 – 12/31/2015
+Kettle Creek near Oleona, PA	Kettle Creek	31	8/7/2012 – 12/31/2015
+*Kitchen Creek near Huntington Mills, PA	Kitchen Creek	38	10/30/2010 – 12/31/2015
*Lackawanna River near Forest City, PA	Lackawanna River	20	7/14/2010 – 12/31/2015
+Larrys Creek near Salladasburg, PA	Larrys Creek	42	3/30/2010 – 12/31/2015
+*Little Clearfield Creek near Dimeling, PA	Little Clearfield Creek	51	4/28/2010 – 12/31/2015
*Little Mehoopany Creek near North Mehoopany, PA	Little Mehoopany Creek	26	9/8/2010 – 12/31/2015
+*Little Muncy Creek near Moreland, PA	Little Muncy Creek	40	8/6/2010 – 12/31/2015
+*Little Pine Creek near Waterville, PA	Little Pine Creek	43	7/1/2011 – 12/31/2015
*Long Run near Gaines, PA	Long Run	18	12/17/2010 – 12/31/2015
*Loyalsock Creek near Ringdale, PA	Loyalsock Creek	36	6/3/2010 – 12/31/2015
+Marsh Creek near Ansonia Station, PA	Marsh Creek	23	6/9/2011 – 12/31/2015
*Marsh Creek near Blanchard, PA	Marsh Creek	48	6/30/2010 – 12/31/2015
*Meshoppen Creek near Kaiserville, PA	Meshoppen Creek	21	1/27/2010 – 12/31/2015
*Moose Creek near Plymtonville, PA	Moose Creek	50	5/2/2011 – 12/31/2015
*Nanticoke Creek near Maine, NY	Nanticoke Creek	4	12/16/2010 – 12/31/2015
+*Ninemile Run near Walton, PA	Ninemile Run	24	5/25/2011 – 12/31/2015
+Pine Creek near Blackwell, PA	Pine Creek	29	8/8/2011 – 12/31/2015
*Portage Creek near Emporium, PA	Portage Creek	34	8/22/2011 – 12/31/2015
*Sangerfield River near Poolville, NY	Sangerfield River	1	12/2/2010 – 12/31/2015
*Sing Sing Creek near Big Flats, NY	Sing Sing Creek	6	12/1/2010 – 12/31/2015
*Snake Creek near Lawsville Center, PA	Snake Creek	14	6/2/2010 – 12/31/2015
*South Branch Tunkhannock Creek near La Plume, PA	South Branch Tunkhannock Creek	25	7/1/2010 – 12/31/2015
*Starrucca Creek near Stevens Point, PA	Starrucca Creek	13	7/1/2010 – 12/31/2015
*Sugar Creek near Troy, PA	Sugar Creek	16	4/27/2010 – 12/31/2015
*Sugar Run near Sugar Run, PA	Sugar Run	27	9/21/2011 – 12/31/2015
+Tioga River near Fall Brook, PA	Tioga River	22	6/23/2010 – 12/31/2015

Site	**Stream Name**	**Site ID**[1]	**Period of Data Collection**
*Tomjack Creek near Burlington, PA	Tomjack Creek	15	4/27/2010 – 12/31/2015
*Trout Brook near McGraw, NY	Trout Brook	3	12/16/2010 – 12/31/2015
*Trout Run near Shawville, PA	Trout Run	49	4/28/2010 – 12/31/2015
*Upper Tuscarora Creek near Woodhull, NY	Tuscarora Creek	8	12/16/2010 – 12/31/2015
+*Upper Pine Creek near Telescope, PA	Pine Creek	19	5/25/2011 – 12/31/2015
*Wappasening Creek near Windham Center, PA	Wappasening Creek	11	6/2/2010 – 12/31/2015
*West Branch Pine Creek near Galeton, PA	West Branch Pine Creek	32	6/3/2010 – 12/31/2015
+Young Womans Creek near North Bend, PA	Young Womans Creek	44	8/7/2012 – 12/31/2015

[1] Matches ID on Map 1

*Sites with cellular telemetry

+Sites with satellite telemetry

+*Sites started at satellite telemetry and switched to cellular telemetry in 2015

APPENDIX B

Streamflow Estimation Results

Remote Water Quality Station (Waterbody) Name	**USGS Reference Gage**	**Field Discharge Measurements (Sample Size)**	**DA Ratio**	**Slope from Log Space Regression**	**Intercept from Log Space Regression**	**Correlation Coefficient (R) for DA Ratio Method**	**Correlation Coefficient (R) for Log Space Regression**	**Preferred Estimation Method**
Apalachin Creek	0142400103 Trout Creek near Trout Creek, NY	26	2.12	1.17	-0.34	0.86	0.87	Streamflow Correlation
Baker Run	01545600 Young Womans Creek near Renovo, PA	21	0.76	0.94	-0.10	0.86	0.86	Streamflow Correlation
Baldwin Creek	01518862 Cowanesque River at Westfield, PA	20	0.39	1.13	-1.03	0.77	0.74	DA Ratio
Blockhouse Creek	01549500 Blockhouse Creek near English Center, PA	NA	NA	NA	NA	NA	NA	USGS Gage Record
Bobs Creek	01560000 Dunning Creek at Belden, PA	33	0.10	1.12	-1.13	0.93	0.93	DA Ratio
Bowman Creek	01552000 Loyalsock Creek at Loyalsockville, PA	41	0.12	0.89	-0.60	0.92	0.92	DA Ratio
Catatonk Creek	04234000 Fall Creek near Ithaca, NY	25	0.24	0.93	-0.58	0.74	0.75	Streamflow Correlation
Cherry Valley Creek	01423000 WBr Delaware River at Walton, NY	17	0.14	0.86	-0.59	0.85	0.85	DA Ratio
Chest Creek	01542500 WestBr. Susquehanna River at Karthaus, PA	27	0.03	1.01	-1.71	0.93	0.93	DA Ratio
Choconut Creek	01534000 Tunkhannock Creek near Tunkhannock, PA	24	0.10	1.28	-1.84	0.92	0.92	DA Ratio
Crooked Creek	01518420 Crooked Creek bl Catlin Hollow at Middlebury Center, PA	NA	NA	NA	NA	NA	NA	USGS Gage Record
Driftwood Branch Sinnemahoning Creek	01543000 Driftwood Branch Sinnemahoning Creek at Sterling Run, PA	23	0.31	0.88	-0.29	0.85	0.87	Streamflow Correlation
East Branch Fishing Creek	01552500 Muncy Creek near Sonestown, PA	17	0.53	0.91	0.04	0.96	0.96	DA Ratio
East Fork First Fork Sinnemahoning Creek	01544500 Kettle Creek at Cross Fork, PA	23	0.22	0.97	-0.53	0.96	0.96	Streamflow Correlation
Elk Run	01548500 Pine Creek at Cedar Run, PA	28	0.03	0.63	-0.48	0.95	0.91	DA Ratio
Grays Run	01550000 Lycoming Creek near Trout Run, PA	19	0.11	0.97	-0.88	0.98	0.98	Streamflow Correlation
Hammond Creek	01518862 Cowanesque River at Westfield, PA	22	0.32	1.53	-1.80	0.93	0.98	Streamflow Correlation
Hicks Run	01543500 Sinnemahoning Creek at Sinnemahoning, PA	19	0.05	1.08	-1.57	0.97	0.97	DA Ratio
Hunts Run	01543500 Sinnemahoning Creek at Sinnemahoning, PA	15	0.04	1.03	-1.47	0.98	0.98	DA Ratio
Kettle Creek	01544500 Kettle Creek at Cross Fork, PA	14	0.60	1.02	-0.25	0.99	0.99	DA Ratio
Kitchen Creek	01539000 Fishing Creek near Bloomsburg, PA	32	0.07	1.05	-1.22	0.96	0.95	DA Ratio

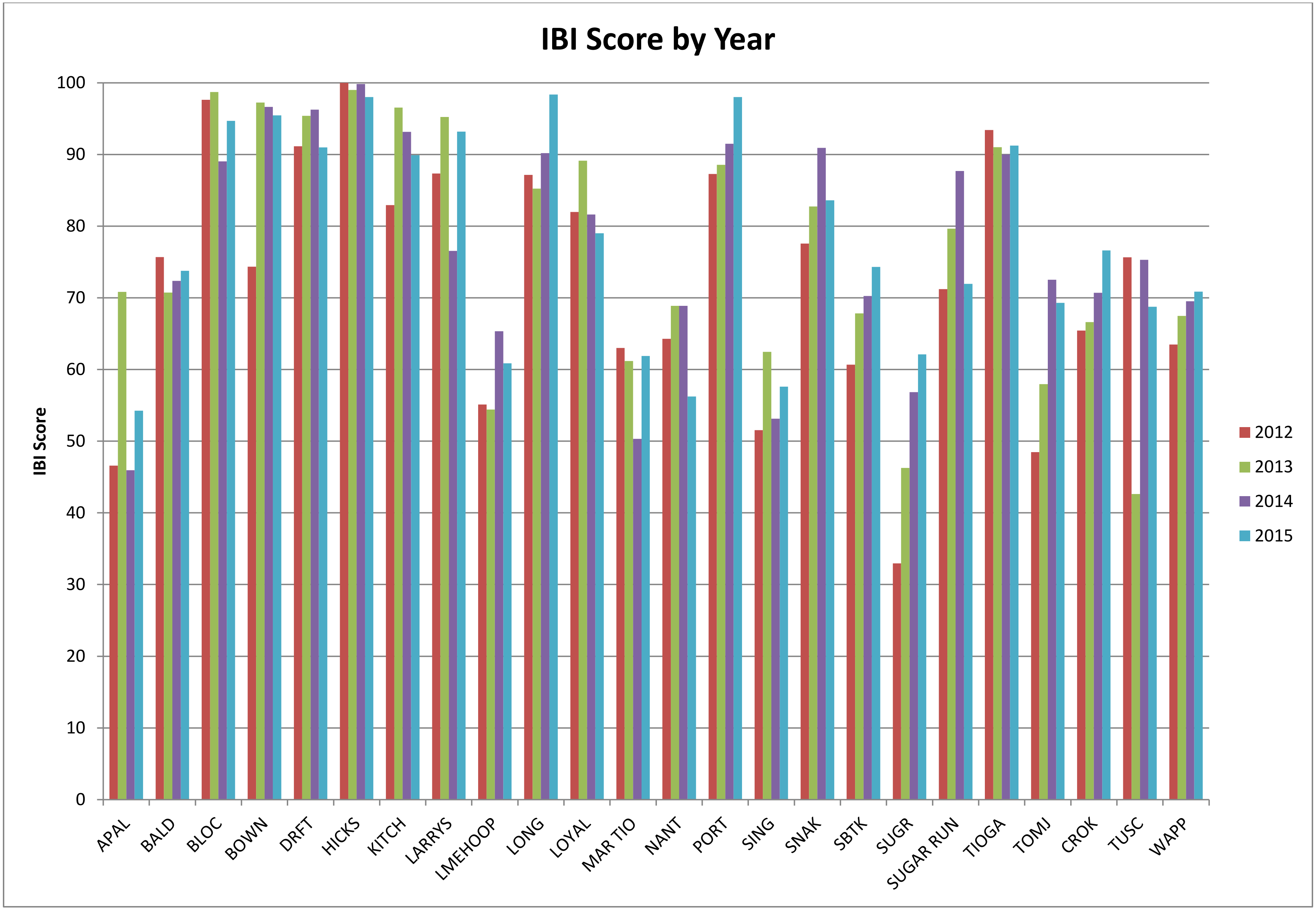
Remote Water Quality Station (Waterbody) Name	**USGS Reference Gage**	**Field Discharge Measurements (Sample Size)**	**DA Ratio**	**Slope from Log Space Regression**	**Intercept from Log Space Regression**	**Correlation Coefficient (R) for DA Ratio Method**	**Correlation Coefficient (R) for Log Space Regression**	**Preferred Estimation Method**
Lackawanna River	01534300 Lackawanna River near Forest City, PA	NA	NA	NA	NA	NA	NA	USGS Gage Record
Larrys Creek*	01549500 Blockhouse Creek near English Center, PA	0	0.77	NA	NA	NA	NA	DA Ratio
Little Clearfield Creek	01542500 WestBr. Susquehanna River at Karthartus, PA	28	0.03	1.08	-1.95	0.95	0.95	DA Ratio
Little Mehoopany Creek	01534000 Tunkhannock Creek near Tunkhannock, PA	36	0.03	1.41	-2.88	0.95	0.92	DA Ratio
Little Muncy Creek	01552500 Muncy Creek near Sonestown, PA	24	2.17	0.91	0.26	0.96	0.95	DA Ratio
Little Pine Creek	01549500 Blockhouse Creek near English Center, PA	15	4.78	1.02	0.61	0.95	0.96	Streamflow Correlation
Long Run	01548500 Pine Creek at Cedar Run, PA	21	0.03	1.16	-2.13	0.99	0.99	Streamflow Correlation
Loyalsock Creek	01552500 Muncy Creek near Sonestown, PA	24	1.13	0.96	-0.04	0.95	0.95	DA Ratio
Marsh Creek - Tioga	01548500 Pine Creek at Cedar Run, PA	17	0.13	0.87	-0.72	0.88	0.87	DA Ratio
Marsh Creek	01547700 Marsh Creek at Blanchard, PA	NA	NA	NA	NA	NA	NA	USGS Gage Record
Meshoppen Creek	01534000 Tunkhannock Creek near Tunkhannock, PA	25	0.14	1.02	-0.99	0.97	0.97	DA Ratio
Moose Creek	01543500 Sinnemahoning Creek at Sinnemahoning, PA	22	0.01	1.19	-2.74	0.98	0.97	DA Ratio
Nanticoke Creek	0142400103 Trout Creek near Trout Creek, NY	18	2.38	1.11	-0.17	0.80	0.80	Streamflow Correlation
Ninemile Run	03007800 Allegheny River at Port Allegany, PA	20	0.07	0.86	-0.82	0.97	0.97	DA Ratio
Pine Creek*	01548500 Pine Creek at Cedar Run, PA	1	0.64	NA	NA	NA	NA	DA Ratio
Pine Creek	01544500 Kettle Creek at Cross Fork, PA	28	0.26	1.10	-1.48	0.29	0.29	DA Ratio
Portage Creek	01542810 Waldy Run near Emporium, PA	22	13.47	0.99	1.17	NA	NA	DA Ratio
Sangerfield River	0142400103 Trout Creek near Trout Creek, NY	16	2.63	0.64	0.79	0.74	0.74	Streamflow Correlation
Sing Sing Creek	01518862 Cowanesque River at Westfield, PA	24	0.39	0.77	-0.06	0.97	0.97	DA Ratio
Snake Creek	0142400103 Trout Creek near Trout Creek, NY	32	2.24	0.78	0.46	0.88	0.88	DA Ratio
South Branch Tunkhannock Creek	01534000 Tunkhannock Creek near Tunkhannock, PA	35	0.18	0.92	-0.62	0.97	0.97	DA Ratio
Starrucca Creek	01428750 West Branch Lackawaxen River near Aldenville, PA	25	1.28	0.49	0.90	0.38	0.49	Streamflow Correlation
Sugar Creek	01516500 Corey Creek near Mainesburg, PA	28	4.62	0.89	0.62	0.88	0.89	Streamflow Correlation

Remote Water Quality Station (Waterbody) Name	USGS Reference Gage	Field Discharge Measurements (Sample Size)	DA Ratio	Slope from Log Space Regression	Intercept from Log Space Regression	Correlation Coefficient (R) for DA Ratio Method	Correlation Coefficient (R) for Log Space Regression	Preferred Estimation Method
Sugar Run	01532000 Towanda Creek near Monroeton, PA	34	0.16	1.03	-1.02	0.86	0.86	Streamflow Correlation
Tioga River	01516500 Corey Creek near Mainesburg, PA	23	1.11	0.74	0.40	0.93	0.93	Streamflow Correlation
Tomjack Creek	01532000 Towanda Creek near Monroeton, PA	24	0.13	1.04	-1.32	0.73	0.73	DA Ratio
Trout Brook	0142400103 Trout Creek near Trout Creek, NY	20	1.80	0.78	0.48	0.93	0.93	DA Ratio
Trout Run	01543500 Sinnemahoning Creek at Sinnemahoning, PA	42	0.05	0.98	-1.21	0.89	0.85	Streamflow Correlation
Tuscarora Creek	01525981 Tuscarora Creek above South Addison, NY	22	0.52	0.96	-0.42	0.87	0.87	DA Ratio
Wappasening Creek	0142400103 Trout Creek near Trout Creek, NY	23	2.34	1.23	-0.36	0.91	0.90	DA Ratio
West Branch Pine Creek	01544500 Kettle Creek at Cross Fork, PA	31	0.52	0.98	-0.18	0.91	0.90	DA Ratio
Young Woman's Creek	01545600 Young Womans Creek near Renovo, PA	11	0.89	0.93	0.05	1.00	1.00	Streamflow Correlation

*Less than 10 field measured flows; not considered for the regression analyses.

APPENDIX C

Macroinvertebrate IBI Scores by Year for Stations with Increasing Conductance


IBI Score by Year
IBI Score
100
90
80
70
60
50
40
30
20
10
0
APAL
BALD
BLOC
BOWN
DRFT
HICKS
KITCH
LARRYS
LMEHOOP
LONG
LOYAL
MAR TIO
NANT
PORT
SING
SNAK
SBTK
SUGR
SUGAR RUN
TIOGA
TOMJ
CROK
TUSC
WAPP
2012
2013
2014
2015