EXECUTIVE SUMMARY

In 2010, the Susquehanna River Basin Commission (Commission) established a real-time, continuous remote water quality monitoring network (RWQMN) to monitor headwater streams for potential impacts from unconventional natural gas drilling and other activities in the Basin. At the time, the natural gas industry was rapidly growing in the Basin and the majority of the activity was located near headwater streams where water quality data were scarce.

The continuous water quality parameters collected at each site include pH, specific conductance (conductance), water temperature, dissolved oxygen (DO), and turbidity. Over time, fluctuations of these parameters may be due to the natural range of variability, changes in land use/land cover including agriculture, urban, and forest cover, impacts from natural gas drilling, or changes in climate and regional hydrologic conditions.

At the conclusion of 2015, 53 out of 59 of the Commission’s monitoring stations had three to six years 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 increasing or decreasing 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 human-influenced 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. 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 (≤0.05) were noted for 57 parameters at 40 stations. Of note, specific conductance trends were observed at 25 stations with an increasing trend at 24 stations. Commission staff investigated potential causes for these trends and the following conclusions were made:

- 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 natural gas 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 Index of Biotic Integrity (IBI) scores, as a function of increased conductance trends.
INTRODUCTION

In 2010, the Commission established a real-time, continuous remote water quality monitoring network (RWQMN) to monitor headwater streams for potential impacts from unconventional natural gas drilling and other activities in the Basin. At the time, the natural gas industry was rapidly growing in the Basin and the majority of the activity was located near headwater streams where water quality data were scarce.

Hydraulic fracturing has greatly increased throughout the Basin, from fewer than 600 wells fractured prior to 2010, to more than 3,600 wells being fractured by the end of 2015 (Pennsylvania Department of Environmental Protection, 2015). Out of 59 watersheds equipped with RWQMN stations (see Figure 1), 39 were identified as having actively fractured wells; the remaining 20 watersheds have not experienced any natural gas activity. Potential impacts commonly associated with unconventional natural gas development are related to spills or leaks of hydraulically fractured fluids which can typically be detected as a function of elevated conductance values. The continuous water quality parameters collected at each site include pH, specific conductance (conductance), water temperature, dissolved oxygen (DO), and turbidity.

The applicability of continuous, real-time monitoring network data is not limited to the impacts of natural gas drilling. Other activities captured by land use/land cover changes were considered as explanatory variables influencing water quality trends. The RWQMN data allow the Commission and others to monitor impacts from various activities in these watersheds to determine if water quality conditions are changing over time and to gain an better understanding of water quality conditions in headwater streams.

Since the continuous monitoring network has been in place for six years (2010-2015),
an appropriate amount of data has been generated 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. 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 long-term monotonic trends.

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. In addition to local geology and human-influenced activities, streamflow and seasonality can also influence fluctuations in water quality. Often, a combination of land use and intense precipitation events can lead to elevated streamflows capable of scouring streambeds and banks and transporting suspended sediments. These conditions may cause 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 hydraulic fracturing 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 the LOWESS smoothing operation, to examine 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.

**STREAMFLOW ESTIMATION METHODS**

Because on-site instantaneous streamflow data were not available for 49 out of the 53 RWQMN site locations, average daily flow time series were estimated 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 ungauged locations (Stuckey et al., 2012). Leveraging long-term daily mean streamflow records from nearby gages, streamflow values at the RWQMN stations were estimated using streamflow correlation (Hirsch, 1982; Reilly and Kroll, 2003) and drainage area (DA) ratio methods (Hirsch, 1979; Emerson et al., 2005).

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 streamflow correlation analyses. The DA ratio method was used to estimate streamflow at 32 sites and the streamflow correlation method was used for 17 sites. 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 by the highest correlation coefficient observed between the two methods. An example of a predicted daily streamflow record from a USGS gage can be found in Figure 2.
TREND TEST METHOD

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 (Cleveland, 1979; Hirsch et al., 1991) used on raw data in order to remove the impact of a variable (streamflow) from the nonlinear relationships (Helsel and Hirsch, 1992). 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. The results of this test indicate whether or not positive or negative water quality trends are observable at the RWQMN stations. For stations with observed increasing conductance trends, a correlation test was performed on various watershed characteristics for each station to determine if human 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.

RESULTS

Water quality conditions in 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). The Commission’s results indicated 57 individual trending parameters ($\alpha \leq 0.05$ significance) (see Table 1) at 40 of the 59 RWQMN stations. Trends were observed in each of the five parameters tested at various stations; however, significant conductance trends were more prevalent than any other parameter.

### Table 1. Number of Water Quality Trends Using Seasonal Mann-Kendall ($\alpha \leq 0.05$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Increasing</th>
<th>Decreasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Conductance</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>pH</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Temperature</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Turbidity</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

SPECIFIC CONDUCTANCE

A total of 25 sites exhibited a statistically significant water quality trend for conductance: 24 of those sites showed increasing trends, and one site showed a decreasing trend. Several different watershed characteristics, including land-cover/land use and hydraulic fracturing activity-related variables were evaluated in order to determine if stations with increasing conductance were unique, compared to those showing no trends or decreasing conductance. Watershed characteristics considered 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 correlation test was used to determine if stations with an increase in conductance had statistically significant different watershed characteristics compared to those watersheds with no trends or a decrease in conductance. The results showed no significant difference of watershed characteristics between stations with increasing or decreasing trends 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.

In addition to looking at watershed characteristics, macroinvertebrate IBI scores were compared by year for all stations with increasing conductance values to see if the scores reflected the increase in conductance. As conductance increases in a system, IBI scores are assumed to decrease. Figure 4 shows mixed results for six stations (of the 24
stations with increasing conductance trends) with a hydraulically fractured well density greater than 1.0 wells/mi². Fluids used to hydraulically fracture wells have very high conductance values. 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. IBI scores for all 24 stations reflected the same pattern.

**pH**

Ten of the 53 stations experienced significant pH trends; nine stations illustrated decreasing pH levels (Baker Run, Blockhouse Creek, Bob Creek, Lackawanna River, Meshoppen Creek, Starrucca Creek, and Trout Brook) and one station illustrated an increase in pH (Hicks Run). With optimal conditions for pH being in the middle of the pH range (generally 7-9), 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, fewer 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 abandoned mine drainage is introduced to a system, an adverse decreasing pH trend would likely be observed. 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. Lower pH in these systems would benefit aquatic life and improve stream health.

**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, Tomjacket 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/mi², 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 results of this study illustrated various trends in water quality parameters at a relatively small number of stations, although no clear cause or correlation with human activity could be discerned. Out of the five separate water quality parameters examined, at least one significant trend was observed at 40 out of the 53 stations. Of these 40 stations, a total of 57 significant water quality trends were identified (see Table 1, page 4). The Commission observed more trends for conductance than any of the other four parameters. For this reason, the stations with specific conductance trends were a major focus of the analyses. 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:

- 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 with the program 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.
REFERENCES


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Starrucca Creek, Susquehanna County, Pa.