Assessing the Temporal and Spatial Patterns of Natural Gas Development around Areas of Unmapped Headwater Streams within the Marcellus Shale Region of the Susquehanna Watershed

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INTRODUCTION

Increases in natural gas exploration within the Marcellus Shale region have brought about much debate over the potential economic benefits versus the potential environmental risks of a relatively new extraction technique called hydraulic fracturing (also known as hydrofracking or fracking). Hydraulic fracturing is a method by which natural gas is released from shale formations through artificial fractures that are created by pumping large quantities of highly pressurized fluid down a wellbore and into the target shale formation. The fracking fluid contains water, chemicals, and sand that are used to open and expand fractures to facilitate the release of natural gas (Figure 1) (USEPA 2013).

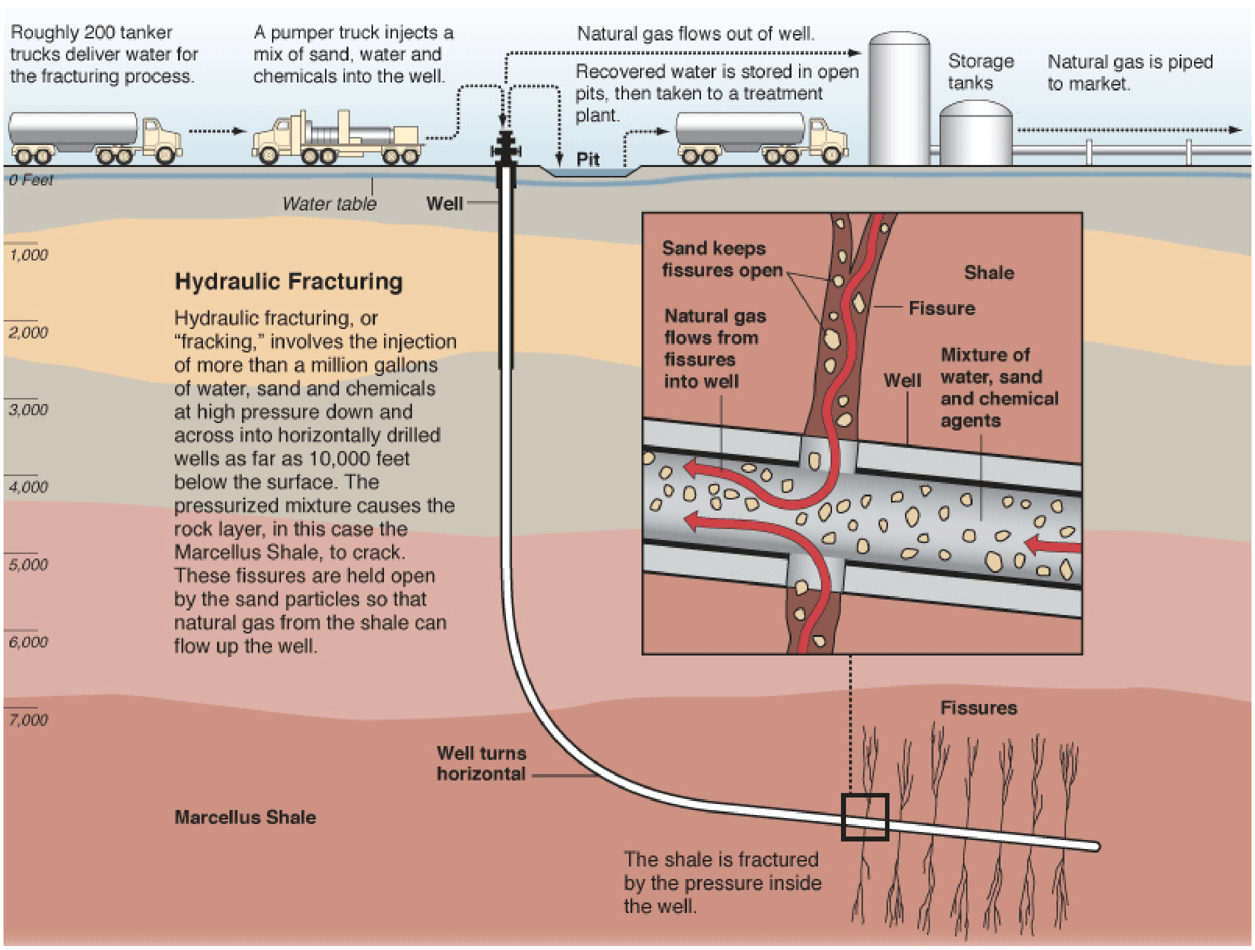

Figure 1 *– the process of hydraulic fracturing. Source: ProPublica, http://www.propublica.org/special/hydraulic-fracturing-national.*

Much of the environmental concern about hydraulic fracturing has been centered on the potential for water contamination due to the improper handling and treatment of “flowback”, or the wastewater that returns to the surface after hydrofracking. Relatively less attention has been given to the environmental impacts due to forest fragmentation and loss resulting from Marcellus Shale drilling infrastructure development. However, a few studies highlight that this is a legitimate concern (Drohan et al. 2012, Kiviat 2013), especially because unconventional natural gas pads typically disturb a larger area (3 – 5 acres) than conventional shallow natural gas wells (2.5 acres or less) (Drohan et al. 2012).

In order to protect surface water sources from potential contamination and riparian buffer loss, Pennsylvania lawmakers have established legislation that disallows unconventional gas well development within a minimum distance from surface water sources. Prior to April 16th 2012, Title 58 required that Marcellus Shale well bores maintain a distance of at least 100 feet from a stream or river as depicted by a USGS 1:24,000 topographic map. After April 16th 2012, Act 13, an amendment to the original Title 58 legislation, increased the required minimum distance to 300 feet (PADEP 2013).

Although Title 58 and subsequent Act 13 amendment provide protection for several streams and rivers, numerous small, headwater streams are left unprotected because they are not depicted by a “blue-line” on a USGS 1:24,000 topographic maps. Although headwater streams account for 50-80% of total stream length in the United States (Lowe et al. 2005, Fritz et al. 2008, Jaeger et al. 2007), they are often absent from published maps because of their small size (Figure 2) (Brooks et al. 2011). However, headwater streams are exceedingly important to the overall health of a watershed because they determine the transfer of sediments, nutrients and pollutants to downstream rivers and provide a unique ecosystem for aquatic and terrestrial organisms (Elmore et al. 2013). Because the overall health of a watershed relies directly upon functions provided by headwater streams (Lowe et al. 2005), the loss of riparian forest and contamination of surface water due to Marcellus Shale development should be of great concern in areas where USGS 1:24,000 “blue-lines” do not accurately depict the extent of headwater streams.

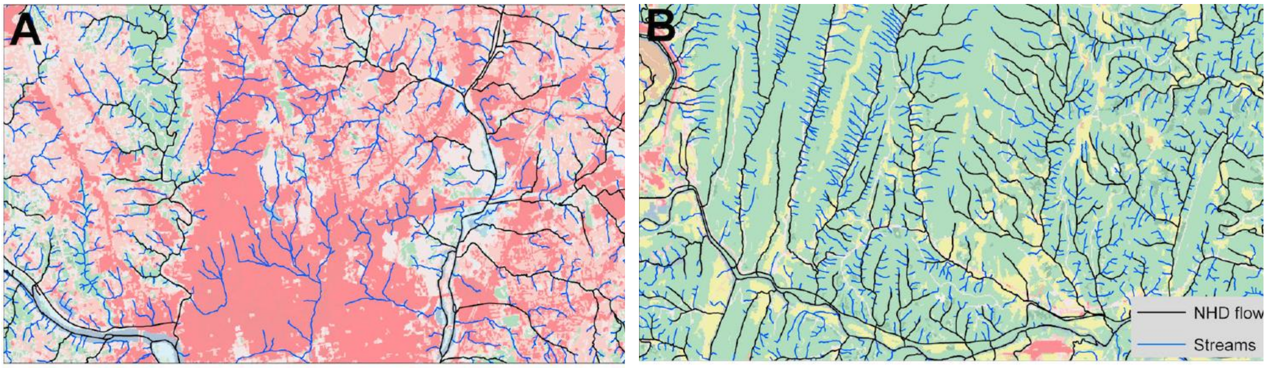

Figure 2 *- Examples of predicted stream density in areas of the Mid-Atlantic Region for (A) a predominantly urban watershed and (B) a predominantly forested watershed. Black lines represent streams that are depicted on a USGS map, while blue lines represent streams that are predicted from a computer model. Source: Elmore et al. 2013.*

PURPOSE AND SCOPE

This research assesses the temporal and spatial patterns of Marcellus Shale natural gas well pad development with respect to a digitally extracted stream network that depicts a greater extent of headwater streams. The following research questions are addressed:

- How does the extent of the digitally extracted stream network compare to that of the National Hydrography Dataset (NHD) stream network?
- How many Marcellus Shale well pads have been constructed within 100 feet of a surface water source as displayed on the digitally extracted stream network and the NHD stream network?
- How many Marcellus Shale well pads have been constructed within 300 feet of a surface water source as displayed on the digitally extracted stream network and NHD stream network?
- How does the average nearest distance between Marcellus Shale well pads and a surface water source differ between the digitally extracted stream network and the NHD stream network?
- How has the average distance between Marcellus Shale well pads and the nearest stream fluctuated during the time period between of 2005 and 2013?

STUDY AREA

The research was conducted in the northern portion of the Susquehanna Watershed within six Pennsylvania counties where exploration of natural gas within the Marcellus Shale formation has occurred most intensely (Figure 3). The counties included in the study area were Tioga, Bradford, Susquehanna, Lycoming, Sullivan, and Wyoming.

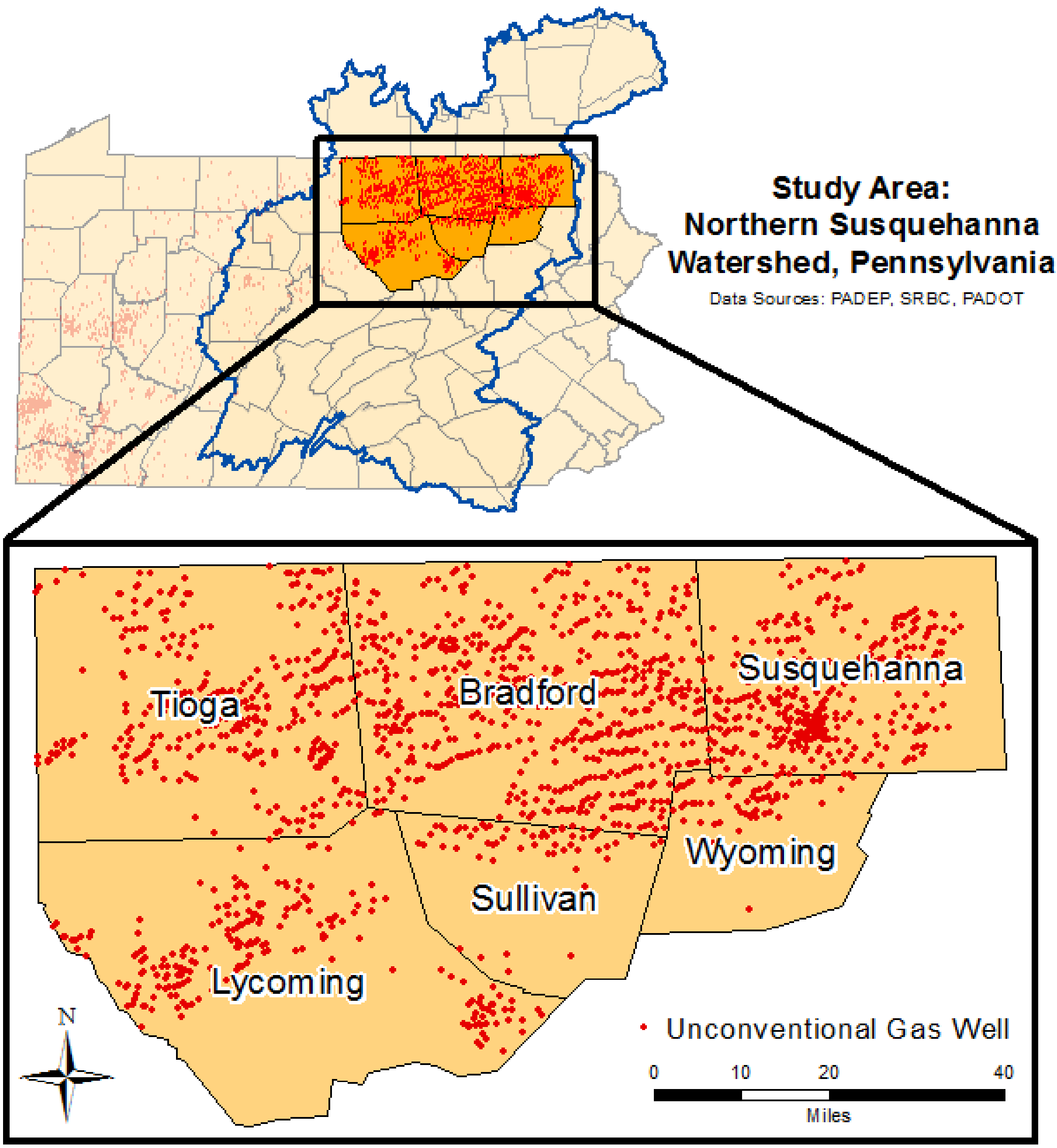

Figure 3 *– Pennsylvania counties included in study area. Maps display all locations of unconventional natural gas wells that have been drilled as of July 27th, 2013.*

The dominant land cover types within the study area are forest and agriculture (Figure 4). Being the Chesapeake Bay's largest contributing tributary, the Susquehanna Watershed provides nearly fifty percent of the fresh water that enters the Bay (Chesapeake Bay Program 2013). Because of the degraded state of the Chesapeake Bay, the land area within the Susquehanna Watershed has been the focus of forest conservation and reestablishment (Horton 2003). For this reason, it is important to study the possible effects of forest fragmentation that may be occurring due to increased Marcellus Shale natural gas extraction, especially in areas that may affect the health of headwater riparian buffers.

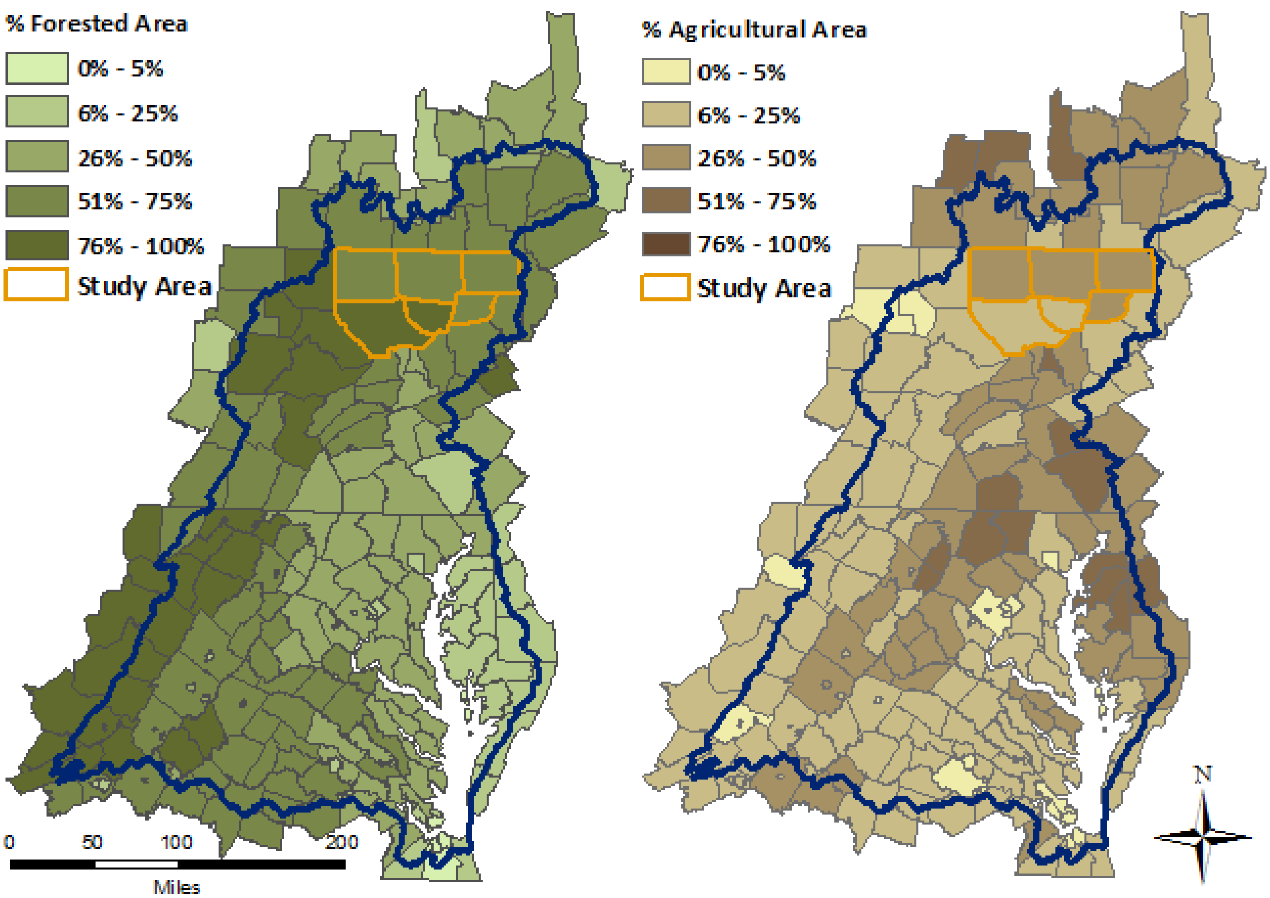

Figure 4 *- Percent forest and agricultural land cover within the Chesapeake Bay counties with study area highlighted for reference.*

DATA AND METHODS

The data that were used for analyses were collected from a variety of sources. 10 meter resolution digital elevation models (DEMs) were downloaded from the United States Department of Agriculture (USDA) Geospatial Data Gateway and are a part of the USGS National Elevation Database. The published stream network data were also obtained from the USDS Geospatial Data Gateway and are a part of the USGS National Hydrography Dataset (referred to as the NHD stream network hereafter). Marcellus Shale well data were obtained from FracTracker.org and contained information that is made publicly available by the Pennsylvania Department of Environmental Protection (PADEP). These data reflect all unconventional wells that have been drilled prior to July 27th, 2013. LiDAR DEMs were downloaded from the PASDA database and were produced by the PAMAP Program, a part of the Pennsylvania Department of Conservation and Natural Resources (PADCNR). All data manipulations and distance functions were done using ArcMap 10.2, an ESRI software product.

Digital Extraction of a Stream Network

In order to prepare the 10 meter DEMs, they were first mosaicked to create a new, single DEM covering the entire study area. The DEM was then “filled” in order to account for any extraneous sinks that were likely due to data errors. The filled DEM was used to produce a flow direction raster, displaying the direction that water was most likely to flow out of each raster cell. The flow direction raster was used to create a flow accumulation raster, which classifies cells by the cumulative number of cells draining into them. Therefore, cells with a high flow accumulation were most likely to contain a stream or river.

The stream network was extracted by choosing a minimum flow accumulation threshold that represented a stream. The minimum flow accumulation threshold was chosen in a trial and error process until a stream network was developed that corresponded best to the channels and gullies displayed by the 10 meter DEM (Figure 5). Because this type of trial and error method has errors associated with it when using a 10 meter DEM, fifteen random headwater areas were validated by using a 1 meter DEM derived from high resolution LiDAR data. After testing several thresholds, a 1000 cell flow accumulation minimum threshold was chosen. Therefore, the minimum drainage area of a stream or river was approximately 25 acres. Overall, the trial and error process was done conservatively so as to avoid type I errors at the expense of type II errors. Once the best-fit digitally extracted stream network was complete, the extent was compared to the extent of the current NHD stream network within the same area.

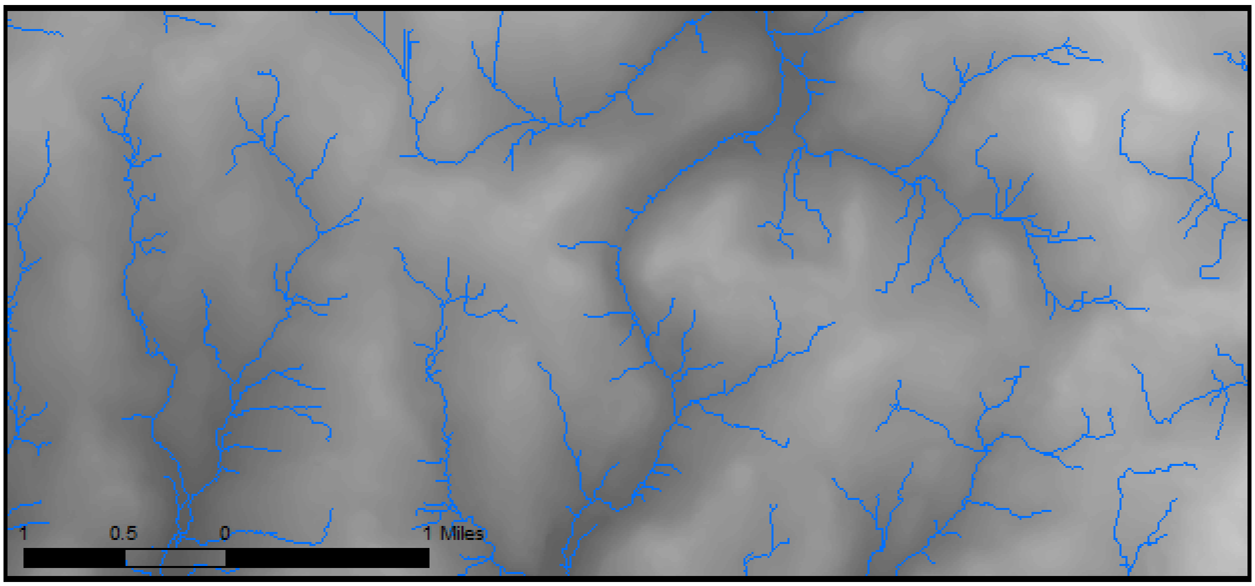

Figure 5 *- Digitally extracted stream network with a minimum flow accumulation threshold of 1000 cells (drainage area of 25 acres) overlaid on the 10 meter DEM.*

Temporal and Spatial Analyses

100 foot and 300 foot buffers were created on all surface water sources displayed by the digitally extracted stream network and the NHD stream network. The number of Marcellus Shale well pads within each of these buffer zones were tallied according to year. Charts illustrating the results were constructed using Microsoft Excel.

The average distance between Marcellus Shale well pads and the nearest stream was calculated and compared for the digitally extracted stream network and the NHD stream network. These results were calculated as a whole, as well as annually. These results were also illustrated using Microsoft Excel.

RESULTS AND DISCUSSION

As expected, the digitally extracted stream network showed a significantly greater extent of headwater streams than did the NHD stream network (Figure 6). According to the digitally extracted stream network derived from a 1000 cell flow accumulation minimum threshold, the NHD stream network underestimated drainage density and stream length by approximately 240%. This is consistent with the results of several other studies that predicted the NHD to underestimate stream density by anywhere from 170% to 300% in different regions of the United States (Elmore et al. 2013, James et al. 2010).

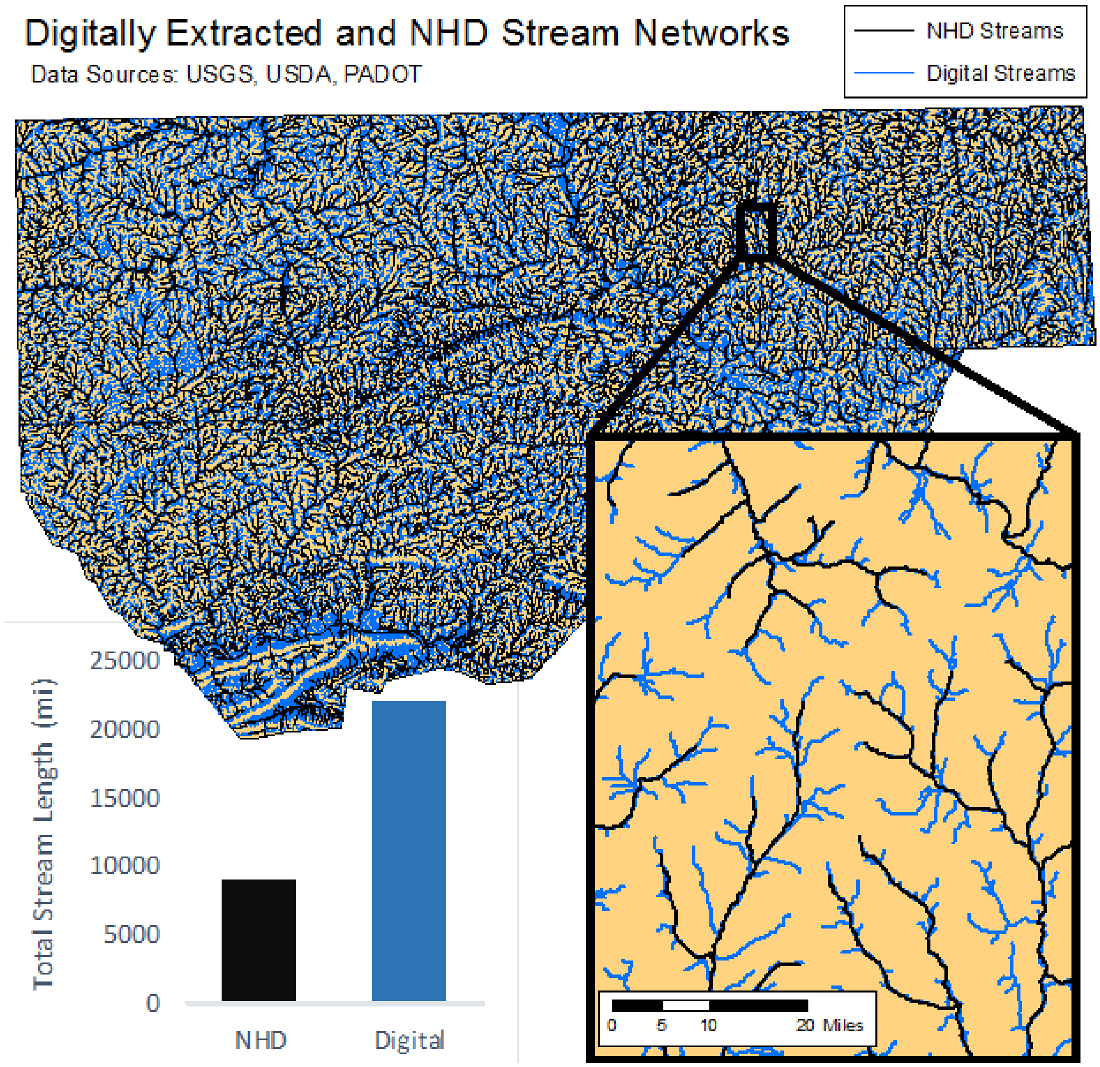

Figure 6 *– Comparison of a digitally extracted stream network derived from a 10 meter DEM and the stream network as displayed by the National Hydrography Dataset (NHD) in the study area of Tioga, Bradford, Susquehanna, Lycoming, Sullivan, and Wyoming counties in Northern Pennsylvania.*

A greater number of Marcellus Shale gas wells were located within the 100 foot and 300 foot buffer zones of the digitally extracted stream network than the buffer zones of the NHD stream network (Table 1). This was likely due to the greater drainage density of the digitally extracted stream network, in addition to the lack of setback regulations for any stream that is not depicted by the NHD stream network. Surprisingly, no Marcellus Shale gas wells were located within the 100 foot buffer of the NHD stream network, indicating that the Title 58 setback regulations have been implemented within this study area without exceptions since drilling began in 2005. Alternatively, two exceptions have been made to the 300 foot setback regulation of the Act 13 amendment that took effect after April, 2012.

Table 1 *– Number of Marcellus Shale gas wells per year located within 100 foot and 300 foot buffer zones of the digitally extracted stream network and the NHD stream network within the Northern Pennsylvania study area.*

	NHD 1:24,000 Stream Network		**Digitally Extracted Stream Network**	
	Wells within 100ft	Wells within 300ft	Wells within 100ft	Wells within 300ft
2005	0	0	0	0
2006	0	0	0	0
2007	0	0	0	1
2008	0	4	5	21
2009	0	6	19	83
2010	0	9	34	125
2011	0	10	26	136
2012	0	1	2	38
2013	0	1	6	19

The temporal variation of Marcellus Shale gas wells within the 100 and 300 foot buffer zones followed similar patterns for both the digitally extracted stream network and the NHD stream network (Figure 7). The percentage of total Marcellus Shale gas wells located within the 100 and 300 foot buffers increased significantly in the year 2008, followed by steady annual decreases. The 2008 peak and the subsequent decline is difficult to explain because minimum setback requirements did not increase until April, 2012. Although the significant increase in Marcellus Shale gas wells within the buffer zones that occurred in 2008 could be due to coincidence, further exploration into the history of regulations and relevant policy discussions may provide additional insight into what may have caused this interesting temporal pattern. As expected, after 2012, Marcellus Shale gas wells within buffer zones have decreased or stayed relatively constant for all categories except for wells within 100 feet of the digitally extracted stream network, which increased slightly.

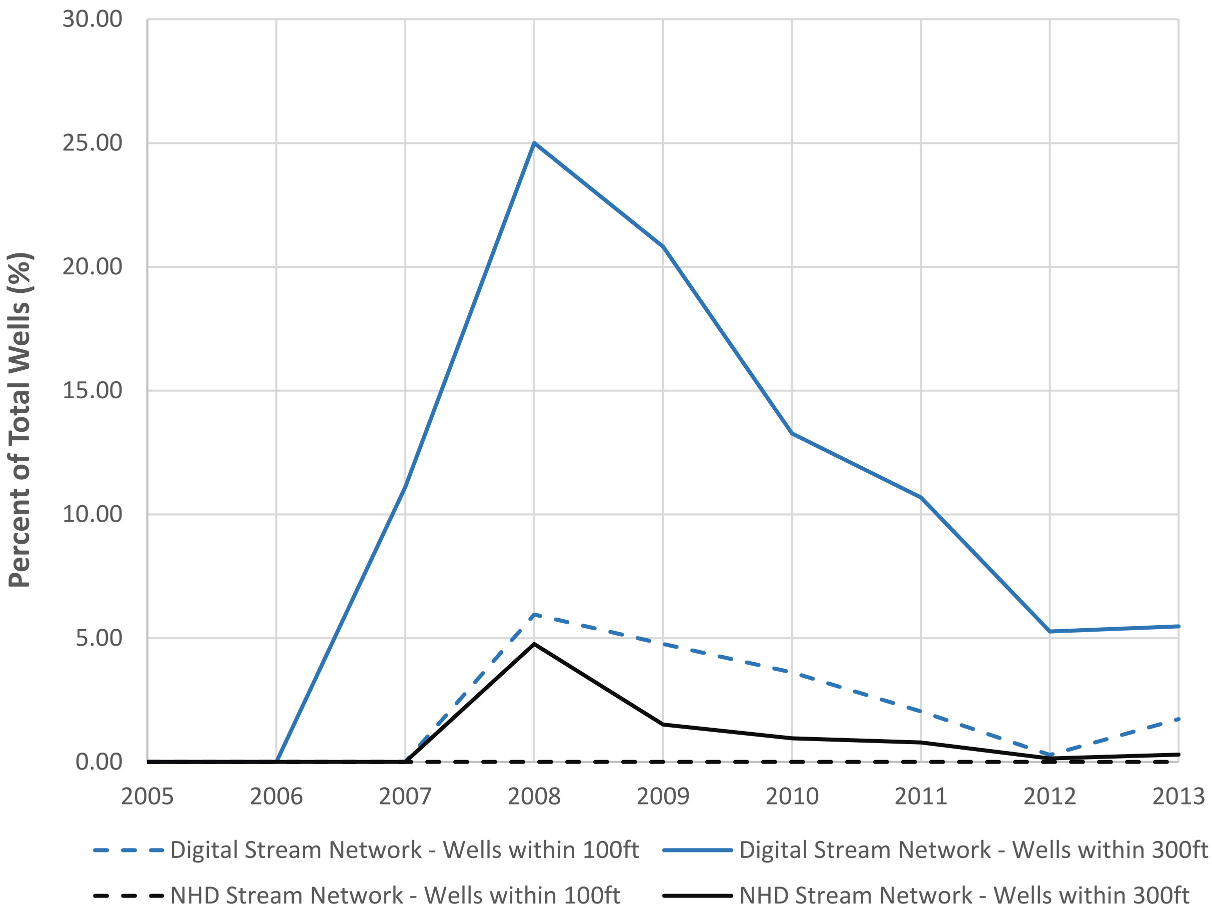

Figure 7 *- Percent of total Marcellus Shale natural gas wells within a 100 foot and 300 foot buffer of the digitally extracted stream network and the NHD stream network within the Northern Pennsylvania study area.*

Because the digitally extracted stream network displayed a significantly greater drainage density, the average distance of Marcellus Shale gas wells to the nearest surface water source was consistently greater for the NHD stream network than the digitally extracted stream network for all years (Table 2). Temporally, the average nearest distance of Marcellus Shale gas wells to both stream networks showed a linear increasing trend after the year 2008 (Figure 8). This is consistent with the previous results illustrating the peak of Marcellus Shale gas well activity within the 100 and 300 foot buffers occurring in 2008 and then subsequently decreasing. Prior to 2008, the limited number of total wells may influence the variable results in average nearest distance.

Table 2 *– The average distance per year of all Marcellus Shale gas wells to the nearest surface water source for the NHD stream network and digitally extracted stream network.*

	Average Nearest Distance (ft.)		
	NHD Stream Network	Digital Stream Network	**Total Wells**
2005	1328.13	934.89	1
2006	696.75	547.61	4
2007	1214.45	659.60	9
2008	1085.74	552.38	84
2009	1032.60	585.23	399
2010	1256.57	676.10	942
2011	1296.76	712.81	1274
2012	1277.62	799.92	721
2013	1356.25	792.97	347

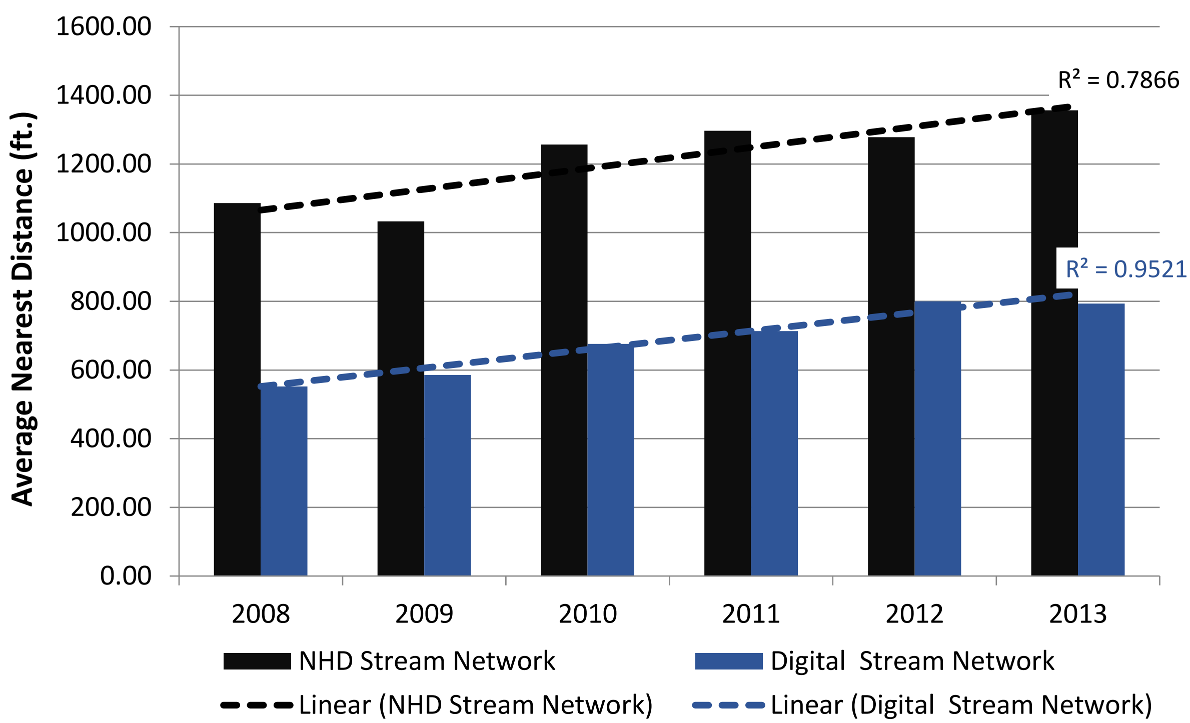

Figure 8 *- Average nearest distance per year of Marcellus Shale gas wells to surface water sources as depicted by the NHD stream network (black) and the digitally extracted stream network (blue). Linear trend lines show an increasing trend after the year 2008.*

CONCLUSION

Headwater streams play an essential role in the health of a watershed. However, because of their small size, the majority of headwater streams are excluded from published sources. The results of this study demonstrate that there is likely a vast network of streams beyond those that are displayed on a typical USGS 1:24,000 topographic map within the study area of Northern Pennsylvania. Additionally, the results of this study demonstrate that the vast network of unmapped streams are more vulnerable to the impacts associated with Marcellus Shale natural gas well development because of the lack of setback requirements for unmapped streams. Future research should focus on identifying the drivers that have historically influenced the temporal pattern of setback distance. Additional research should also focus on the potential impacts of Marcellus Shale natural gas development within critical buffer areas of unmapped headwater streams.

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