IDENTIFYING CRITICAL WATERSHEDS AND STREAMS DUE TO ACCIDENTAL SPILLS FROM UNCONVENTIONAL DRILLING SITES

by

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The Marcellus Shale is a marine sedimentary rock formation that has attracted many drilling operators to extract natural gas. Hydraulic fracturing is the major gas recovery technique used today, but it produces large amount of fluid wastes that may potentially pollute water bodies. One of the major risks is identified as water contamination by accidental spills of shale gas wastes. Therefore, it is extremely important to understand how contaminants can travel from drilling sites into streams, and to identify and quantify risks of stream contamination. To this end, there are four objectives in this study: (1) delineate surface pathways from drilling sites to nearby streams, (2) quantify pollutant travel time based on the physical characteristic variations across the geography of Pennsylvania, (3) identify critical watersheds that are under high risks for spill occurrence, and (4) carry out environmental monitoring of critical watershed. Geographic Information System (GIS) is utilized for spatial analyses. The Analytic Hierarchy Process (AHP) is applied to introduce weight distribution among influencing factors such as land cover, soil type and slope. The cost path analysis delineates travel pathways and areas around shale gas drilling sites with cheapest pollutant travel cost for the entire Pennsylvania. Travel times are calculated by using these cost paths. Results identify areas where the contaminants can potentially travel in a short time into nearby stream network. Based on this analysis, critical HUC-10 watersheds are identified with potential risk of contaminating water bodies and should be considered for further analysis of their water quality and stream importance. Herein, for the purpose of environmental monitoring of critical watershed, two of them are chosen: (1) South Fork Tenmile in the southwest PA, (2) Tioga River in the northeast PA. Future work will include using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) for modeling contaminant transport and the application of the Baseline Streamflow Estimator (BaSE) and the StreamStats program to obtain water discharges for ungaged streams, typically found in PA. This framework will be able to provide useful information for sensor placement, water surface management and monitoring for critical watersheds and streams.

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PREFACE

Foremost, I would like to express my sincere gratitude to my advisor Dr. Jorge D. Abad for the continuous support of my M.S. study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my master study.

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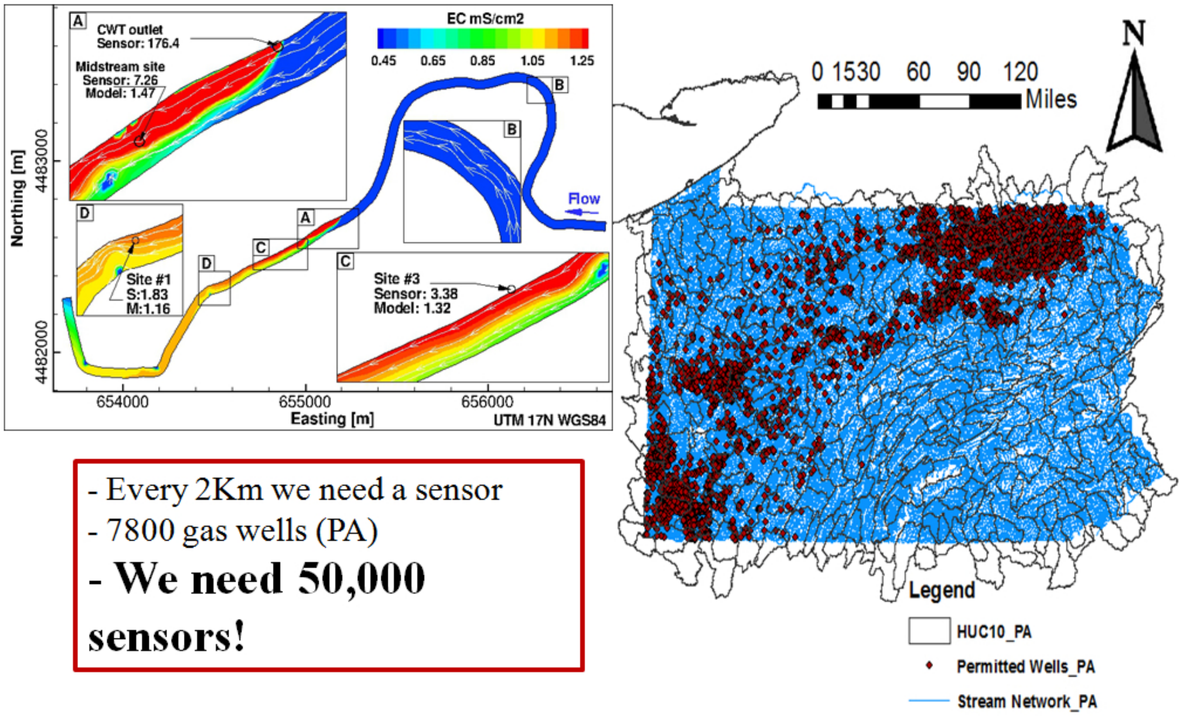
Last but not the least, I would like to thank my family for offering support and love.

1.0 INTRODUCTION

This chapter discusses the motivation, objectives and structure of this thesis.

1.1 MOTIVATION

An increase in the drilling operations has created additional possibilities for pollution around the Marcellus Shale in Pennsylvania. Surface waters from rivers are extremely important sources of public water supplies because of the high withdrawal rates they can normally sustain. Surface water is open to all kinds of pollution, of which contamination by shale gas wastes from accidental spills has been identified as a major risk (Olmstead et al., 2013). From Simon and others (2014), a water quality model was constructed in the Blacklick Creek and the results illustrated that every 500 to 2000 meters of the stream needs a water quality sensor (Figure 1) to detect spills contamination. They claimed that at least 48,075 sensors are needed considering all shale gas wells in PA, the whole number is approximately 7800 (Simon et al., 2014). I am interested in an optimal way to reduce the monitoring cost while detecting the as many events as possible. To achieve this goal, it is imperative to understand how contaminants can travel from drilling sites into streams, and to identify and quantify risks of stream contamination. Based on the locations of drilling sites and potential spills, a model is created to delineate the most probable pathway of oil and gas contaminant migration into nearest streams, and to model contaminant transport through the stream network.



- Every 2Km we need a sensor
- 7800 gas wells (PA)
- **We need 50,000 sensors!**

Figure 1. *Water quality model, shale gas wells and stream network in Pennsylvania (Simon et al., 2014)*

1.2 OBJECTIVES AND STRUCTURE OF THE THESIS

Two studies are conducted for this work. The objectives of the first study (see Chapter 2) are to delineate surface pathways from drilling sites to nearby streams, to calculate pollutant travel time based on the physical characteristic variations across the geography of Pennsylvania, and to identify critical watersheds that are under high risk for spill occurrence. In the second study (see Chapter 3), two critical watersheds are selected for monitoring critical streams – the South Fork Tenmile and the Tioga River watershed are selected in the southwest and northeast area separately. Further, this monitoring model for critical streams will be able to provide useful information for sensor placement and therefore it will help watershed scale surface water management. Chapter 4 concludes this thesis and presents future work.

2.0 EVALUATION OF POTENTIAL PATHWAYS OF ACCIDENTAL SPILLS FROM UNCONVENTIONAL DRILLING SITES TO NEARBY STREAMS

The Marcellus Shale formation attracts lots of operators to drill natural gas. Along with increasing exploration, more contaminants are produced during the process. This chapter discusses the methodology to evaluate potential pathways of shale gas spills from drilling sites to nearby streams.

2.1 INTRODUCTION

The Marcellus Shale is a marine sedimentary rock formation underlying Pennsylvania, New York, Ohio, West Virginia, Maryland, Kentucky and Virginia (Pennsylvania Department of Environmental Protection, 2013). This formation is comprised of black shales, dark gray shales, limestones and siltstones (Vidic et al., 2013). Abundant natural gas resources (approximately 489 trillion cubic feet) could be extracted from the Marcellus Shale (Vidic et al., 2013). Hydraulic fracturing is the major gas recovery technique, which required vertical and then horizontal drilling, to penetrate into the shale and extract natural gas from the shale formation. Water is the major part of fracturing fluid and the rest components are proppants, acids, biocides, etc. (Vengosh et al., 2014). During the hydraulic fracturing process, produced water would be extracted along with natural gas production, and flowback water would flow back to the surface during and after the hydraulic fracturing. Most chemicals in flowback and produced fluids are harmful to the environment (Wiseman et al., 2009). The major contaminants are heavy metals, naturally occurring radioactive material (NORM), volatile organic compounds, and high levels of total dissolved solids (Paleontological Research Institution, 2011).

Among shale gas operations that might affect water resources, one of the potential risks to be concerned in this study is the stream pollution caused by the accumulation of toxic and radioactive elements in accidental spills (Vengosh et al., 2014). According to the Pennsylvania Department of Environment Protection (PADEP) oil and gas reports, more than 7,000 wells were drilled from 2005 to 2014. Although PADEP formulated regulations for operation safety and environmental protection measures, potential risks still exist (Rozell et al., 2012).

Contaminant sources that can potentially travel from drilling sites into the nearby streams include spills at the well pad, spills from ponds, truck overturn, illegal dumping, and leaky pipelines (Oil and Gas Reports, 2014). In addition, violations are common, which include cementing, casing and well construction issues, not maintaining best practices, encroachment issues, erosion and sedimentation issues, failure to plug adequately, permitting or reporting issues, pit and impoundment issues, and pollution incidents. Among them, three types that cause surface water pollutions that are (1) erosion and sedimentation, (2) pit and impoundment issues, and (3) pollution incident (Vidic et al., 2013, Brantley et al., 2014).

Water contaminations due to accidental spills are the major risk (Olmstead et al., 2013). In order to identify and quantify the risks of stream contamination, we should first understand how the wastewaters would travel into nearby streams. Herein, only surface pathways are considered but no subsurface ones since the travel time of contaminants is shorter for the surface case (Fuchs et al., 2009, Johnson et al., 2005). The objectives are: (1) to describe the surface pathways from drilling sites to nearby streams based on physical geographic variations, (2) to calculate pollutants travel time across Pennsylvania and (3) to identify critical watersheds that are under high risks of potential spills for further monitoring.

2.2 STUDY AREA AND DATA

The study area is the entire state of Pennsylvania in the northeast of the United States with a total area of 46,055 square miles. The Marcellus Shale covers most part of Pennsylvania. In order to obtain the surface pathways from unconventional drilling sites to nearby streams, several data are needed:

The permitted and drilled unconventional wells (Figure 2 (a)) were downloaded from PADEP website. The time periods for the two datasets are both from January 1st, 2005 to January 1st, 2014.

The violations (Figure 2 (b)) are listed in PADEP website under Oil and Gas Compliance Report. The dataset was compiled to include geographic locations and grouped to categorize violations (Brantley et al., 2014). It included information about operators, inspections, violations, dates, etc.

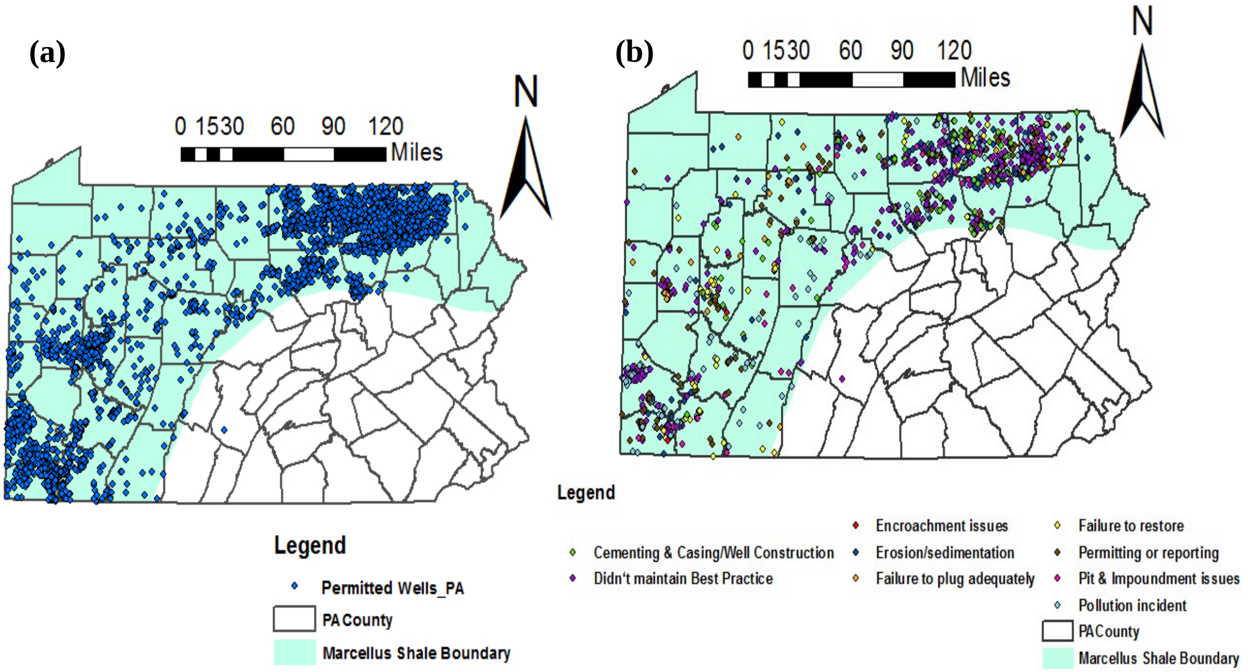


Figure 2. *(a) Permitted (including drilled) wells, (b) Violations reported by PADEP. As observed in Figure 2 (a), the wells are mostly located in the North East (NE) and South West (SW) of the PA state. Typically, the location of the violations is correlated to the distribution of wells*

Digital Elevation Models (DEM) of 10, 30 and 90 meters were downloaded from Global Land Cover Facility (GLCF) and Pennsylvania Spatial Data Access (PASDA). The resolution of DEM can affect the surface pathways delineation and its computational time. Thus, herein, 3 types of DEM at different resolutions are tested and compared to increase the accuracy.

The stream network data were also provided by PASDA. It is a vector data with the altitude resolution of 1.000000 decimal degrees. In the study, the stream network is set as the destination accepting the contaminants flow from spills.

Pennsylvania soil type data that were downloaded from PASDA describes the distribution of soils on the landscape. It is the most detailed soil geographic data developed by the National Cooperative Soil Survey. The soil type dataset contains georeferenced digital map for soil type distribution.

Pennsylvania Land cover, downloaded from PASDA, was created from Enhanced Thematic Mapper satellite data and ancillary data sources in the period 2003 to 2007. The resolution of land cover is 30 meters.

Additionally, the Hydrologic Unit Code (HUC) 10, which was provided by the United States Department of Agriculture (USDA) was used in this study. Watersheds at this scale generally consist of major tributary streams with drainage areas ranging from 75 to 150 square miles.

To deal with datasets with different resolutions, resampling technique in ArcGIS was used to create consistency (same cell sizes).

In GIS, there are two basic data types: raster and vector. Features could be expressed as points, lines, and polygons in vector format, while a raster consists of a matrix of cells (grids) where each cell contains a value representing information.

2.3 CALCULATING PATHWAYS FROM WELLS TO STREAMS

The methodology considers geographically distributed characteristics such as slope, soil type, and land cover. Spilled fluids travel down slope overland and most often end up in a stream or other surface water bodies. Several steps were required to take in order to identify pollutants travel routes. Figure 3 illustrated these steps.

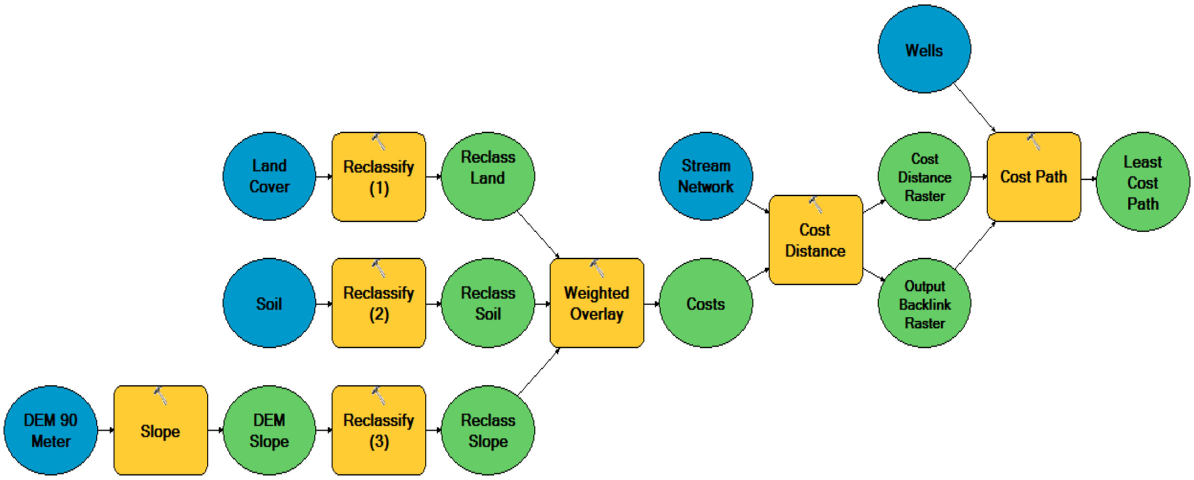


Figure 3. *Conceptual Flow Chart of the Cost Path Analysis Model. Main steps are to (1) get slope from DEM, (2) reclassify the layers of land cover, soil and slope, (3) weight value given for each layer to obtain weighted overlay layer, (4) cost distance calculated through stream network and costs layer, (5) cost path tool to obtain least cost path*

2.3.1 Slope

Slope measures how steep a straight line is. In ArcGIS, slope for a cell is the maximum change in elevation over the distance between the cell and its eight neighbors. Figure 4 (a) shows the slope output calculated for DEM 90 meters for the entire Pennsylvania. Lower slope value represents flatter terrain and higher slope value means steeper terrain.

2.3.2 Reclassification of soil, land cover and slope

Reclassification in GIS means replacing the old value with a new value for each cell. The purposes for data reclassification are to: (1) replace values according to new information, (2) reclassify values to a common scale, and (3) group certain values together. Generally, higher values will be given to more suitable attributes (for example, 1 to 10, herein 10 is for the most suitable attribute).

Based on soil permeability, USDA ranks soil types into seven classes of A, B, C, D, A/D, B/D, or C/D. Soils with high permeability are represented by A (porous and sandy) while D (non-porous clay) represents the low permeable soil. Permeability is directly correlated with runoff and indirectly correlated to infiltration. Figure 4 (b) describes the reclassified soil distribution. Soil type classes by Natural Resources Conservation Service (1986) and Keith et al. (2012) are listed in Table 1.

Table 1. Soil type classes by Natural Resources Conservation Service, 1986

Hydraulic Soil Group	Description based on infiltration	Classes
A	Sand, loam (rate of water transmission greater than 0.30 in/hr).	1
B	Silt, silt loam (rate of water transmission (0.15-0.30 in/hr).	2
C	Sandy clay loam (rate of water transmission (0.05-0.15 in/hr).	3
D	Clay loam, sandy clay, clay (rate of water transmission (0-0.05 in/hr).	4
A/D B/D C/D	*“If a soil is assigned to a dual hydrologic group (A/D, B/D, or C/D), the first letter is for drained areas and the second is for undrained areas. Only the soils that in their natural condition are in group D are assigned to dual classes.”*	2 2 1

As shown in Figure 4 (c) and Table 2, land cover is classified based on infiltration. Pasture and grass, golf courses reduce infiltration and so are represented by the lowest number

“1”, while forest, farmland, Residential and roads, wetlands, and water are represented from 2 to 6 (Keith et al, 2012).

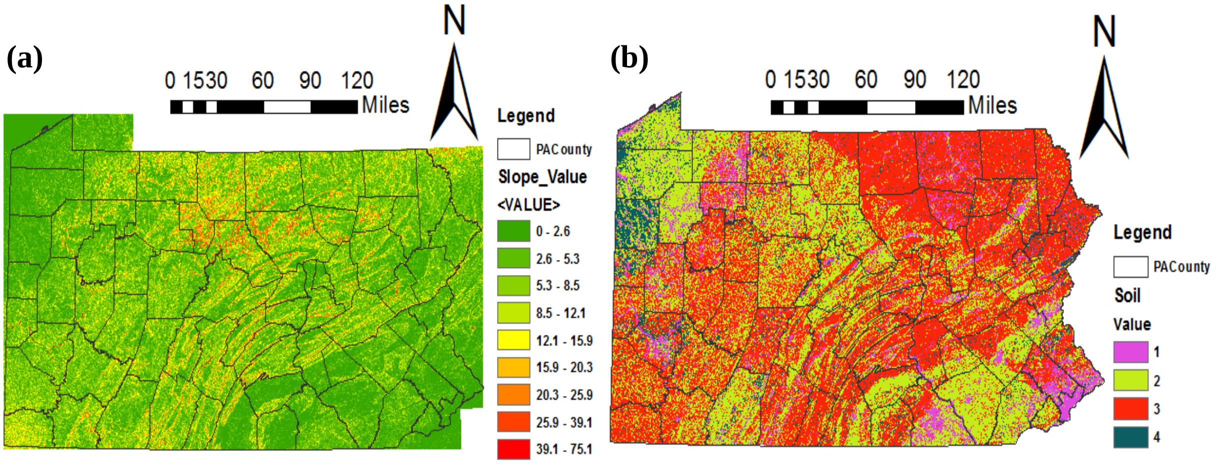
Table 2. Input for land cover reclassification adopted from PASDA

Land Cover Type	Classes
Pasture/grass, golf courses	1
Forest	2
Row crops	3
Residential, institutional, industrial, commercial land, airport, roads, bare, active mines	4
Wetlands	5
Water	6

According to EPA, runoff increases along with slope (US Environmental Protection Agency, 2010). Flat areas slow down the runoff. When the terrain is steep, flow velocity increases, then there is less time for water to infiltrate. By using the equal interval method, slope is grouped into ten classes (see Figure 4 (d) and Table 3) ranging from 1 to 10.

Table 3. Reclassification of slope

Slope (degree)	Classes
0 – 7.5	1
7.5 —15.0	2
15.0– 22.5	3
22.5 –30.0	4
30.0–37.6	5
37.6–45.1	6
45.1–52.6	7
52.6–60.1	8
60.1 –67.6	9
67.6– 75.1	10



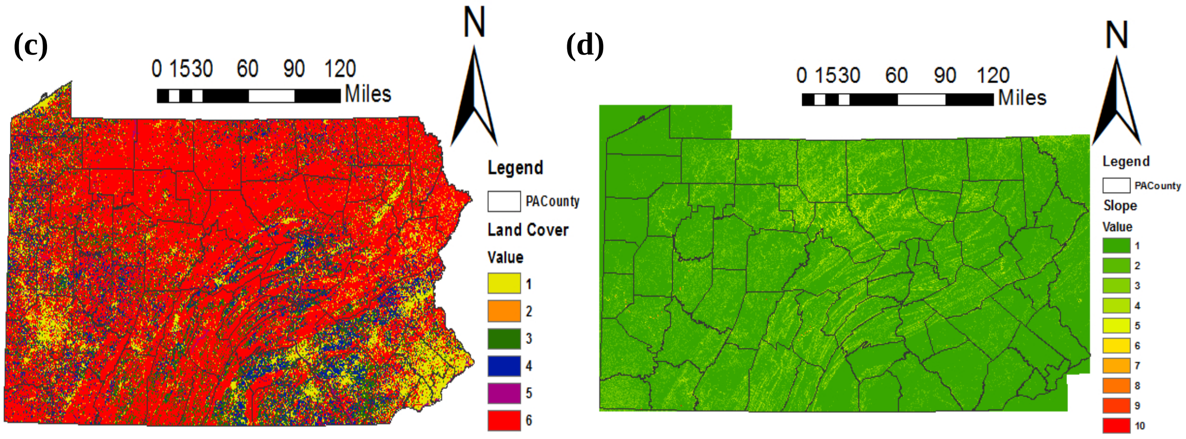


Figure 4. *(a) Computed slope from DEM 90-meter resolution, (b) Reclassification of soil, (c) Reclassification of land cover, (d) Reclassification of slope*

2.3.3 Weighted overlay

Weighted overlay has two steps: (1) giving each raster a weight based on its importance, (2) overlaying those rasters using a common measurement scale. As a result, the runoff susceptibility mapping in the entire Pennsylvania will be generated.

The input rasters include slope, soil type and land cover. It is critical to estimate weight values for influencing factors. In this case, Analytic Hierarchy Process (AHP) is applied to calculate the influencing percentage of each layer (Quan et al., 2012). Analytic Hierarchy Process (AHP) by Saaty (1980, 1986, 1990, and 1994) is a decision-making system based on pair-wise criteria comparison. For example, by using AHP, a weight will be given to slope based on its importance for runoff, the higher the weight, the more importance of slope for runoff (Chowdary et al., 2013). The standard for the pair-wise comparison is 1 for Equally preferred, 2 for Equally to moderately preferred, 3 for Moderately preferred, 4 for Moderately to strongly preferred, 5 for Strongly preferred, 6 for Strongly to very strongly preferred, 7 for Very strongly preferred, 8 for Very to extremely strongly preferred, 9 for Extremely preferred (Hojat et al., 2013). According to this standard, higher score is referred as better performance for each factor. After assigns a score to each raster, comparisons between every two rasters start and the weight could be calculated using AHP (Chang et al., 2009). As shown in Table 4 and Figure 5, the calculated weights are 55% for slope, 28% for soil, 17% for land cover (Chandio et al., 2013).

Table 4. Pair wise comparisons for least cost path criteria

Criteria	Slope	Soil type	Land cover	3rd root	Priority vector	Weight
Slope	1	2	3	1.82	0.55	55%
Soil type	1/2	1	3/2	0.91	0.28	28%
Land cover	1/3	2/3	1	0.61	0.17	17%
Sum	11/6	11/3	11/2	3.34	1	100%

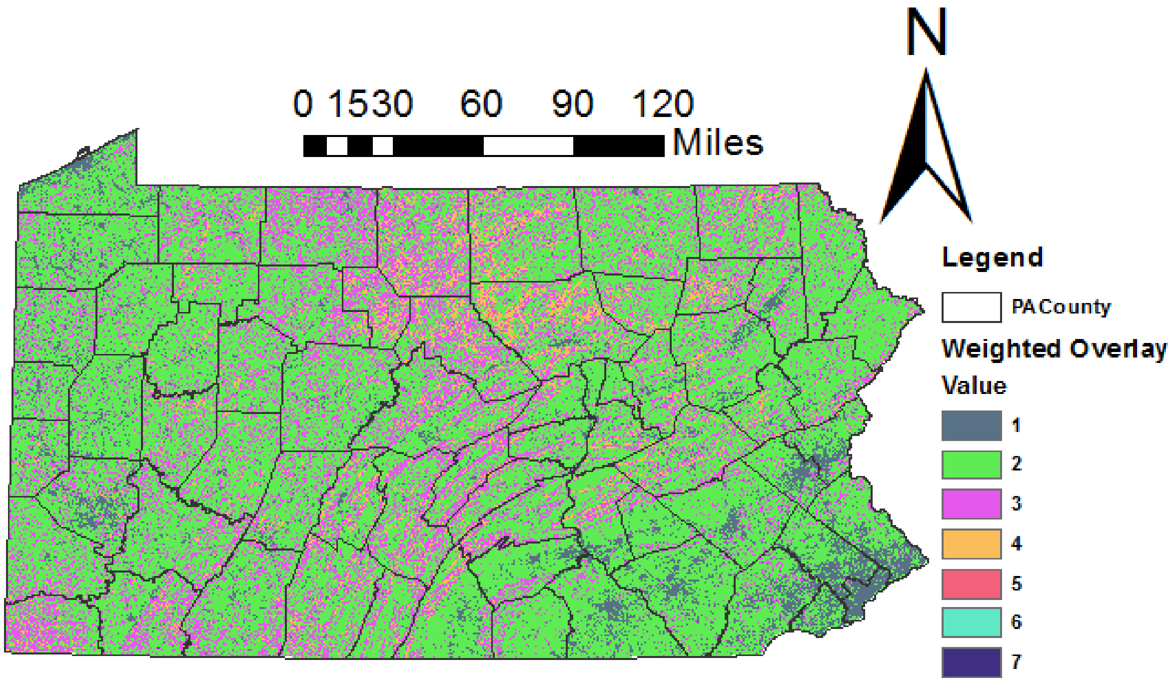


Figure 5. *Weighted overlay result for potential runoff, the value represents the suitability for runoff, 7 means the most suitable while 1 means least suitable*

2.3.4 Cost distance and cost path analysis

With the same principle of physical shortest distance between two points, cost distance created shortest weighted distance between each cell to the nearest source in ArcGIS (Kennedy, 2013). The weighted overlay surface, created earlier, and the contamination sources which are the location of well pads, are used in cost distance calculation.

By using the Cost Path tool, the least cost path from an origin to the closest destination can be calculated (Park et al., 2013). It is an accumulative function from source cells to destination cells, herein, from gas well to streams (Desrochers et al., 2011). Figure 6 (a) shows the cost path results for the entire Pennsylvania for DEM 90 meters. This calculation is based on runoff potential, considering slope, soil type, land cover, and thus obtain the cheapest routes.

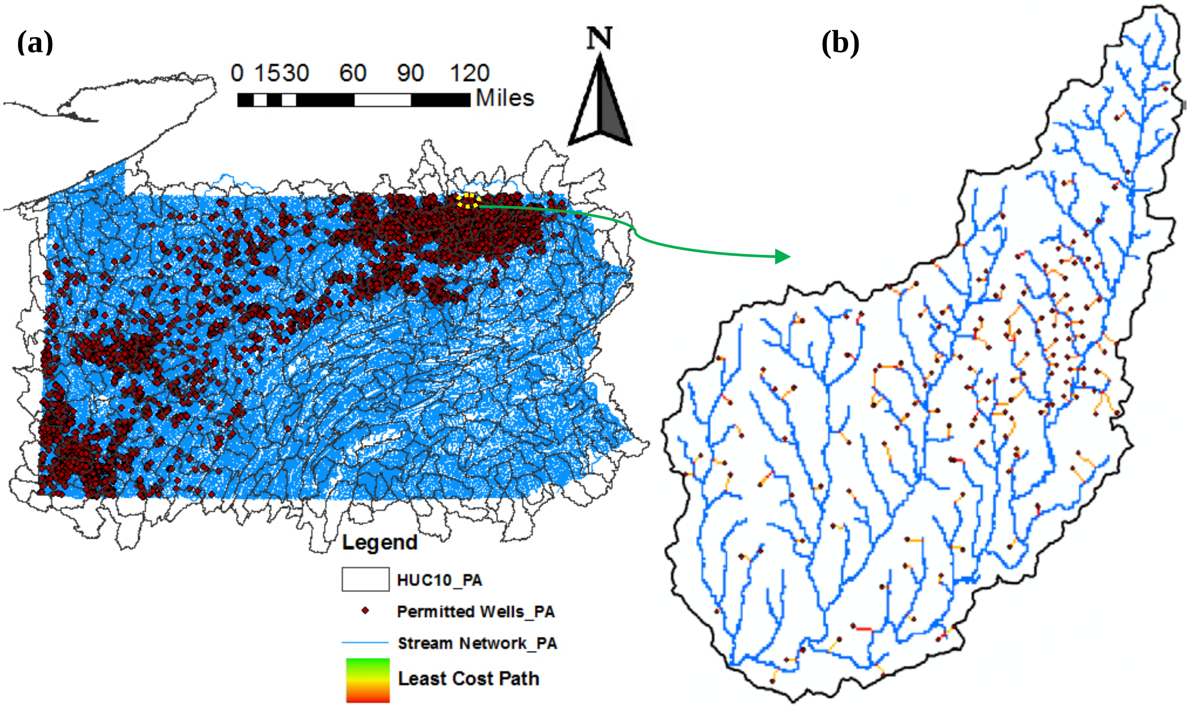


Figure 6. *(a) Cost path results for the entire PA state, (b) Least cost path from drilling sites to nearby streams for East Branch Wyalusing Creek*

2.3.5 Sensitivity analysis calculation of the cost path

A sensitivity analysis on the DEM resolution is performed with DEM resolution of 10m, 30m, and 90m. A small study area is selected to test sensitivity to DEM covering three HUC10 watersheds of Tunkhannock Creek, Lower Susquehanna River, and East Branch Tunkhannock Creek. It is observed that different resolution might have different routes for the same origin and destination (see Figure 7 for routes 1, 2 and 3). Therefore, the percentage of different routes for each DEM resolution is calculated. Moreover, the angle between two routes with the same origin and same destination is measured for different resolutions, and the number of routes is counted separately whenever angles are greater than 60, 90, and 120. This number is normalized by the total number of routes. The results could be seen in Table 5.

Table 5. Direction difference among DEM 10m and 90 m

Angle (degree)	Percentage (%)
Greater than 60	6.77
Greater than 90	5.25
Greater than 120	3.82

Because the percentage errors are relatively small, it is decided to only use the 90 meter DEM resolution for all calculations and analysis. This made the computations feasible for the entire Pennsylvania.

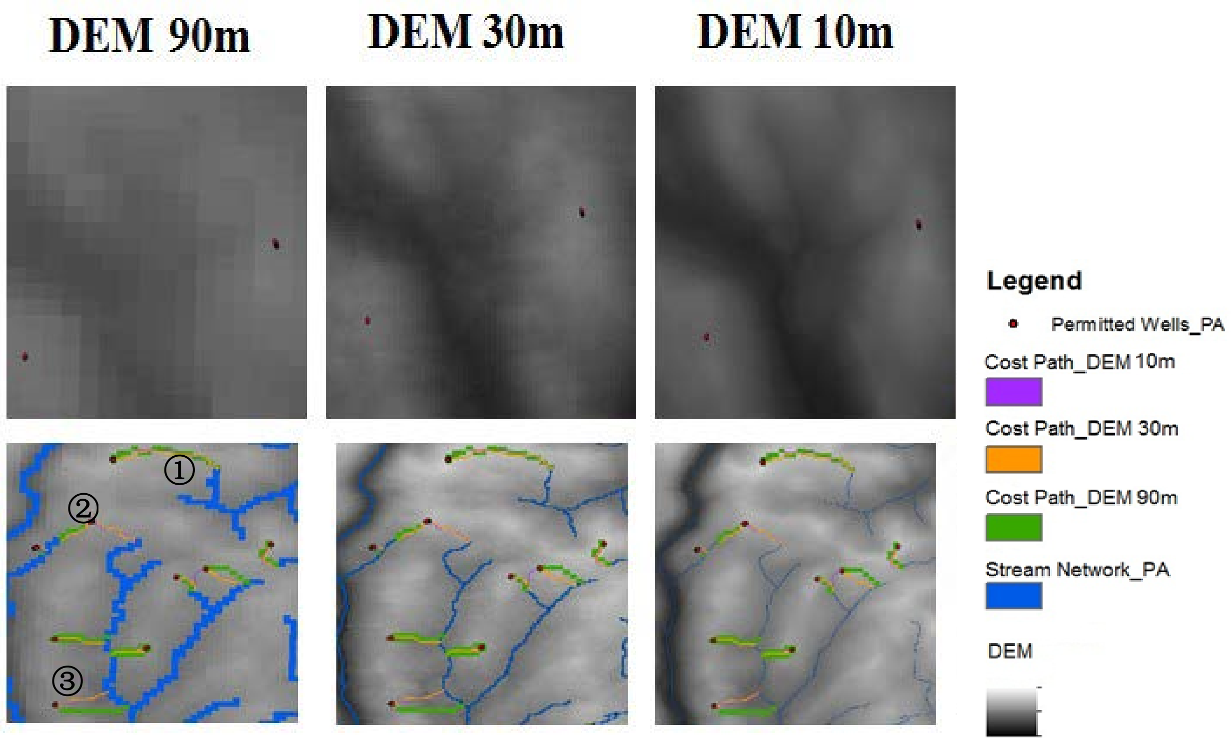


Figure 7. *Comparisons of three DEM resolutions for least cost paths from well pads to nearby streams*

2.4 OVERLAND FLOW MODEL

Overland flow describes water flowing over the land, down slope toward a surface water body. Its forming based on the soil infiltration capacity (Smith et al., 2007). Overland flow is formed when the soil is saturated to full capacity. Then the excess water on the soil starts moving downslope by gravity (Leopold et al., 1964).

In order to reduce the complexity of overland flow, herein I describe the following assumptions: (1) the flow can be described as uniform, (2) the flow is parallel to the surface, (3) the flow has a constant width, and the boundary to the flow is longitudinally uniform, (4) grain roughness is homogeneous over the wetted perimeter and can be considered as random, (5) form roughness and other sources of flow resistance can be ignored, (6) resistance is independent of flow depth, (7) resistance can be represented as a function of the Reynolds number (Smith et al., 2007). Based on the uniform flow assumption, the Manning's equation is used to calculate the overland flow velocity as:

$V = 1/n \times R^{2/3} \times S^{1/2}$

Where V is the velocity (m/s), R is the hydraulic radius, S is the bed slope, and n is the dimensionless number that characterizes the flow resistance. Following Farrar et al. (2010), R = 0.122m is used (Farrar et al., 2010). Moreover, to estimate overland flow velocities, Manning's roughness coefficients were determined by considering land cover information. Based on land cover dataset, different Manning's roughness coefficients are selected for this analysis. Table 6 summarizes the input Manning's coefficient (ODOT Hydraulics Manual, 2011).

Table 6. Manning's roughness coefficient values (ODOT Hydraulics Manual, 2011)

Surface Material	Manning's Roughness Coefficient Values "n"
Asphalt / Concrete	0.014
Floodplains - pasture, farmland	0.035
Natural streams - major rivers	0.035
Floodplains- light brush	0.05
Floodplains - trees	0.15

By substituting different Manning's coefficients into the overland flow equation, velocities for each cell are obtained. The range of velocity is from 0 to 12.39 m/s.

2.5 CALCULATING TRAVEL TIME FROM WELLS TO STREAMS

To get the travel time for each path, two steps are required: (1) compute time for each cell from the velocity and the length (Chinh et al., 2013), (2) accumulate time for each path.

$t_1 = L_1 / V_1$

$t_c = t_1 + t_2 + \ldots + t_n$

t_1, L_1 V_1 – time, length and velocity for cell one

$t_2 \ldots t_n$ – time for cell 2 … cell n

t_c –accumulated time for one path

By using velocity and length, the travel time could be calculated based on the above equations. Figure 8 (a) is the histogram of accumulated travel time for each route in PA State. The range of accumulated travel time for each path is 0 to 3273 seconds with an average of 345 seconds. A well with a shorter travel time has a higher possibility for polluting streams. In order to identify critical wells causing potential stream contamination, the shortest time well is defined as follows: 1% shortest time is o.o1 times 3273 seconds (the longest time) equals to 32.73 seconds. Therefore, 1% shortest time well is the one with a travel time less than 32.73 seconds, which highlighted in red color. Similarly, I color 3% shortest time wells in green, 5% shortest time wells in blue, and 10% shortest time wells in yellow. A map version could be seen in Figure 8 (b).

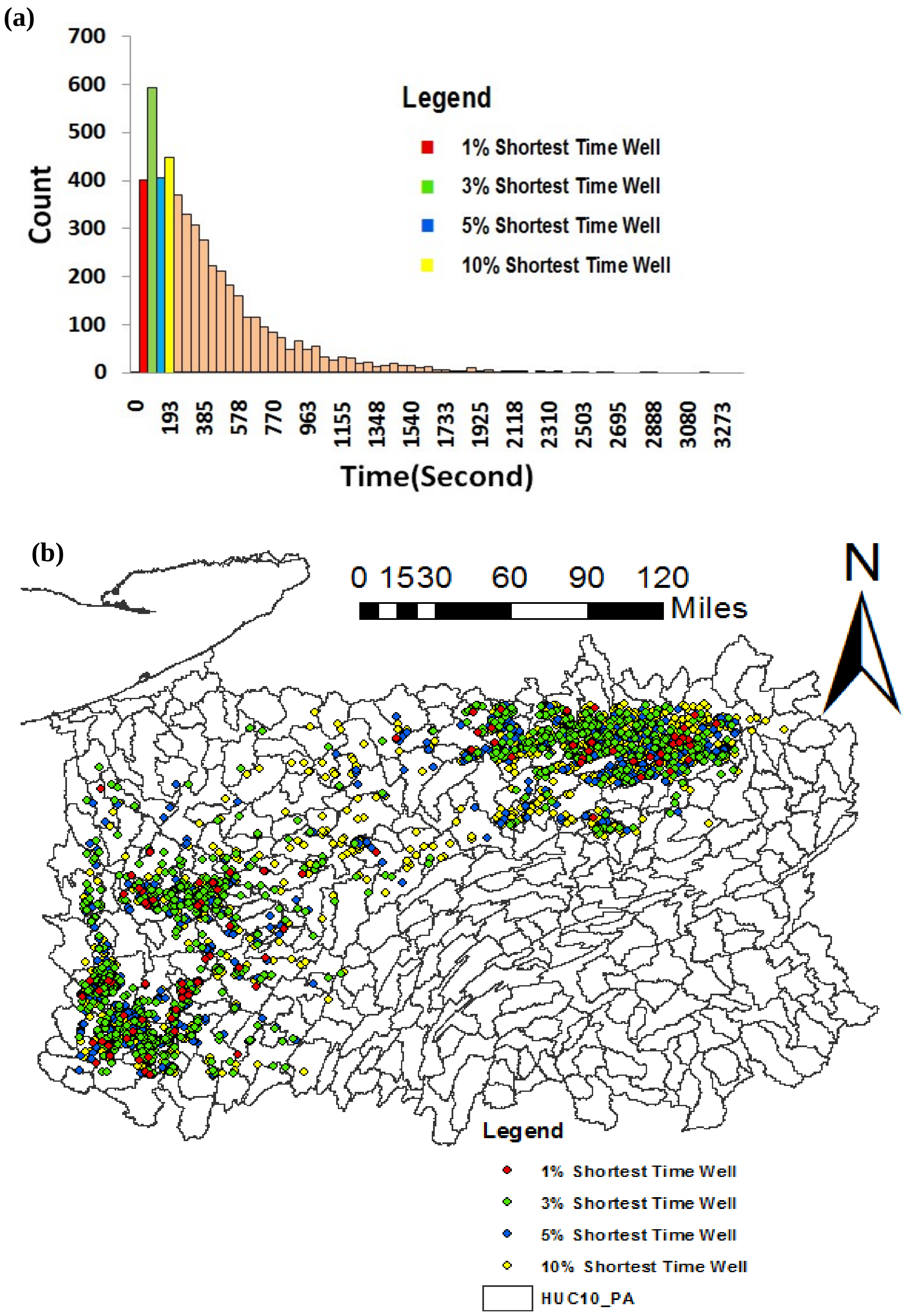


Figure 8. *(a) Histogram of time for each path, (b) Spatial distribution of wells that are placed within 1% (red points) 3% (green points) 5% (blue) and 10% (yellow) range travel time in each HUC10 watershed*

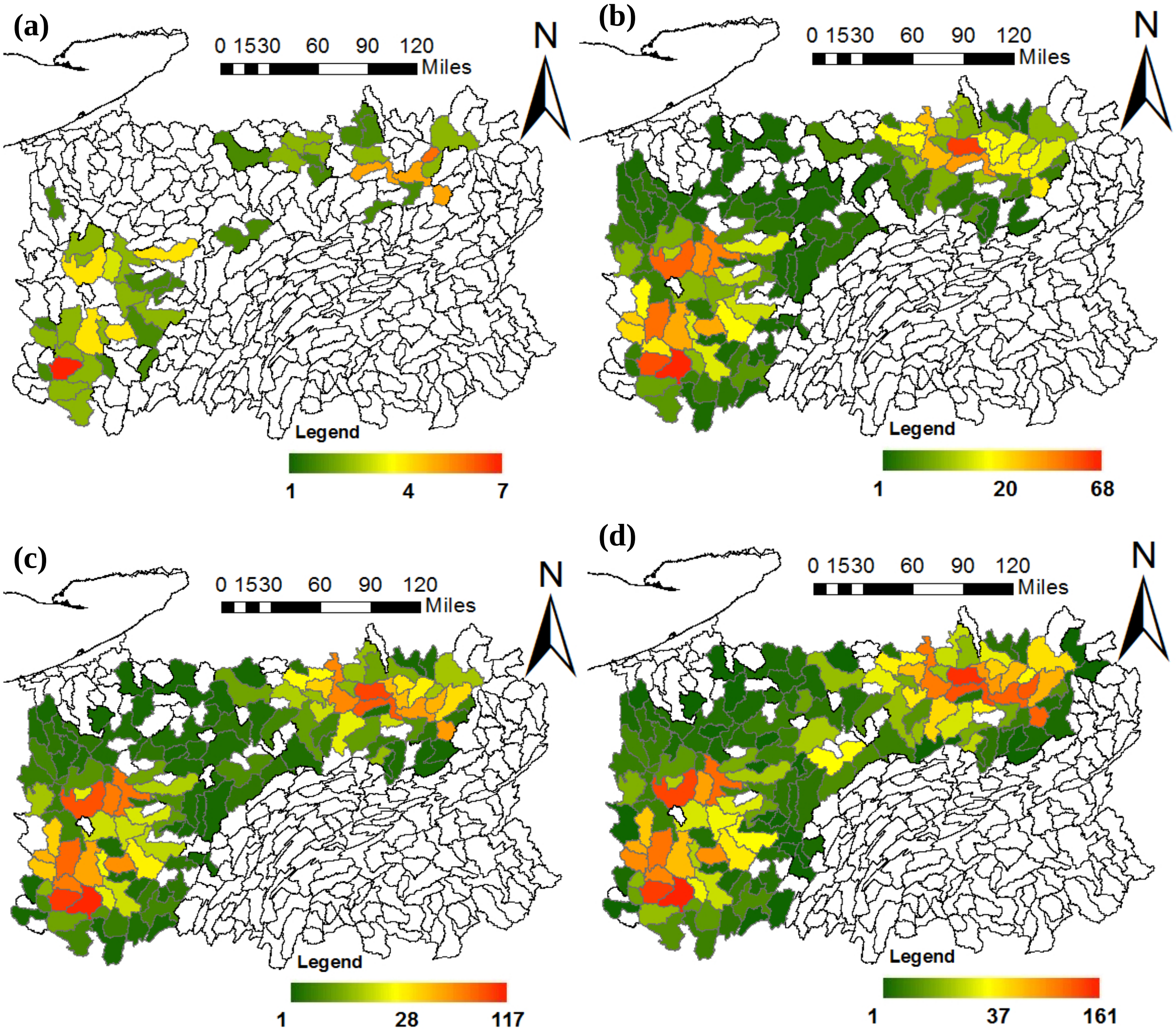


Figure 9. *Number of wells with shortest times per HUC10, (a) 1%, (b) 3%, (c) 5% and (d) 10%*

The number of shortest time wells is counted for each HUC10 watershed. Figure 9 (a) is the result for the number of 1% shortest time wells in each HUC10 watershed. The range is between 1 and 7, of which take place in Upper Monongahela River watershed. From the number of 3%, 5%, 10% shortest time wells per HUC10 in Figure 9 (b) (c) (d), the spatial distribution of wells are similar. In the southwest, Tenmile Creek, South Fork Tenmile, Upper Monongahela River and Connoquenessing Creek have the largest amount of shortest time wells. In the northeast, Sugar Creek and Towanda Creek are the typically critical ones. Since the watershed with a larger number of shortest time wells indicates more potential risks, it is crucial to attach importance to those watersheds.

2.6 DISCUSSION

2.6.1 Normalization

A percentage could be calculated by normalizing the number of shortest time wells with total number of permitted wells per HUC10. Figure 10 (a) shows the 1% shortest time wells normalized by total wells per HUC10. It ranges from 0.3% to 11.1%. The heat map shows red for 11.1% (Upper Monongahela River) that is the region needs more attention about any accidental spills. Figure 10 (b) (c) (d) are the normalization for 3%, 5%, 10% shortest time wells, respectively. Compared with Figure 9, the distribution for critical watersheds (red ones) changed. After normalization, critical watersheds are not the ones with the most number of shortest time wells. For example, a watershed with only one well would be the most critical one if that well is shortest time well. Therefore, the normalization results reflected a specific weight of critical watersheds in each HUC10.

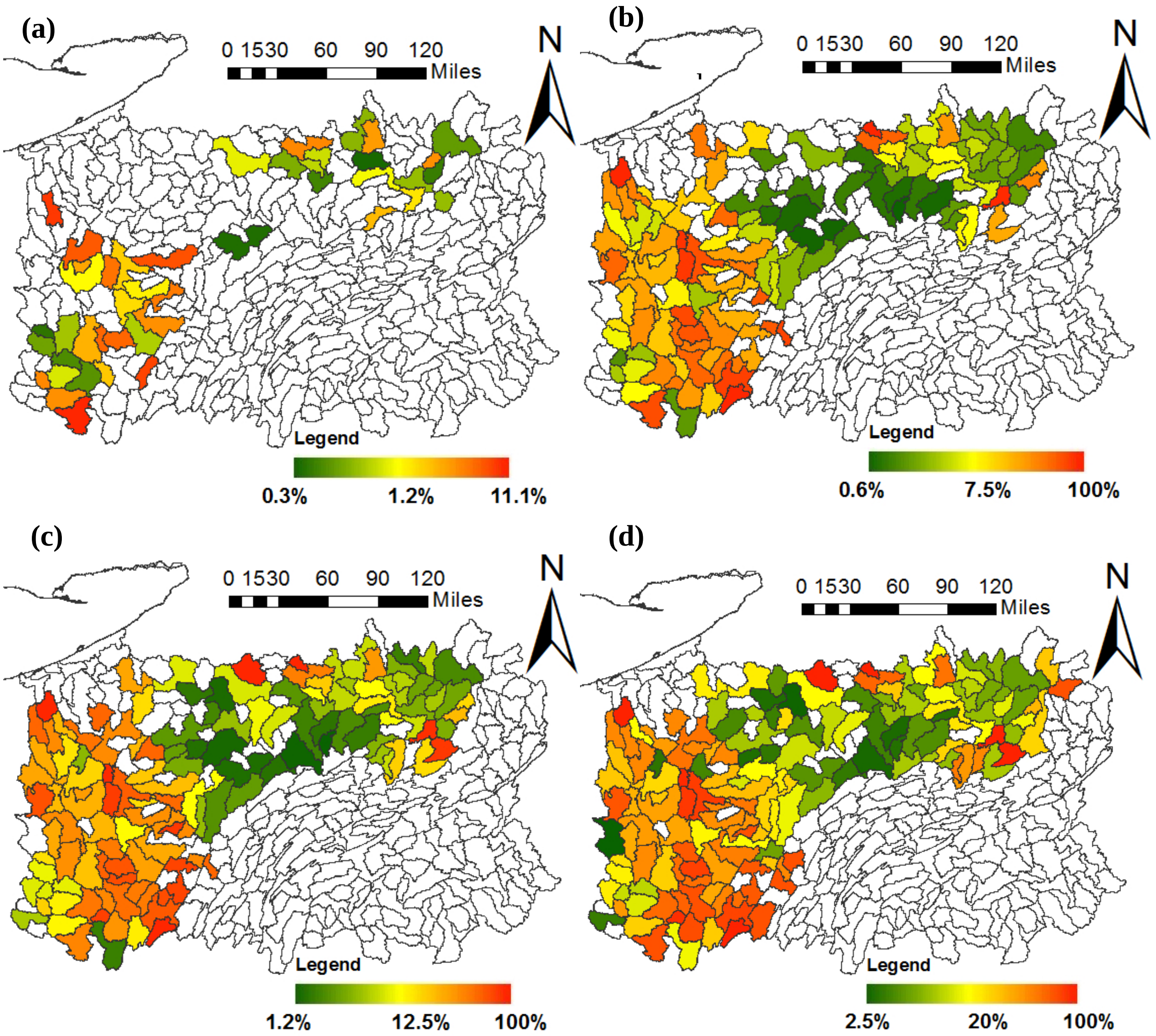


Figure 10. *Normalized shortest time wells per HUC10, (a) 1%, (b) 3%, (c) 5% and (d) 10%. The normalization was done using the total number of permitted wells per HUC10*

2.6.2 Critical watershed and violations' report

Figure 11(a) is the heat map for the number of violations normalized by the number of drilled wells in each HUC10 watershed. The values range between 10.8% and 747%. To decrease the number of violations and attach importance on those pollution caused violation (three types causing pollutions: erosion and sedimentation, pollution incident and pit and impoundment issues), Figure 11 (b) is plotted just normalized by 3 specific kinds of violation lead to contamination. This map is a generalization for the pollution risk control across the whole Pennsylvania. Moreover, for the volunteer groups, which are the high school investigation groups, this map would be a useful guidance displaying where to go sampling.

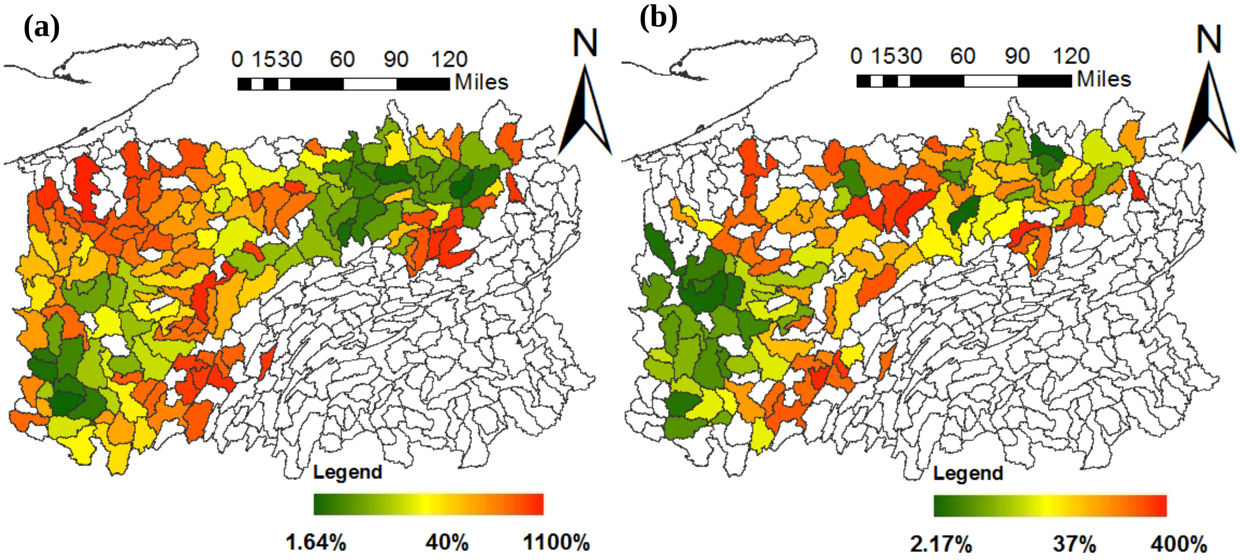


Figure 11. (*a) Normalization of number of violations over number of drilled wells per HUC10, (b) Normalization of number of 3 type violations over number of drilled wells per HUC10*

2.6.3 Stream importance

Stream existing use data for water bodies is from PASDA, which involves two major parameters: high quality water and exceptional value water. High quality water is the one to be regarded as "good" water in the view of chemistry or biology. This kind of water is favorable for the propagation of aquatic community as fish, shellfish, wild animals and recreation. The standards to judge the exceptional value water are: " *(1) The water meets the requirements of subsection (a) and one or more of the following: (i) the water is located in a National wildlife refuge or a*

State game propagation and protection area, (ii) the water is located in a designated State park natural area or State forest natural area, National natural landmark, Federal or State wild river, Federal wilderness area or National recreational area, (iii) the water is an outstanding National, State, regional or local resource water, (iv)the water is a surface water of exceptional recreational significance,(v)the water achieves a score of at least 92% (or its equivalent) using the methods and procedures described in subsection (a)(2)(i)(A) or (B), (vi)the water is designated as a ''wilderness trout stream'' by the Fish and Boat Commission following public notice and comment. (2) The water is a surface water of exceptional ecological significance (Pennsylvania Code § 93.4b.）.”

The heat map (Figure 12) gives the idea for protecting those watersheds. This map sums the length of existing stream use per HUC10. Those critical watersheds have higher accumulative length either for the high quality water or exceptional value water, and they are Lycoming Creek, Tioga River, Babb Creek, Little Pine Creek, Lower Pine Creek, Larrys Creek, Lower Loyalsock Creek and Muncy Creek.

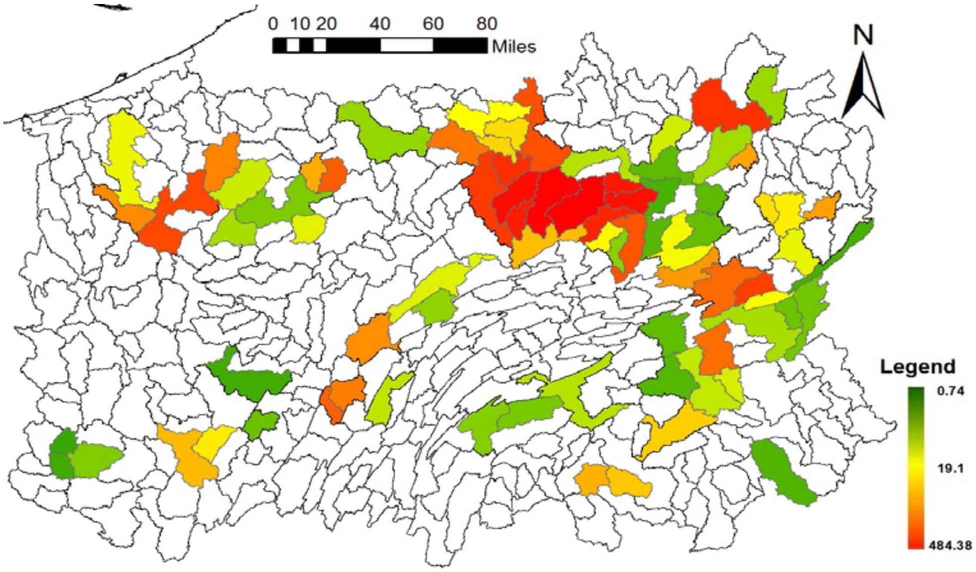


Figure 12. *Sum length for existing stream use per HUC10*

2.7 CONCLUSION

This study integrated topography and physical characteristics of PA into potential risk analysis of surface water contamination from shale gas wells. Cost path analysis is the major technique used in the assessment. The Analytic Hierarchy Process (AHP) is created to introduce weight distribution among influencing factors such as land cover, soil and slopes. Overland flow principle is applied based on the physical geographic characteristics for the study area. Several assumptions were made to simplify Manning's equation. With different Manning's coefficient "n", velocities for each path are calculated. Therefore, the accumulative travel time for each path is computed from velocity and length.

Based on this analysis, critical HUC-10 watersheds, which have potential risks of contaminating water bodies, are identified. A well with a shorter travel time has a higher possibility for polluting streams. In order to identify critical wells causing potential stream contamination, the 1%, 3%, 5% and 10% shortest time wells are defined. Compared with the distribution of number of shortest time wells per HUC10, the normalization results reflected a specific weight of critical watersheds in each HUC10. Meanwhile, the normalization of 3 types of violations also provides useful information to guide volunteer groups for sampling. Furthermore, to protect the watersheds with high quality water and exceptional value water, a map of the accumulative length for existing stream use is created based on HUC10 watersheds. It is a suggestion to attach more importance to those critical watersheds.

For further analysis, more attention will be paid to the interaction of surface and sub-surface processes. For now, this study just concentrates on spills at the well pads. To improve the accuracy, a probability will be considered for the spills occurrence at the well pads. In addition, this work will be improved by considering the practical requirements of the volunteer groups and working with them to monitor some critical streams and critical watersheds based on this research result. Meanwhile, cooperating with watershed communities and guiding their monitoring projects and activities in critical streams will be performed based on this study. This methodology could be used to monitor critical watersheds and serve as sensor placement design across the entire Pennsylvania.

3.0 IDENTIFYING CRITICAL STREAMS NEAR UNCONVENTIONAL DRILLING SITES: ANALYSIS OF DATA AND PREPARATION FOR 1D CONTAMINANT MODELING

Pathways from unconventional drilling sites to nearby streams are delineated in Chapter 2. Herein, an analysis and preparation for contaminant transport model in critical watersheds is illustrated.

3.1 INTRODUCTION

3.1.1 Contaminants' fate related to Marcellus Shale

In Pennsylvania, the Marcellus shale is an important resource for oil and natural gas (Kargbo et al., 2010). Natural gas extraction has hugely expanded as a result of increasing demands (Bamberger, M. et al., 2012). Environmental pollutants could be produced during oil and gas exploration which are related to water quality as accidental spills, violations, gas migration, contaminant transport through induced and natural fractures, and wastewater discharge (Rozell et al., 2012, Vidic et al., 2013). In addition, human factors such as illegal dumping and the accidents in well sites, roads, or pipelines also play an important role (Arthur et al., 2009, Entrekin et al., 2011).

Once the spill occurs, contaminants will start polluting surface water. Along with rainfall, the contaminants produced by those spills will go down through soil, and after infiltration or evaporation, they will flow into the streams in the end (Myers, T., 2012). The soil not only has the function to percolate liquid into the ground as a filter but also blocks large solid particles. Smaller contaminants, although not physically blocked, may adhere to the soil particles, being either removed or seeped into groundwater later on. Runoff is influenced by various factors such as land cover, soil type, slope, etc. (Han et al., 2014). After contaminants are incorporated into stream, complex scenarios such as dilution, suspension, reaction, will take place. Therefore, the development of a quantitative model for contaminant transport is essential for pollution management.

3.1.2 Geographic Information System (GIS) and hydrology model

Spatially distributed rainfall runoff model is widely applied to the hydrological processes (Storck et al., 1998). A more complete mathematical framework was proposed by Francisco Olivera and David Maidment at the University of Texas at Austin. They put forward a spatially distributed unit hydrograph method which redefined GIS as a modeling tool by adding a bridge between the heterogeneous terrain and an existing lumped mode (Olivera et al., 1999). Coroza et al. (1997) combined GIS and runoff model together. Their goal is to avoid the single tool drawback aand improve the analysis efficiency (Coroza et al., 1997). In addition, Chang et al (2000) developed a GIS-assisted distributed watershed model; which simulated flooding and inundation levels of large watersheds with different rainfall return time.

Among various analysis techniques, GIS and the Hydrologic Engineering Center's River Analysis System HEC-RAS are widely used and they are combined in various manners. To combine GIS and HEC-RAS, a feature called HEC-GeoRAS was developed for HEC-RAS pre-processor. Geometric, boundary and initial conditions could be prepared in GIS and then HEC-RAS would handle wide kinds of hydraulic structures either for simple dendritic streams or complex networks.

Least cost paths from spills to nearest streams are obtained using ArcGIS-based framework developed by Han et al (2014). From this previous analysis, boundary conditions for 1D transport of contaminants will be incorporated. For this purpose, the first step is to consider all influencing factors and make preparations for data exported from GIS; after that, HEC-RAS river network model will be built in order to provide detailed information for contaminant transport; then strategies for sensor placement and surface water management will be discussed (Yang et al., 2006).

3.2 MATERIALS AND METHODS

3.2.1 Choosing study area

Data on permitted and drilled unconventional wells were downloaded from PADEP website. The time periods for the two datasets are both from January 1st, 2005 to January 1st, 2014. The violations are listed in PADEP website under Oil and Gas Compliance Report. The dataset was compiled to include geographic locations and grouped to categorize violations (Brantley et al., 2014). It included information about operators, inspections, violations, dates, etc Based on a previous study (Han et al., 2014), the pathways of potential contaminants from well pad to nearby streams were determined and critical HUC10 watersheds (based on the 1%, 3%, 5%, 10%

shortest time wells) were identified. Herein, only the 5% shortest time wells were considered and set as the boundary condition in flow runoff model. Digital Elevation Model (DEM) of 10 meters was downloaded from Pennsylvania Spatial Data Access (PASDA). Stream existing use for water bodies was downloaded from PASDA, which involves two major parameters: high quality water and exceptional value water. United States Geological Survey (USGS) gauging stations supplied the information on the distribution of the stations along the continental USA (USGS).

Permitted wells, drilled wells, 3 types violations (based on PADEP), permitted wells minus drilled wells, 5% shortest time wells (based on Han et al., 2014), stream existing use and USGS gaging stations are introduced as influencing factors for choosing the watersheds.

The methodology to choose critical watersheds was developed in two steps, of which the first step is the reclassification of the input data and the second step is the overlay of all the data to calculate the weighted layer. An average weight value was given to each influencing factor, e.i. permitted wells have a weight value of 15%, drilled wells 15%, permitted wells minus drilled wells 14%, three types violations 14%, 5% shortest time wells 14%, stream existing use 14%, and USGS gauge stations 14%. The weighted layer will show each watershed with a value that represents its environmental relevance. A summary of the results is described in Table 7. As shown in Table 7, critical watersheds are indicated based on HUC10.

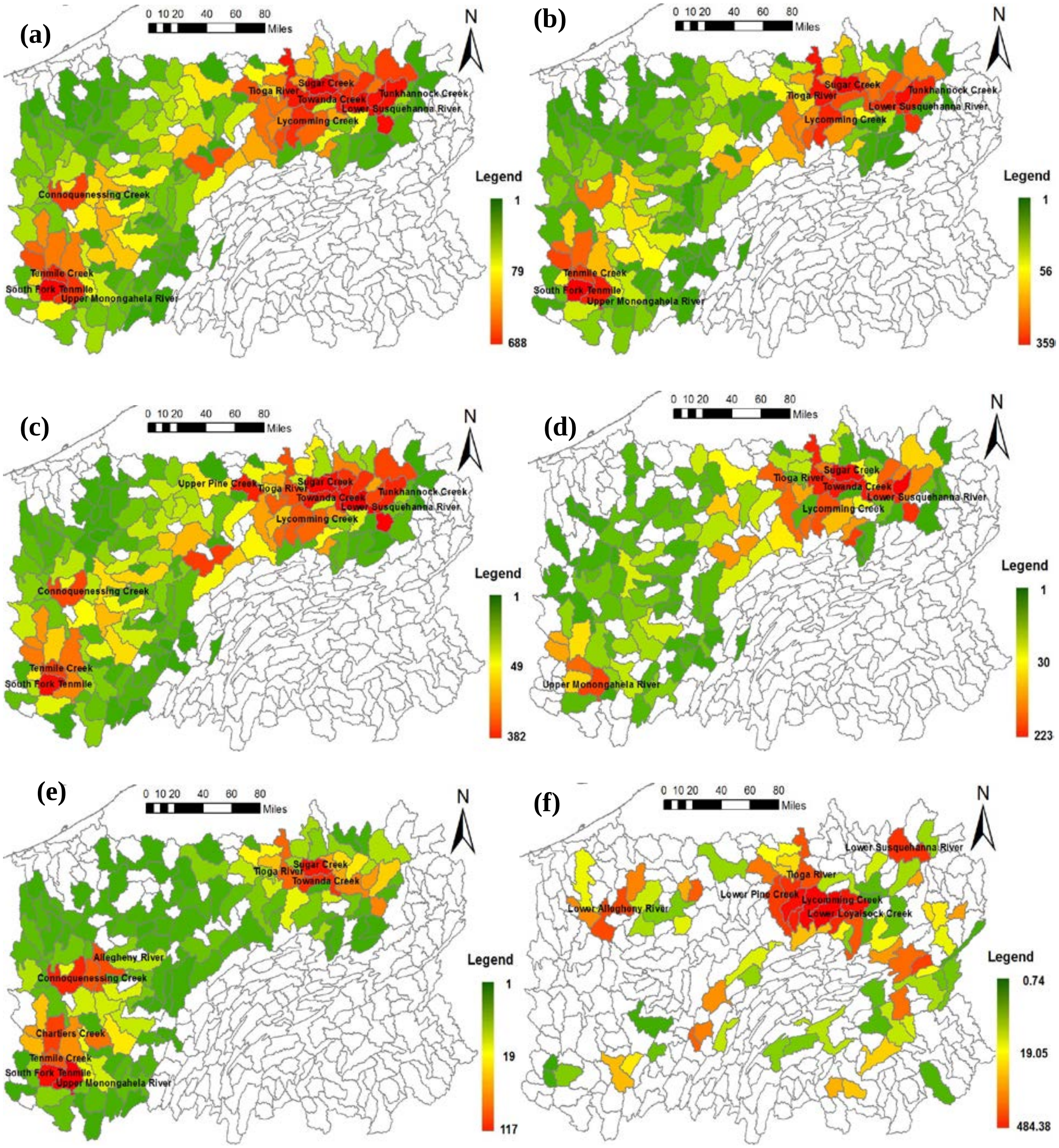
Table 7. Critical watersheds on HUC 10 in Pennsylvania

HUC10 Name	Number of Permitted Wells / HUC10	Number of Drilled Wells / HUC10	Number of 5% Shortest Time Wells / HUC10	Number of 3 Type Violations / HUC10	Number of Permitted Minus Drilled Wells / HUC10	Number of Gaging Stations / HUC10	Sum Length of Stream Use / HUC10
South Fork Tenmile	**critical**	**critical**	**critical**	**critical**	**critical**		
Tioga River	**critical**	**critical**	**critical**	**critical**	**critical**		**critical**
Lycoming Creek	**critical**	**critical**		**critical**	**critical**		**critical**
Sugar Creek	**critical**	**critical**	**critical**	**critical**	**critical**		
Upper Monongahela River	**critical**	**critical**	**critical**				
Lower Branch Susquehanna River						critical	
Lower Susquehanna River	critical	critical					

Table 7 (continued)

Tenmile Creek	critical	critical					
Upper Pine Creek							critical
Lower Pine Creek							critical
Babb Creek							critical
Larrys Creek							critical
Towanda Creek	critical		critical	critical	critical		
Lower Loyalsock Creek							critical
Wyalusing Creek	critical			critical	critical		
Meshoppen Creek	critical	critical		critical	critical		
Tunkhanock Creek	critical	critical			critical		

The results of weighted overlay are shown in Figure 13. Those red watersheds are more critical than the green ones. Thus, South Fork Tenmile, Tioga River, Lycoming Creek, Sugar Creek, Upper Monongahela River are considered as the most critical ones.


(a)
0 10 20 40 60 80
Miles
N
Tioga River
Sugar Creek
Towanda Creek
Tunkhannock Creek
Lower Susquehanna River
Lycomming Creek
Connoquenessing Creek
Tenmile Creek
South Fork Tenmile
Upper Monongahela River
Legend
1
79
688
(b)
0 10 20 40 60 80
Miles
N
Sugar Creek
Tioga River
Tunkhannock Creek
Lower Susquehanna River
Lycomming Creek
Tenmile Creek
South Fork Tenmile
Upper Monongahela River
Legend
1
56
359
(c)
0 10 20 40 60 80
Miles
N
Upper Pine Creek
Tioga River
Sugar Creek
Towanda Creek
Tunkhannock Creek
Lower Susquehanna River
Lycomming Creek
Connoquenessing Creek
Tenmile Creek
South Fork Tenmile
Legend
1
49
382
(d)
0 10 20 40 60 80
Miles
N
Tioga River
Sugar Creek
Towanda Creek
Lower Susquehanna River
Lycomming Creek
Upper Monongahela River
Legend
1
30
223
(e)
0 10 20 40 60 80
Miles
N
Sugar Creek
Tioga River
Towanda Creek
Allegheny River
Connoquenessing Creek
Chartiers Creek
Tenmile Creek
South Fork Tenmile
Upper Monongahela River
Legend
1
19
117
(f)
0 10 20 40 60 80
Miles
N
Lower Susquehanna River
Tioga River
Lower Pine Creek
Lycomming Creek
Lower Loyalsock Creek
Lower Allegheny River
Legend
0.74
19.05
484.38

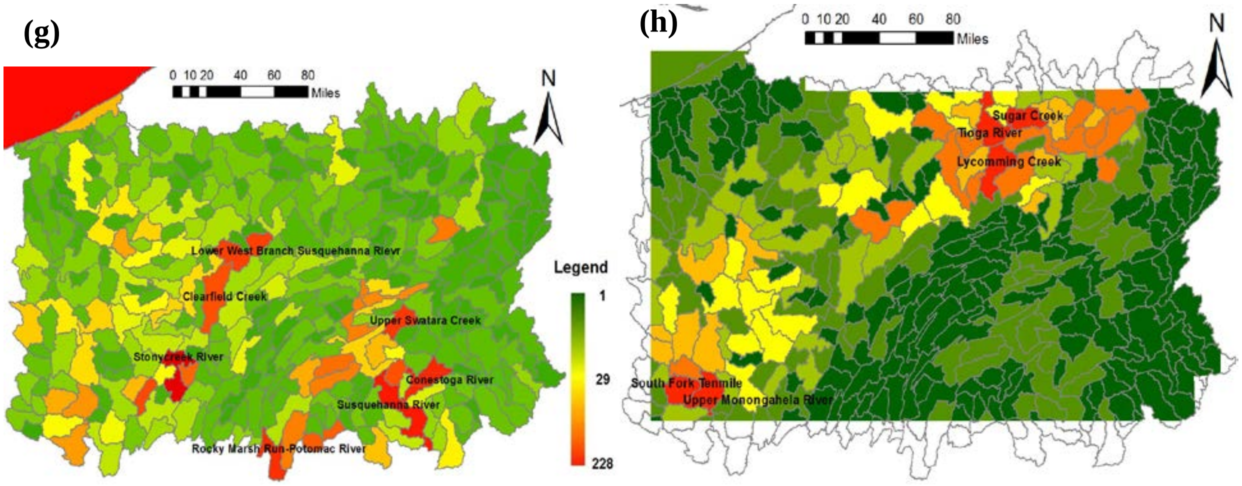


Figure 13. *(a) Number of permitted wells per HUC10, the range is from 1 to 688, (b) Number of drilled wells per HUC10, the range is from 1 to 359, (c) Number of permitted wells minus drilled wells per HUC10, the range is from 1 (green) to 382 (red), (d) Number of three types violations per HUC10 from 1 to 223, color increasing from green to red, (e) 5% shortest time wells per HUC10 from 1 to 117, (f) Sum length of the existing stream use per HUC10, the longest sum length is 484.38 miles in red, and shortest sum length of 0.74 miles in green, (g) Number of USGS gaging stations per HUC10 ranging from 1 (green) to 228 (red), (h) Critical watersheds results after weighted overlay, which indicated more critical on red areas than the green areas*

According to those most critical watersheds shown in Figure 13 (h) and Table 7, a statistical analysis is put forward, as shown in Table 8. Based on these data, South Fork Tenmile (southwest) and Tioga River (northeast) watersheds are chosen for modeling transport of contaminants, and to identify the critical streams inside of these watersheds.

Table 8. Most critical watersheds with statistical data

HUC10 Name	Number of Permitted Wells / HUC10	Number of Drilled Wells / HUC10	Number of 5% Shortest Time Wells / HUC10	Number of 3 Type Violations / HUC10	Number of Permitted Minus Drilled Wells / HUC10	Number of Gaging Stations / HUC10	Sum Length of Stream Use / HUC10 (mile)
South Fork Tenmile	657	359	77	35	298	37	5.484
Tioga River	481	300	42	115	181	25	53.776
Lycoming Creek	426	254	18	69	172	8	200.046
Sugar Creek	688	340	76	146	348	6	0
Upper Monongahela River	397	293	117	76	104	40	0

3.2.2 Data applied to South Fork Tenmile watershed

South Fork Tenmile (Hydrologic Unit 05020005), which is located in Greene County (with latitude: 39.923131 and longitude: -80.072558) is determined as the study area in southwest PA. The drainage area is 180 square miles. USGS gaging station number 03073000 is the only available one in the area; station recording started from Oct. 1931. Digital Elevation Model (DEM) of 10 meters from Pennsylvania Spatial Data Access (PASDA) is used for flow routing preparing process; this 10-meter resolution DEM is appropriate for watershed delineation and geometric construction. PASDA published the stream network data (Year 1998), a shapefile of vector format dataset that depicts the streams and waterways in Pennsylvania. National Cooperative Soil Survey published the Pennsylvania soil type data, which describes the distribution of soils on the landscape and it is the most detailed soil geographic data. Land cover comes from PASDA with data sources in the period from 2003 to 2007. With resolution of land cover being 30 meters. According to PASDA, the major land cover types contain residential, institutional, industrial land, farmland, grass / pasture, forest and water as illustrated in the metadata document.

3.2.3 Data applied in Tioga River watershed

Tioga River (Hydrologic Unit 0205010408) is another study area in northeast PA. It is located in Tioga County with the latitude of 41.908333 and longitude of -77.129722. The drainage area of Tioga River watershed is 282 square miles. Three USGS gaging stations are located here: 01518000 for Tioga River at Tioga, 01516350 for Tioga River near Mansfield, and 01518700 for Tioga River at Tioga Junction. DEM 10 meter, stream network, soil type, and land cover data are the same as those for South Fork Tenmile.

3.2.4 HEC-RAS data preparation using ArcGIS

Hec-GeoRas is an extension tool developed by GIS. It is convenient for users to export GIS data into HEC-RAS for further analysis. The main steps are: TIN computation, Manning’s n value calculation, and River geometric delineation.

Raster to TIN: The purpose of converting digital elevation model (DEM) to triangulated irregular network (TIN) is to achieve a better surface. This tool can improve the surface definition. In raster-to-TIN conversion, z-tolerance is the maximal difference allowed between the z-value of the input raster cell and the z-value of the output TIN at the location corresponding to the raster cell center. In the raster to TIN tool, digital elevation model is set as the input data to get the TIN.

Manning’s roughness coefficients: Based on runoff potential, the land cover is sorted into six categories. Ranking form high to low for the runoff potential, the types of land cover are water, wetlands, roads, residential/commercial, row crops, forest, pasture / grass, respectively. Manning’s roughness coefficients were determined using land cover information. For the asphalt and concrete, I set the Manning’s roughness coefficient as 0.014, floodplains (pasture, farmland) as 0.035, natural streams (major rivers) as 0.035, floodplains (light brush) as 0.05, and floodplains (trees) as 0.15 (ODOT Hydraulics Manual, 2011).

River geometric delineation: After flow delineation, HEC-GeoRAS will help to produce stream centerline, bank line, flow path centerline, and XS cut line. Once all necessary information collected, HEC-GeoRAS could be ready to export the data package.

3.2.5 Preparation of streamflow calculation

For the streamflow calculation, I decided to use Baseline Streamflow Estimator (BaSE) and the StreamStats Program to obtain the streamflow data for ungaged sites (Stuckey et al., 2012, Steeves et al., 2005, Ries III, 2002). "*The BaSE is developed by USGS, collaborated with PADEP, Susquehanna River Basin Commission, and The Nature Conservancy, which is a tool for streamflow simulation at a daily time step for an ungauged site during water years 1960 – 2008*" (Stuckey et al., 2012). Meanwhile, StreamStats is a Web-based GIS which could delineate watershed using an outlet point and estimate streamflow based on regression equations for ungauged site.

Instead of complex streamflow computing procedures like getting precipitation data and interpolating precipitation data within limited gaging stations, BaSE and StreamStates Program takes advantage of simplified steps which can improve efficiency. In addition it can lead to higher accuracy, especially for the ungaged sites (Li, et al., 2000, Lin et al., 2002, Peng et al., 2005, Blume et al., 2007).

3.2.6 Preparation of HEC-RAS models

HEC-RAS is a one-dimensional, steady-flow, water surface profiling program (U.S. Army Corps of Engineers, 1998). HEC-RAS model construction requires definition for the land surface and flow data for hydrologic events. The geometric and flow data are used to calculate steady, gradually varied flow water surface profiles from energy loss computations. HEC-RAS is capable of modeling a full network of channel, a dendritic system, or a single river reach.

In this research, in order to improve calculation efficiency of those softwares, the streams are simplified based on the locations of 5% shortest time wells. However, the junctions of each branch are kept for the streamflow calculation precision. Figures 14 and 15 show the original and simplified stream network for South Fork Tenmile and Tioga River watersheds.

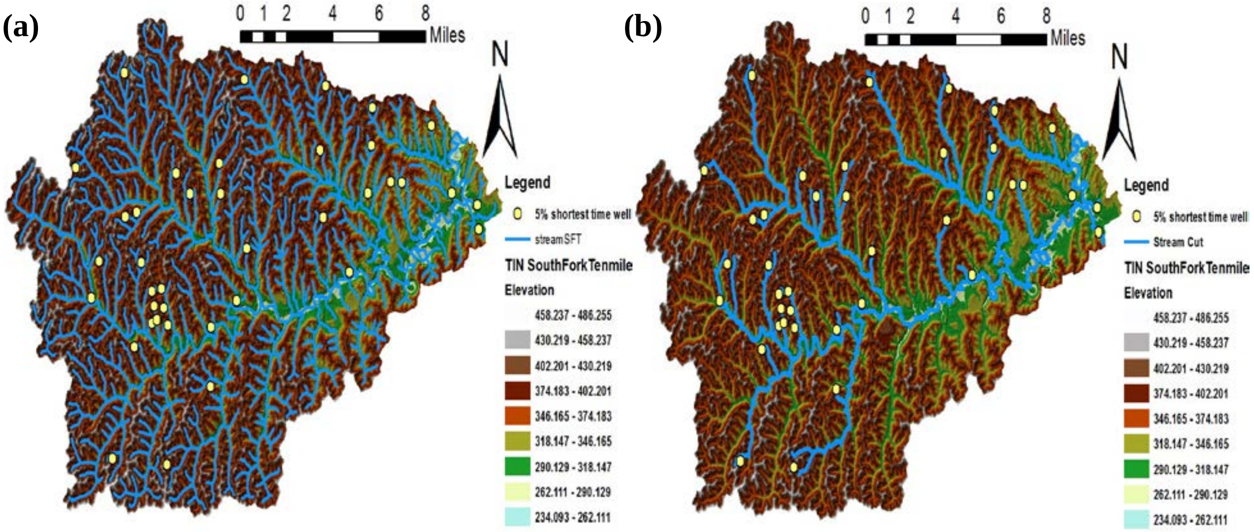


Figure 14. *(a) Stream network with DEM TIN as the background, (b) Simplified stream with DEM TIN as the background. South Fork Tenmile Watershed*

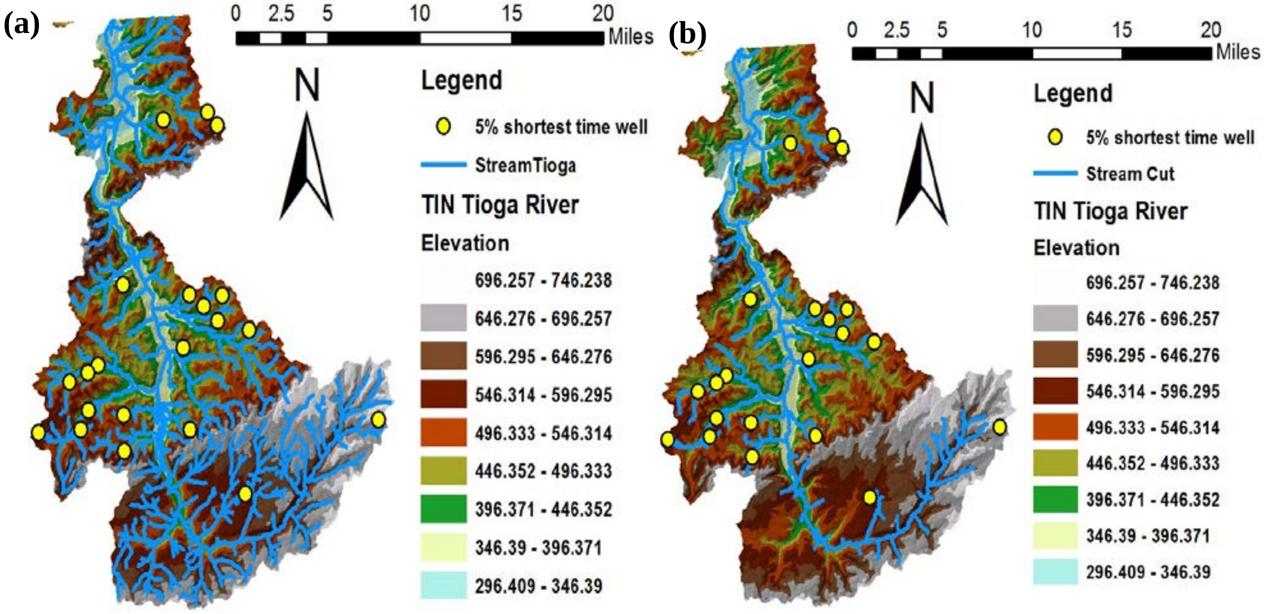


Figure 15. *(a) Stream network with DEM TIN as the background, (b) Simplified stream with DEM TIN as the background. Tioga River Watershed*

3.3 DISCUSSION AND CONCLUSION

As mentioned above, simplified dataset would be used in HEC-RAS model. Now, all the input datasets are ready. According to the increase in drilling operations, a water quality simulation is necessary in the future for this study. Practical conditions would be considered, and besides, only for the spills happened at the well pad, I will add a probability to make the model more precise. The scenarios for water quality 1D model would be constructed using HEC-RAS.

A methodology based on overlay has used for identifying two watersheds as the most critical ones for further analysis of contaminant transport into the streams: South Fork Tenmile in the southwest and Tioga River in the northeast. These two watersheds are chosen according to the number of permitted wells, drilled wells, violations, permitted wells minus drilled wells, 5% shortest time wells, existing stream use as well as USGS gauge station. The research is based on GIS and allows creating the HEC-RAS project for flow simulation, which will be developed in the near future (similar to Simon et al., 2014). DEM and TIN datasets are used to delineate river system and HEC-RAS importing preparation. In addition, an important goal of the present study is that the model applied would enable managers and operators to optimize the surface water management of this river basin.

4.0 CONCLUSIONS AND FUTURE WORK

Two studies are conducted for this work. In the first study (Chapter 2), topography and physical characteristics of PA are integrated into potential risk analysis of surface water contamination by shale gas fluids. Cost path analysis is the major technique used in the assessment. The Analytic Hierarchy Process (AHP) is created to introduce weight distribution among influencing factors such as land cover, soil and slopes. Overland flow principle is applied based on the physical geographic characteristics in Pennsylvania. Therefore, the pathways from drilling sites to nearby streams are determined, followed by the identification of critical watersheds.

A methodology based on overlay has been used for identifying two watersheds as the most critical ones for further analysis of contaminant transport into the streams. The two watersheds are South Fork Tenmile in the southwest and Tioga River in the northeast. These two watersheds are chosen according to the number of permitted wells, drilled wells, violations, permitted wells minus drilled wells, 5% shortest time wells, existing stream use as well as USGS gauge station. The research is based on GIS and allows creating the HEC-RAS project for flow simulation, which will be developed in the near future (similar to Simon et al., 2014). DEM and TIN datasets are used to delineate river system and HEC-RAS importing preparation.

In the future, this work will concentrate on improving the first study by considering the practical requirements of the volunteer groups and working with them to monitor some critical streams and critical watersheds based on this research result. Meanwhile, cooperating with watershed communities and guiding their monitoring projects and activities in critical streams will be performed based on this study.

Another interesting idea is to develop a web – based tool for identifying critical watersheds and obtaining stream models simply through online request. I plan to put the whole methodology and data information into this web – based tool.

To improve the accuracy, a probability will be considered for the spills occurrence at the well pad in the first study. At the same time, I would like to include hydrologic assessment of scenarios in the second study. Currently, the second study just focuses on scalar transport and surface runoff. Therefore, for future work, the water quality simulation and one-dimensional surface and subsurface flow model would be added to improve the output of the study.

Furthermore, I will combine this study with risk analysis. Where should be attached more importance across the entire Pennsylvania? – That’s one of our goals to make actual useful efforts for the environmental protection.

BIBLIOGRAPHY

Allen, D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., Herndonc, S. C., Kolbc, C.E., Fraserd, M. P., Hille, A. D., Lambf, B. K., Miskiminsg, J.,. Sawyerh, R. F., & Seinfeld, J. H. (2013).Measurements of methane emissions at natural gas production sites in the United States. Proceedings of the National Academy of Sciences, 110(44), 17768-17773.

Appendix- Hydraulic Roughness (Manning's n) Values of Conduits and Channels

Arthur, J. D., Bohm, B., & Layne, M. (2009). Hydraulic fracturing considerations for natural gas wells of the Marcellus Shale.

Bamberger, M., & Oswald, R. E. (2012). Impacts of gas drilling on human and animal health. New solutions: a journal of environmental and occupational health policy, 22(1), 51-77.

Blume, T., Zehe, E., & Bronstert, A. (2007). Rainfall—runoff response, event-based runoff coefficients and hydrograph separation. Hydrological Sciences Journal, 52(5), 843-862.

Brantley, S. L., Yoxtheimer, D., Arjmand, S., Grieve, P., Vidic, R., Pollak, J.,Llewellyn, G.T., Abad, J.D., & Simon, C. (2014). Water resource impacts during unconventional shale gas development: The Pennsylvania Experience. International Journal of Coal Geology, 126, 140-156.

Carr, R. D., Greenberg, H. J., Hart, W. E., Konjevod, G., Lauer, E., Lin, H., ... & Phillips, C. A. (2006). Robust optimization of contaminant sensor placement for community water systems. Mathematical Programming, 107(1-2), 337-356.

Castro, M., Iglesias, L., Sánchez, J. A., & Ambrosio, L. (2011). Sight distance analysis of highways using GIS tools. Transportation research part C: emerging technologies, 19(6), 997-1005.

Chandio, I. A., Matori, A. N. B., WanYusof, K. B., Talpur, M. A. H., Balogun, A. L., & Lawal, D. U. (2013). GIS-based analytic hierarchy process as a multicriteria decision analysis instrument: a review. Arabian Journal of Geosciences, 6(8), 3059-3066.

Chang, N. B., Chang, Y. H., & Chen, H. W. (2009). Fair fund distribution for a municipal incinerator using GIS-based fuzzy analytic hierarchy process. Journal of environmental management, 90(1), 441-454.

Chang, T. J., Hsu, M. H., Teng, W. H., & Huang, C. J. (2000). A GIS - assisted DISTRIBUTED watershed model for simulating flooding and inundation1. JAWRA Journal of the American Water Resources Association, 36(5), 975-988.

Chapman, E. C., Capo, R. C., Stewart, B. W., Kirby, C. S., Hammack, R. W., Schroeder, K. T., & Edenborn, H. M. (2012). Geochemical and strontium isotope characterization of produced waters from Marcellus Shale natural gas extraction. Environmental science & technology, 46(6), 3545-3553.

Chowdary, V. M., Chakraborthy, D., Jeyaram, A., Murthy, Y. K., Sharma, J. R., & Dadhwal, V. K. (2013). Multi-criteria decision making approach for watershed prioritization using analytic hierarchy process technique and GIS. Water resources management, 27(10), 3555-3571.

Colborn, T., Kwiatkowski, C., Schultz, K., & Bachran, M. (2011).Natural gas operations from a public health perspective. Human and Ecological Risk Assessment: An International Journal, 17(5), 1039-1056.

Coroza, O., Evans, D., & Bishop, I. (1997). Enhancing runoff modeling with GIS. Landscape and Urban Planning, 38(1), 13-23.

Desrochers, A., Bélisle, M., Morand-Ferron, J., & Bourque, J. (2011). Integrating GIS and homing experiments to study avian movement costs. Landscape Ecology, 26(1), 47-58.

Entrekin, S., Evans-White, M., Johnson, B., & Hagenbuch, E. (2011). Rapid expansion of natural gas development poses a threat to surface waters. Frontiers in Ecology and the Environment, 9(9), 503-511.

Environmental Protection Agency, Erosion, Sediment and Runoff Control for Roads and Highways, http://www.epa.gov/owow/nps/education/runoff.html (Accessed April 12, 2010).

Farrar, W., Galagan, C., Isaji, T., & Knee, K. (2005). GIS technology applied to modeling oil spills on land. In ESRI international user conference.

Fuchs, J. W., Fox, G. A., Storm, D. E., Penn, C. J., & Brown, G. O. (2009). Subsurface transport of phosphorus in riparian floodplains: Influence of preferential flow paths. Journal of environmental quality, 38(2), 473-484.

Greenlee, D. D. 1987. "Raster and Vector Processing for Scanned Linework." Photogrammetric Engineering and Remote Sensing 53 (10): 1383–1387.

Han, Y., Arjmand, S., Simon, C., Abad, J. D., Fu, C., Vidic, R., Brantley, S., Vastine, J., Candie, W. (2014).Evaluation of Potential Pathways of Accidental Spills from Unconventional Drilling Sites to Nearby Streams, In preparation.

Hojat, D. A., Monereh, M. GIS and the Analytic Hierarchy Process Methods for Site Selection of Waste Landfills: A Case Study in Iran, International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081US.

Iseri, H., Hiramatsu, K., Harada, M., & Mori, M. (2013). Simulation of rainfall runoff and pollutant load for Chikugo River basin in Japan using a GIS-based distributed parameter model. Paddy and Water Environment, 11(1-4), 97-112.

Jenson, S. K., and J. O. Domingue. 1988. "Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis." Photogrammetric Engineering and Remote Sensing 54 (11): 1593–1600.

Johnson, R. D., Mendez, G. O., La, J. X., & Izbicki, J. A. (2005, December). Sources and Pathways of Bacterial Contamination in Urban Streams and Ocean Beaches, Santa Barbara, California. In AGU Fall Meeting Abstracts (Vol. 1, p. 1313).

Kargbo, D. M., Wilhelm, R. G., & Campbell, D. J. (2010). Natural gas plays in the Marcellus shale: Challenges and potential opportunities. Environmental Science & Technology, 44(15), 5679-5684.

Keith, A. K. GIS-based analysis of potential water infiltration in the DOG river watershed, Mobile, AL.

Kennedy, M. D. (2013). Introducing geographic information systems with ARCGIS: a workbook approach to learning GIS. John Wiley & Sons.

Lee, B. H., & Deininger, R. A. (1992). Optimal locations of monitoring stations in water distribution system. Journal of Environmental Engineering, 118(1), 4-16.

Leopold, L. B., & Leopold, L. B. (1995). Fluvial processes in geomorphology. Courier Dover Publications.

Li, X., Cheng, G., & Lu, L. (2000).Comparison of spatial interpolation methods [J]. Advance in Earth sciences, 3, 003.

Lin, Z. H., Mo, X. G., Li, H. X., & Li, H. B. (2002). Comparison of Three Spatial Interpolation Methods for Climate Variables in China [J]. ActaGeographicaSinica, 1, 005.

Manning, R., Griffith, J. P., Pigot, T. F., & Vernon-Harcourt, L. F. (1890). On the flow of water in open channels and pipes.

Myers, T. (2012). Potential contaminant pathways from hydraulically fractured shale to aquifers. Groundwater, 50(6), 872-882.

Olivera, F., & Maidment, D. (1999). Geographic Information Systems (GIS) ‐ based spatially distributed model for runoff routing. Water Resources Research, 35(4), 1155-1164.

Olmstead, S. M., Muehlenbachs, L. A., Shih, J. S., Chu, Z., & Krupnick, A. J. (2013). Shale gas development impacts on surface water quality in Pennsylvania. *Proceedings of the National Academy of Sciences*, *110*(13), 4962-4967.

Park, W. I., Kim, D. J., & Lee, H. J. (2013). Terrain trafficability analysis for autonomous navigation: A GIS-based approach. International Journal of Control, Automation and Systems, 11(2), 354-361.

Peng, S. H. I., & Xiao-fang, R. U. I. (2005). Comparison and improvement of spatial rainfall interpolation methods [J]. Journal of Hehai University (Natural Sciences), 4, 001.

Pennsylvania Code § 93.4b. Qualifying as High Quality or Exceptional Value Waters.

Pennsylvania Department of Environmental Protection, Marcellus Shale Development

Quan, H. C., & Lee, B. G. (2012). GIS-based landslide susceptibility mapping using analytic hierarchy process and artificial neural network in Jeju (Korea).KSCE Journal of Civil Engineering, 16(7), 1258-1266.

Ries III, K. G. (2002). STREAMSTATS: A US Geological Survey web site for stream information. In Hydroinformatics 2002: Proceedings of the Fifth International Conferences on Hydroinformatics, RA Falconer, ELB Lin, and EL Harris (Editors), Cardiff, United Kingdom, July (pp. 1-5).

Rozell, D. J., & Reaven, S. J. (2012). Water pollution risk associated with natural gas extraction from the Marcellus Shale. Risk Analysis, 32(8), 1382-1393.

Saaty, T. L. (1980). The analytic hierarchy process: planning, priority setting, resources allocation. New York: McGraw.

Saaty, T. L. (1986). Axiomatic foundation of the analytic hierarchy process. Management science, 32(7), 841-855.

Saaty, T. L. (1990).An exposition of the AHP in reply to the paper “remarks on the analytic hierarchy process”. Management science, 36(3), 259-268.

Saaty, T. L. (1994). Fundamentals of decision making and priority theory with the analytic hierarchy process.(The Analytic Hierarchy Process Series, vol. 6), Pittsburgh.

Simon, C., Neal, A., Abad, J. D., Brantley, S., (2014). Application of In-Situ Spectrophotometry for Water Quality Analysis.In review, Applied Geochemestry.

Smith, I. R., Withers, K., & Billingsley, J. (2007). Maintaining the ancient bunya tree (Araucaria bidwillii Hook.)-dispersal and mast years. In Proceedings of the 5th International Southern Connection Conference (p. 62).University of Adelaide.

Smith, M. W., Cox, N. J., & Bracken, L. J. (2007). Applying flow resistance equations to overland flows. Progress in Physical Geography, 31(4), 363-387.

Steeves, P. A., Coles, J. D., Rea, A. H., & Stewart, D. W. (2005). StreamStats: a US Geological Survey web application for stream information. US Geological Survey.

Storck, P., Bowling, L., Wetherbee, P. and Lettenmaier, D. (1998), Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. Hydrol. Process., 12: 889–904. doi: 10.1002/(SICI)1099-1085(199805)12:6<889::AID-HYP661>3.0.CO;2-P

Stuckey, M. H., Koerkle, E. H., & Ulrich, J. (2012). Estimation of Baseline Daily Mean Streamflows for Ungaged Locations on Pennsylvania Streams, Water Years 1960-2008. US Department of the Interior, US Geological Survey.

Tarboton, D. G., R. L. Bras, and I. Rodriguez–Iturbe. 1991. "On the Extraction of Channel Networks from Digital Elevation Data." Hydrological Processes 5: 81–100.

Van Loon, E. (2002). Overland flow: interfacing models with measurements. WageningenUniversiteit.

Van Stempvoort, D., Maathuis, H., Jaworski, E., Mayer, B., & Rich, K. (2005). Oxidation of fugitive methane in ground water linked to bacterial sulfate reduction. Groundwater, 43(2), 187-199.

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., & Kondash, A. (2014). A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environmental science & technology.

Vidic, R. D., Brantley, S. L., Vandenbossche, J. M., Yoxtheimer, D., & Abad, J. D. (2013). Impact of shale gas development on regional water quality. Science,340(6134), 1235009.

Warner, N. R., Jackson, R. B., Darrah, T. H., Osborn, S. G., Down, A., Zhao, K., ... & Vengosh, A. (2012). Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. Proceedings of the National Academy of Sciences, 109(30), 11961-11966.

Wiseman, H. (2009). Untested Waters: The Rise of Hydraulic Fracturing in Oil and Gas Production and the Need for Revisit Regulation. Fordham Envtl. L. Rev., 20, 115.

Xu, J., Johnson, M. P., Fischbeck, P. S., Small, M. J., & VanBriesen, J. M. (2010). Robust placement of sensors in dynamic water distribution systems.European Journal of Operational Research, 202(3), 707-716.

Yang, J., Townsend, R. D., & Daneshfar, B. (2006). Applying the HEC-RAS model and GIS techniques in river network floodplain delineation. Canadian Journal of Civil Engineering, 33(1), 19-28.

USGS. USGS 01516350 Tioga River near Mansfield, PA. Retrieve June, 204, from http://waterdata.usgs.gov/usa/nwis/uv?01516350

USGS. USGS 01518700 Tioga River at Tioga Junction, PA. Retrieve June, 204, from http://waterdata.usgs.gov/usa/nwis/uv?01518700

USGS. USGS 01518000 Tioga River at Tioga, PA. Retrieve June, 2014, from http://waterdata.usgs.gov/usa/nwis/uv?site_no=01518000

USGS. USGS 03073000 South Fork Tenmile Creek at Jefferson, PA. Retrive June, 2014 from http://waterdata.usgs.gov/usa/nwis/uv?03073000

USGS (2000). 7.5 minute digital elevation models (DEM) for Pennsylvania 10 meter. Retrieve March, 2014, from http://www.pasda.psu.edu/uci/SearchResults.aspx?shortcutKeyword=topo&searchType=shortcut&sessionID=4575149442014324123210

Environmental Resources Research Institute (1998). Networked streams of Pennsylvania. Retrieve March, 2014, from http://www.pasda.psu.edu/uci/MetadataDisplay.aspx?entry=PASDA&file=netstreams1998.xml&dataset=16

U.S. Department of Agriculture, Natural Resources Conservation Service (2008). Soils. Retrieve on March, 2014, from http://www.pasda.psu.edu/data/soils/

The Pennsylvania State University (2007). PAMAP Program Land Cover for Pennsylvania, 2005. Retrieve March, 2014, from http://www.pasda.psu.edu/uci/MetadataDisplay.aspx?entry=PASDA&file=palanduse05utu18nad83.xml&dataset=1100

U.S. Department of Agriculture, Natural Resources Conservation Service (2013). 10 Digit Watershed Boundary Dataset in HUC8. Retrieve March, 2014, from http://datagateway.nrcs.usda.gov/GDGOrder.aspx

Global Land Cover Facility. 90m Elevation Imagery. Retrieve March, 2014, from http://www.landcover.org/