Orographic Patterns Effect on Water Quality in the Shenandoah National Park

1. Introduction

With the onslaught of the "Green Revolution" environmental issues have taken center stage. Now much of this onslaught is focused on Carbon dioxide and climate change, but what is overlooked many times over are the synergistic effects associated with issues. Many factors influence a particular environment's response and reaction to particular pollutants.

Water quality is directly affected by anthropogenic pollution (Porter et al., 2004; Gibson et al., 1986); however, many of the streams leaving Shenandoah National Park's western slope have been designated as impaired and placed on the Clean Water Act 303d list. This seems bizarre since in theory little human impact is imparted on the park. This can be loosely explained by a synergistic effect that is associated with water quality through adverse air quality and atmospheric deposition (Cosby et al., 2006; Johnson et al., 2000). Furthermore, this effect appears to be influenced by climate and the corresponding orographic effect associated with mountains.

This study will focus on four of the seven first order streams located within the Park along its western slope that have been listed as impaired by the Virginia Department of Environmental Quality (DEQ). All seven of the streams originate within SNP and all of the monitoring stations where the impaired water quality data were collected lie within the boundaries of SNP as well.

1.1 Shenandoah National Park Geography

Shenandoah National Park (SNP) occupies roughly 300 square miles (198,250 acres) of the Blue Ridge Mountains running basically in a North-South fashion (Figure 1.1) (Rice et al., 2005). The park was established as a public works project during the Great Depression in 1935 (NPS, 2007). It was once settled, but now has been revegetated with little semblance of the past settlements.

Shenandoah National Park's ridges are the headwaters for many first order streams flowing into three different river basins where they originate through seepage and springs (Rice et al., 2005). On the western side is the Shenandoah River basin and to the east are the Rappahannock and James River basins, all of which lie within the Chesapeake Bay watershed. Due to its status as a national park, human activities are severely limited within its boundaries; yet, a disturbing trend in impaired water quality affects the aquatic life. Furthermore, occurrence is primarily on the western slope of the park and this report will focus only on acidity impairment and the factors that negatively influence the park's water quality concerning pH.

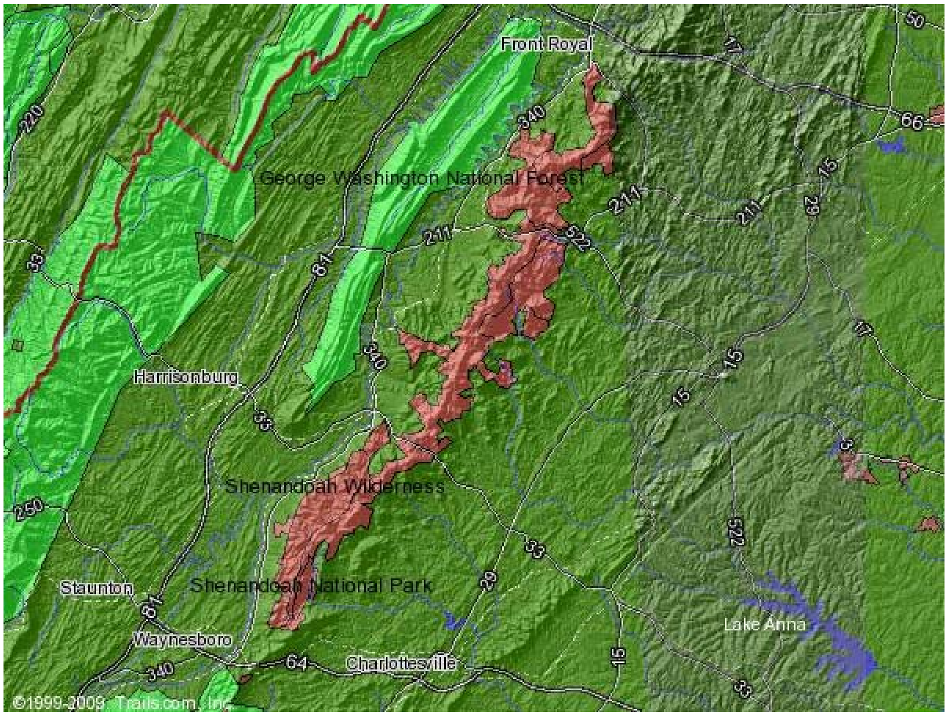

Figure 1.1 **Shenandoah National Park location display in pink**

1.2 Shenandoah National Park Geology and Soil Morphology

The Shenandoah National Park lies within the Blue Ridge physiographic province within the Appalachian Mountains of Virginia. These mountains make up some of the oldest mountains on earth; yet, these mountains replaced the Prehistoric Grenville Mountains (Frye, 1986). The replacement occurred during a 600 million year break in the rock record during which time the Grenville Mountains were eroded. These rock formations are predominantly deep forming igneous rocks having undergone various degrees of metamorphism to produce gneisses (Fichter and Baedke, 2000). Other geologic substratum are the Pedlar Massif that make up the eastern slope of the Blue Ridge and the Catoctin and

Chillowee Group which make up the western slope (See Figure 1.2). All of the above have a defining affect on a stream's water quality.

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Figure 1.2 **Blue Ridge Pysiographic Province Geologic Cross Section**

The Shenandoah National Park soils are dominated by Ultisols and Inseptisols (Brady and Weil, 2008). The suborders that dominate SNP tend to be Ochrepts and Udults; whereas, the Ochrepts are young soils with thin, light colored horizons and Udults represent older moist soils (National Park Service, 2006). The Ochrepts, as well as other suborders have since been deleted as a suborder in the field of soil taxonomy, in turn making the Inceptisol order more consistent with other soil orders in the classification system (Joe Chiaretti, Soil Taxonomy Forum, comment posted March 18, 2009).

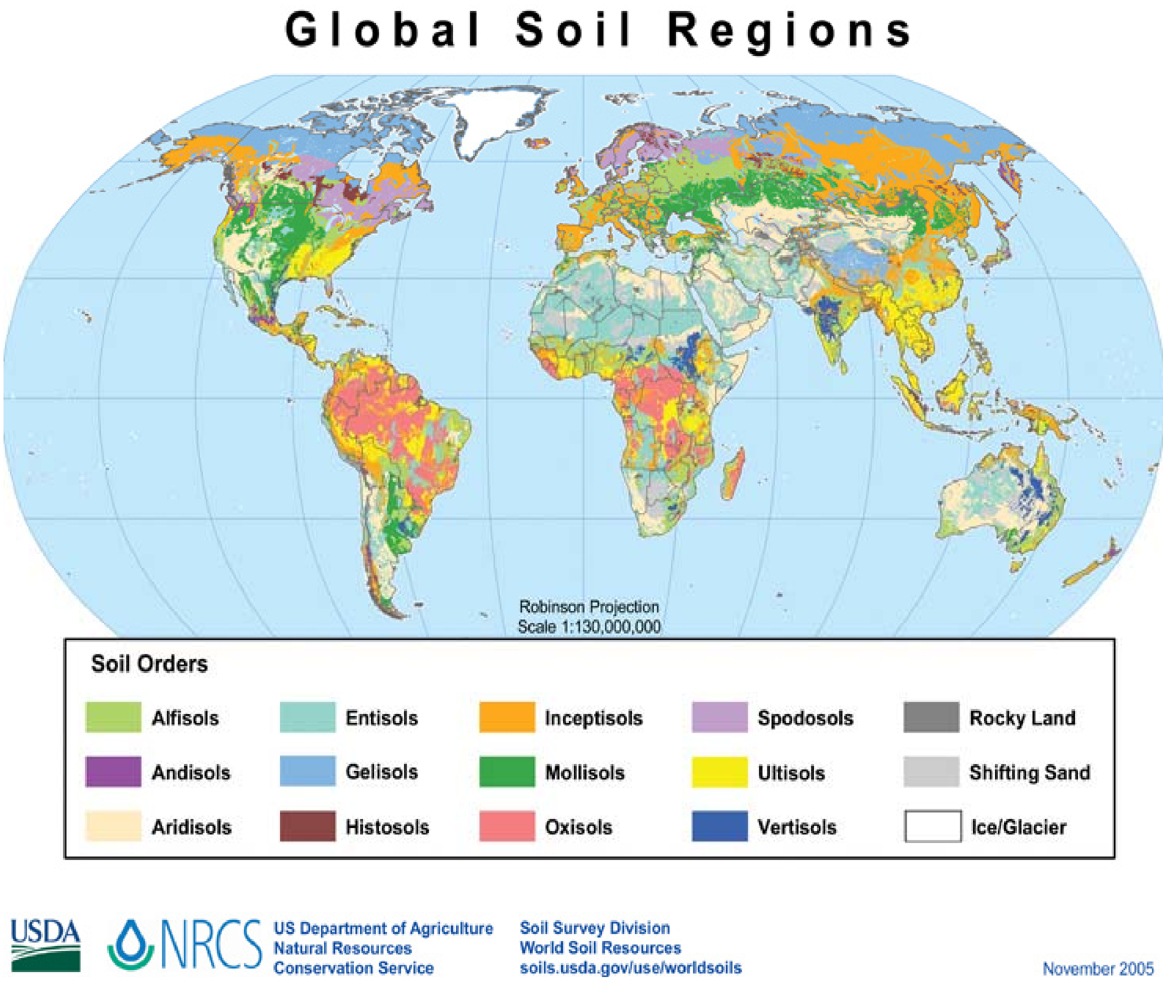


Figure 1.3 Global Soil Orders

1.3 Orographic Effect and Rain Shadow

The orographic effect and the corresponding rain shadow effect is a climatic phenomenon associated with mountainous regions. "The physical mechanisms involved comprise a rich set of interactions encompassing fluid dynamics, thermodynamics, and micron-scale cloud processes, as well as being dependent on the larger-scale patterns of the atmospheric general circulation." (Roe 2005, 645). The physics of the orographic effect are illustrated below (See Figure 1.4).

Due to Shenandoah National Park's (SNP) geographic location and the influences of seasonal weather patterns, SNP's leeward slope is always on the western flank of the ridge. This is a result of the prevailing winds hitting the Alleghany Mountains before the Blue Ridge and the park's close proximity to the Atlantic Ocean. Nevertheless, as the air begins to rise on the western slope of the Blue Ridge an orographic pattern in also noticed (Abraham, 2008).

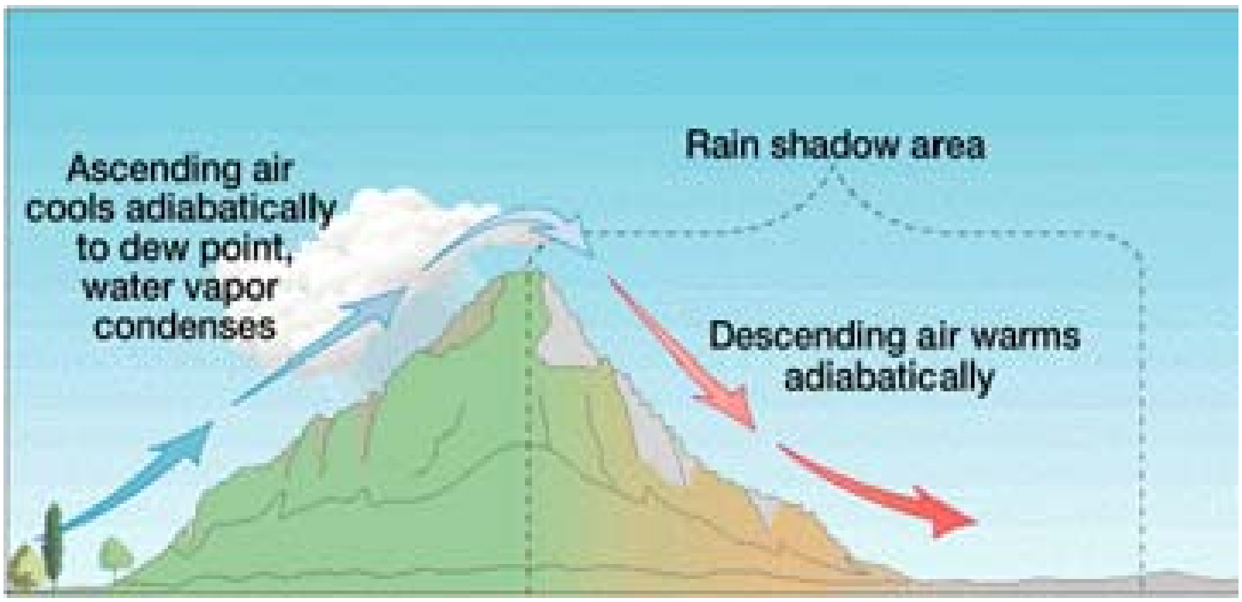


Figure 1.4 Diagram Orographic Effect and Rain Shadow

1.4 Air Quality & Atmospheric Deposition

Atmospheric deposition occurs when pollutants alter the chemistry of the air (Cosby et al., 2006; Rice et al., 2005; Gibson et al., 1986; Calvert et al., 1983). Many pollutants can be deposited via deposition; however, this report will focus on two, Nitrogen and Sulfur due to Shenandoah National Park location in relation to a number of the nations dirtiest coal fired electric power plants. Power plants are known to be a primary cause for excess Sulfur and Nitrogen compounds in the air (Environmental Integrity Project, 2007); however, NOx emission have been linked to mobile sources as their main origin (Tong et al., 2005). Furthermore, Lynch and Dise (1985) noted that 90% of Sulfate in the atmosphere is anthropogenic in origin.

There are also three primary routes that deposition can occur, they are known as wet, dry and cloud deposition (Lovett, et al., 1997; Schwartz, 1989)) (see Figure 1.5). Wet deposition occurs when precipitation or clouds carry gases or particles to the earth's surface sometimes in the form of acid rain (Rice et al., 2005; Maddux, 2001; Weathers et al., 2000). Dry deposition occurs when particles settle to the earth's surface via Brownian or diffusive motion and simple gravitational settling (Rana, 2006; Calvert et al., 1983). Cloud deposition is a form of wet deposition that cannot be measured by rain gauges and has been determined to have a large effect on acid deposition (Dollard et al., 1983)

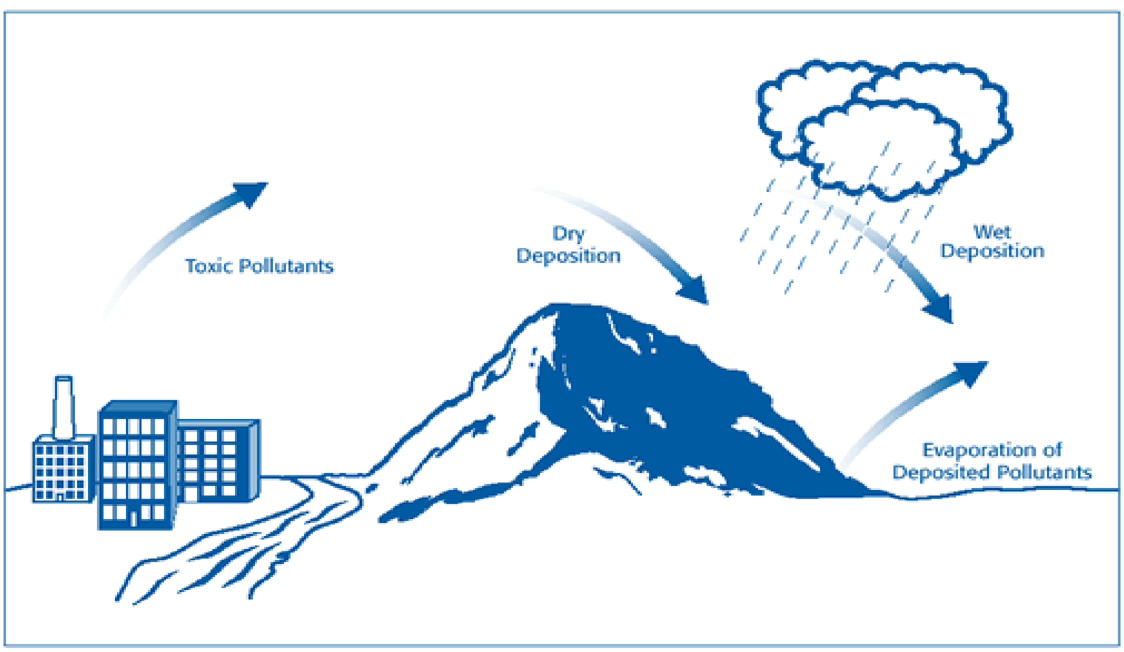


Figure 1.5 Atmospheric deposition

1.5 Water Quality (acidity)

Water quality is directly affected by the aforementioned in a variety of ways. Nevertheless, this report will focus primarily on the pH of the receiving waters within the study. A pH impairment is defined as having a pH outside of the normal range of 6.5-9.5 for mountainous streams and trout streams within Virginia (DEQ, 2006). When the pH of a stream is out of range it drastically affects the ability for a particular stream to support life (Kennard, 2008; Bulger et al., 1995). Even a change of only one pH unit is damaging because the pH scale is logarithmic (Rice et al., 2005).

1.6 Research Objectives

This study will focus on the synergistic effects that are associated with environmental degradation of four (highlighted) of the seven seemingly pristine aquacultures located within SNP (See Table 1.1). The streams within this study all originate in Shenandoah National Park and are listed as impaired for biologicals on the 303d list for pH (Appendix A). It is their headwater status that increases the potential sensitivity to adverse impacts from acidic deposition for a variety of reasons (Cosby et al., 2006).

The goal of this research is to determine the main factors associated with acid deposition and how a streams pH may be affected. This will be done by analyzing spatial data from varying geographies similar to Shenandoah National Park to illustrate how a variety of effects play a role in degrading the western slopes water quality concerning pH. Moreover, that the corresponding orographic lifting and rain shadow effect exasperates the problem on the western slope of the park.

Stream Name	Stream Monitoring Station (SMS)	SMS Approximate Location
Jeremy's Run	USGS Station 01630565	n 38°45'32", w 78°18'35"
Rocky Branch	USGS Station 0163054325	n 38°39'44", w 78°21'20"
Two-Mile Run	SNP Station ID VT53	Figure 1.6
Lower Lewis Run	SNP Station Id RH47	Figure 1.6
Deep Run	SNP Station ID DR01	Figure 1.6
Paine Run	USGS Station 01627395	n 38°11'52", w 78°47'28"
Meadow Run	SNP Station ID VT36	Figure 1.6

Table 1.1 Stream Monitoring Stations that designated the waters impaired

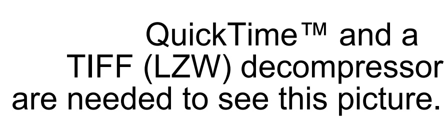


Figure 1.6 Map Locations of the SNP Monitoring Stations (in grey)

The goal of this research is to determine the main factors associated with acid deposition and how a streams pH may be affected. This will be done by analyzing spatial data from varying geographies similar to Shenandoah National Park to illustrate how a variety of effects play a role in degrading the western slopes water quality concerning pH. Moreover, that the corresponding orographic lifting and rain shadow effect exasperates the problem on the western slope of the park.

The data include the geologic record and soil taxonomy of the western slope of the park and are linked to the Acid Neutralization Capacity (ANC) and Cation Exchange Capacity (CEC). Additionally, air quality data associated with the regional airshed were contrasted with seasonal climatic patterns in relation to the park and inferences were made concerning the patterns observed in other research.

Furthermore, field data were collected in an effort to demonstrate and confirm the assumptions inferred from the spatial data collected. Therefore, after review of the existing data and literature on the subject, in addition to the field analysis that was performed, the synergistic effects associated with this particular environmental issue will be clearly expressed. Additionally, the data presented will also display how the orographic lifting and the rain shadow effect have a decided influence on the water quality within the Shenandoah National Park.

2. Experimental Site Information and Methods and Instrumentation

2.1 Experimental Sites

The Shenandoah National Park contains seven streams that are impaired for acidity, all of which are located on the western slope of the park. The park is divided into three districts, the north, central, and south districts (Figure 2.1). Among the seven streams that have been designated as impaired, two of which are located in the north district (Jeremy's Run and Rocky Branch), none in the central district, and five in the south district.

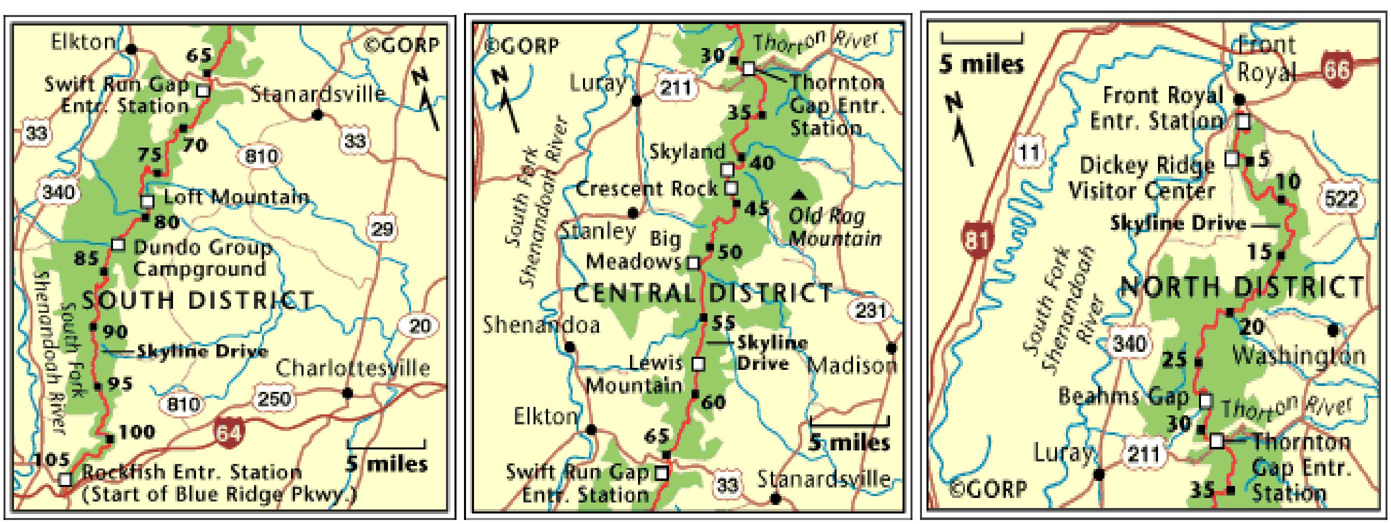
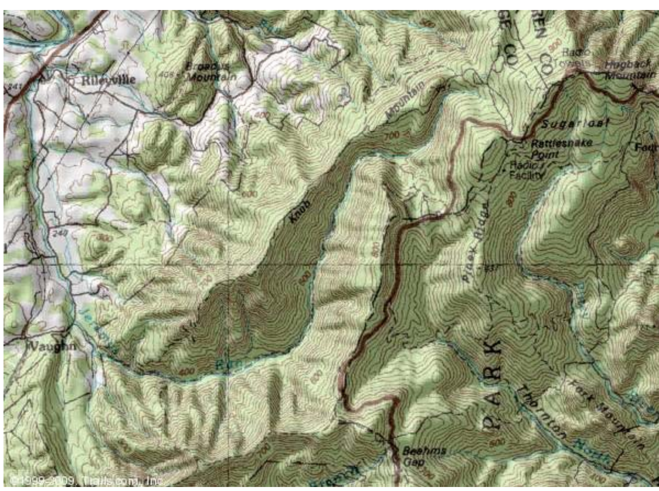
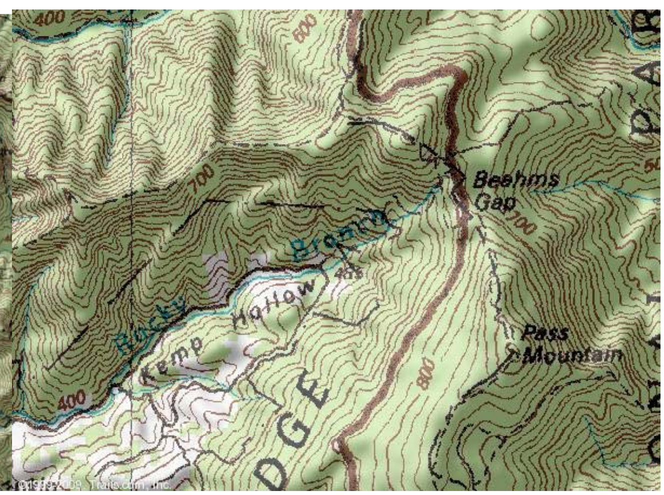


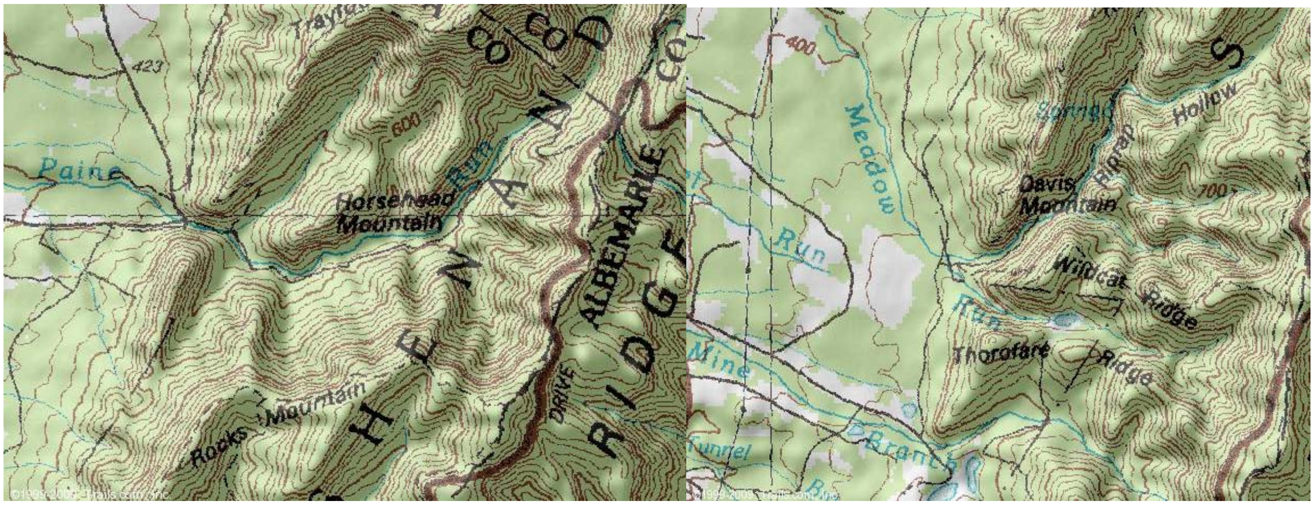
Figure 2.1 Maps of the three districts within Shenandoah National Park

Four of the seven streams were sampled for pH and soil samples were taken in an effort to identify the soil taxonomy. Of the four sample sites, two were in the north district (Jeremy's Run and Rocky Branch) and two in the south district (Meadow Run and Paine Run) (See Figure 2.1). The other three within the south district (Lower Lewis Run, Two Mile Run, and Deep Run) were not sampled due to inaccessibility out of respect for private property and national park rules. Of the four sampled sites pH and soil samples were taken near where the particular stream reach exited SNP. A control sample was also taken from a spring located along a ridge top. The spring was covered and would have been little affected by acid deposition.





Jeremy's Run **Rocky Branch**



Paine Run **Meadow Run**

Figure 2.2 **Topographic maps of the study streams**

2.2 Methods and Instrumentation

Field sample locations were noted in Latitude and Longitude coordinates. The locations were approximated using a Magellan Maestro Geographic Positioning System (Company, city). The selected locations also coincided to some degree with the USGS samples (where they existed) with the exception of Rocky Branch, in which the location given does not correspond with any location of Rocky Branch on a map. Another reason for selecting sites where the stream exited the park was to ensure that most of the water from the particular watershed flowing out of the park was accounted for when considering atmospheric deposition.

The pH samples were taken using an Oakton Waterproof pHTestr (Company, city) obtained from The Catholic University of America's Biology Department. The unit was calibrated at each sample point following the manufacturer's instructions and using a Milwaukee buffer solution pH of 7.01.

This was to assure that each site was adequately sampled and no cross contamination might exist. The probe was then rinsed with distilled water and placed directly in the stream flow until a stabilized reading could be recorded. Once the reading had stabilized it was recorded and a picture was taken to verify (Appendix).

Soil samples were taken from each of the four sites as well as pictures representing soil condition. To be less intrusive on the park, the samples were taken along the banks, which in many cases were eroded away and allowed for a good representative soil pedon. The soil samples were analyzed using field tests outlined in Natural Resource Center's Keys to Soil Taxonomy and the publication *The Nature and Property of Soils, 14th Edition*, as well as use of the Munsell® color rating system. Furthermore, samples were returned to the lab for a pH examination. A 1:1 ratio of the soil sample and distilled water was placed in a 50mL beaker and a pH test following the same procedures mentioned above was taken and recorded.

Finally, atmospheric and climatic data were analyzed for four distinct points around the study area using National Atmospheric Deposition Program (NADP) data for four different monitoring stations: Parsons, WV, James Madison University, Big Meadows (SNP), and Charlottesville, VA. These locations were chosen as closely representing the weather and atmospheric deposition patterns for the study area. A five-year seasonal data set was chosen for the study. In addition to aforementioned the EPA's Clean Air Status and Trends Network

(CASTNET) collects data for both wet and dry deposition. Sites incorporated in this three-year dataset include: Parsons, WV, Big Meadows (SNP), and Prince Edward, VA. The Prince Edward site is the closest monitoring site that will exhibit eastern slope (piedmont) trends in dry deposition. Additionally, it is through the combination of these data that orographic and rain shadow effects will be observed.

3. Results

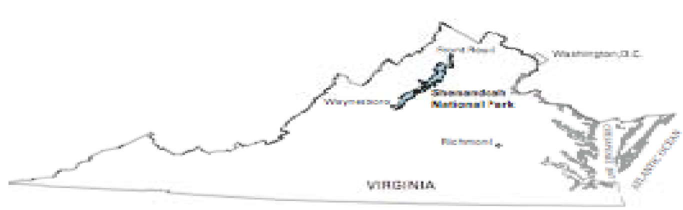
It must be noted that all four of the streams measured, as well as the remaining three in the park that are impaired for pH, share a common topography within Shenandoah National Park, occupying deep ravines ranging from 300′ to 700+ feet deep (See Figure 2.1) (Appendix). The orographic effect and other climatic patterns are known to affect ravines in a variety of ways. This fact coupled with the geologic and soil taxonomy of the two districts, as well as atmospheric deposition trends within Shenandoah National Park and the surrounding region are the likely syncretistic combination that affects the study streams.

The results of the field analysis varied and differed from the original test results in some cases. The south district streams were found to be quite acidic by more than a full pH unit over those tested in the north district. Whereas, the north district streams were not found to exhibit pH impairment at the time of sampling (See Table 3.1). Various research has alluded to why this was the result for the north district field analysis.

The control spring exhibited a normal pH for water derived from a spring. This mildly acidic condition is generally neutralized due to the ANC equaling >50 units. This appears to be the case in the north district streams. In contrast, the ANC for the streams in the study in the south district is <50 units (See Figure 3.1). This presents a neutralization challenge for the atmospheric deposition reaching waters (Rice et al., 2005). This could be due to the surrounding soil's acid neutralization capacity and/or that previous testing had been performed during episodic acidification of the streams in the north district.

Stream Name	**Stream Length**	**Test Location**	**pH**	**District;;**	**Geology**	**Soil Order; Mineral Type**
Control Spring	N/A	n 38°44'35", w 78°17'46"	6.36	North	Mafic	N/A
Jeremy's Run	10.97 miles	n 38°42'54", w 78°22'46"	6.85	North;	Mafic	Inceptisol; Goethite
Rocky Branch	4.17 miles	n 38°41'38", w 78°19'39"	6.86	North	Mafic	Inceptisol; Goethite
Paine Run	6.25 miles	n 38°11'53", w 78°47'31"	5.66	South	Siliceous	Ultisol; Jarosite
Meadow Run	6.87 miles	n 38°09'49", w 78°47'31"	5.36	South	Siliceous	Ultisol; Jarosite

Table 3.1



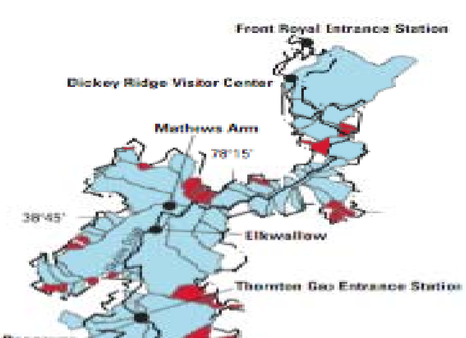


Figure 3.1 The red representing poor ANC and the Blue Representing High ANC.

Episodic acidification occurs when the streams become acidic during high flow events (Lawrence, 2001). Storm flow and snowmelt are often associated with episodes of extreme surface water acidity due to an increase in flow derived from water that has moved laterally through acidic surface soil without infiltration to deeper soil horizons where the potential for ANC may be greater (Webb, 2004). This lack of infiltration can lead to the collection of sulfates and nitrates leading to the acidification of the surface water (Novotny, 2003).

According to the SWAS, hydrologically driven episodic acidification of surface waters has been shown to be a widespread phenomenon. Additionally, Wellington and Driscoll (2004) noted that the deposition of strong inorganic acids contributes to episodic acidification and variations in hydrologic flowpaths may control the extent to which these factors contribute to episodic acidification. During heavy rains associated with summertime advection and orographic lifting, more water is likely routed through upper soil horizons, which tend to be more acidic due to natural soil development processes or acid deposition. It has also been shown to be more severe in waters with chronically low ANC (Webb, 2004; Wellington and Driscoll, 2004). During normal flow, the stream flow largely occurs within lower mineral soils and groundwater storage zones that produce water with higher values of ANC (Wellington and Driscoll, 2004). Lynch and Dise (1985) noted in their research that the streams in the southwest portion of the park had significantly lower alkalinity potential due to their underlying bedrock, resulting in chronic acidification for the streams located in this region. The field analysis performed on Meadow Run and Paine Run, both located within the southwestern section of the park, displayed similar results. Nevertheless, orographic lifting can be associated with causing significant hydrological events (Roe, 2005), which as mentioned above strongly affects a stream's response to acid deposition.

As it happens, both of the streams (Jermey's Run and Rocky Branch) that held normal pH's at the time of the field analysis were located in the north district of SNP. Lynch and Dise (1985) displayed data that show a relatively stable pH for these streams in the north district; yet, the USGS monitoring during the years from 2001-2003 found the pH for each stream to be below the standard. Nevertheless, the Lynch and Dise data are somewhat dated and there is evidence that coal production had increased during the subsequent years, adding more SOx to the atmosphere (Environmental Integrity Project, 2007). This could account for the flux in pH from the 1985 study to the 2001-2003 monitoring data. The Clean Air Act has attempted to lower the SOx emissions considerably; yet even if this reduction is successful NOx deposition is likely to still have an acidifying effect on upland streams (Kennard, 2008).

The USGS sampling for these streams took place in the summer months for a three-year period (Appendix). Accurate precipitation data do not exist for this area concerning summertime advection rains due to the extreme variability associated with the phenomenon. Thus, it must also be noted that pollutant transport is more vigorous during the summer months (Calvert et al., 1983). Therefore, impairment for these particular streams may be associated with an episodic acidification event. Using Figure 3.4 (Cosby et al., 2006) it can be seen that the underlying bedrock within the north district is primarily Mafic, which Lynch and Dise (1985) determined was basaltic in formation and contains a higher Acid Neutralization Capacity (ANC). Therefore, the streams in the north district are not as susceptible to acid deposition as those in the south district, which according to Lynch and Wise (1985) contains siliceous geologic formation made up a sandstones and quartz with a much lower ANC (See Figure 3.1 &3.2).

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are needed to see this picture.

Figure 3.2 **Geologic breakdown of several watershed within SNP**

Soil samples were taken from each site and were determined to be of a different taxonomy between the north and south districts. According to the National Park Service (2006) the two main soil orders represented in Shenandoah National Park are Inceptisols and Ultisols. The sample from the north district revealed a brown color and had a moist granular texture. The soil of the south districts streams had a yellowish brown-color and had a moist sandy texture. The color of this soil in exposed areas exhibited some pyrite oxidation, which is also associated with acid soils and run-off (Barhisel et al., 2000). After review of the existing information on soil taxonomy (NRCS, 2006; Brady and Weil, 2008; Foth and Ellis, 2006) the soil from the north district streams appears to be of the

Inceptisol order and the soil of the south district appears to be of the Ultisol order (See Figures 3.2 and 3.3). This designation would also coincide with a lower ANC for the streams located in the south district partly causing their acidification. Soil ANC and CEC properties are closely linked to the underlying geology (Cosby et al., 2006). Soil samples from the lab indicated, by using the NRCS guide and the Munsell® color system, that the soil from the south district was Jarosite in nature and exhibited a pH of 5.86 when mixed with distilled water. The soil sample for the north revealed a Goethite type soil and a pH of 6.78 was recorded. These pH readings loosely coincide with those from Cosby et al. (2006) where the soils within watersheds situated primarily on siliciclastic bedrock generally showed the lowest soil pH.

Following review of the NADP data the orographic and rain shadow effects can be clearly observed through the precipitation data (See Table 3.2). However, it appears that the windward side of the mountains that causes the rain shadow also have accounted for roughly more wet deposition of NOx and SOx (See Table 3.3). The median pH of acid rain in the northeastern United States is roughly 4.5. The H+ ion is the dominant cation suspended in the atmosphere is largely balanced by SO_4^{2-} and NO_3^-, which are the dominant anions. This ultimately leads to the creation of H_2SO_4 (Sulfuric Acid) and HNO_3 (Nitric Acid), which are the dominant contributors to the precipitation acidity (Jacob, 1999). Both are strong acids which dissociate quantitatively in water to release the H^+ cation and creates the low pH condition (See Figure 3.2).

$$H_2SO_{4(aq)} \rightarrow SO_4^{2-} + 2\ H^+$$

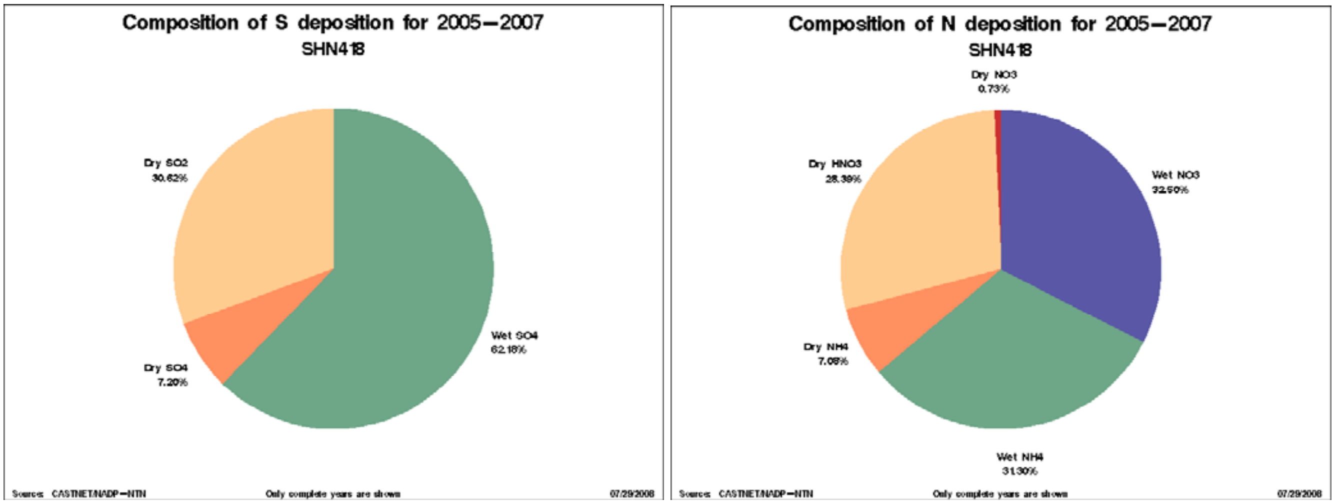
$$HNO_{3(aq)} \rightarrow NO_3^{-} + 2\ H^+$$

Figure 3.2. Caption?

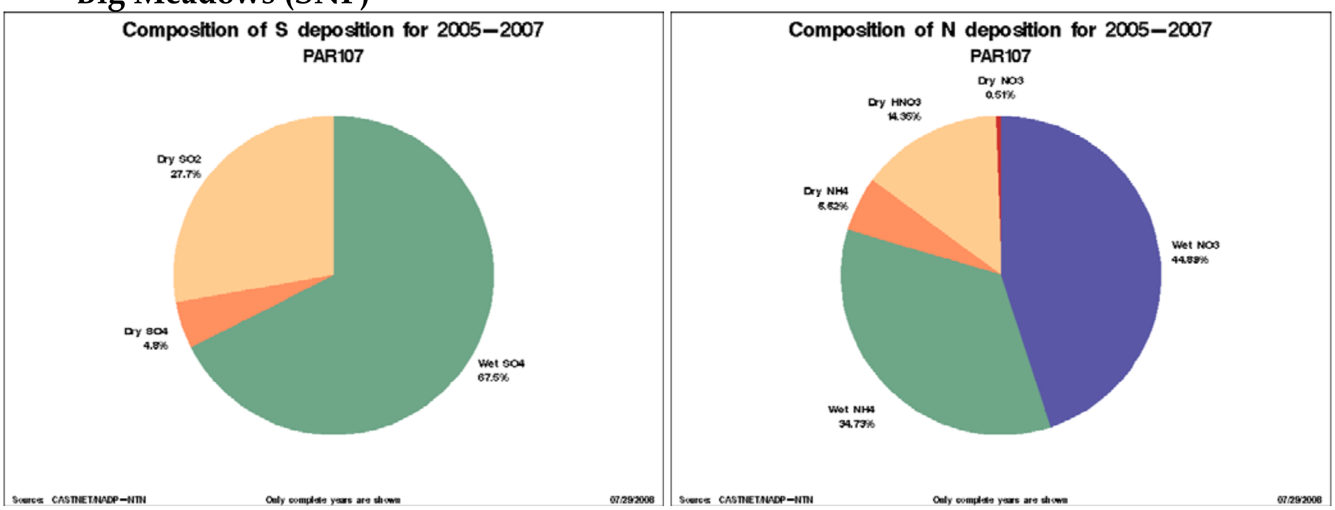
SOx deposition has always been more associated with the acid rain problem (reference?); however, Bowman et al. (2008) have found that NOx deposition becomes a peculiar problem within colder mountainous regions. Much like what is found in Shenandoah National Park where the ridges are ~6°C cooler than the lowlands (Cosby et al., 2006). This cooling is directly related to orographic lifting where the air cools adiabatically on its way up the mountain (Roe, 2005). Fowler et al. (1995) found that the enhancement of the wet deposition of pollutants by orographic patterns, specifically the scavenging of cap cloud droplets by rain falling from above (the seeder-feeder effects). This increases the concentration of pollutants on the summit sites when compared to the lowlands (Weathers et al., 2000). Further illustrating the effects associated with atmospheric deposition and orographic lifting.

Dry deposition is far more difficult to quantify due to the variability of turbulence created in complex terrain such as that which exists in the study streams (Padgett and Minnich, 2008; Kowalski and Vong, 1999; Lovett et al., 1997). Furthermore, Garland (1978) noted that dry deposition is roughly responsible for about 50% of total $S0_2$ deposition emitted to the atmosphere and that conditions that cause turbulence (i.e. mountains and ravines) dominate such deposition. In an effort to quantify this for the study, data from CASTNET were used (See Figure 3.3). These data indicate that dry deposition is more prominent in the more complex mountainous terrain. Furthermore, Padgett and Minnich (2008) noted that dry deposition is more pronounced during the summer months.

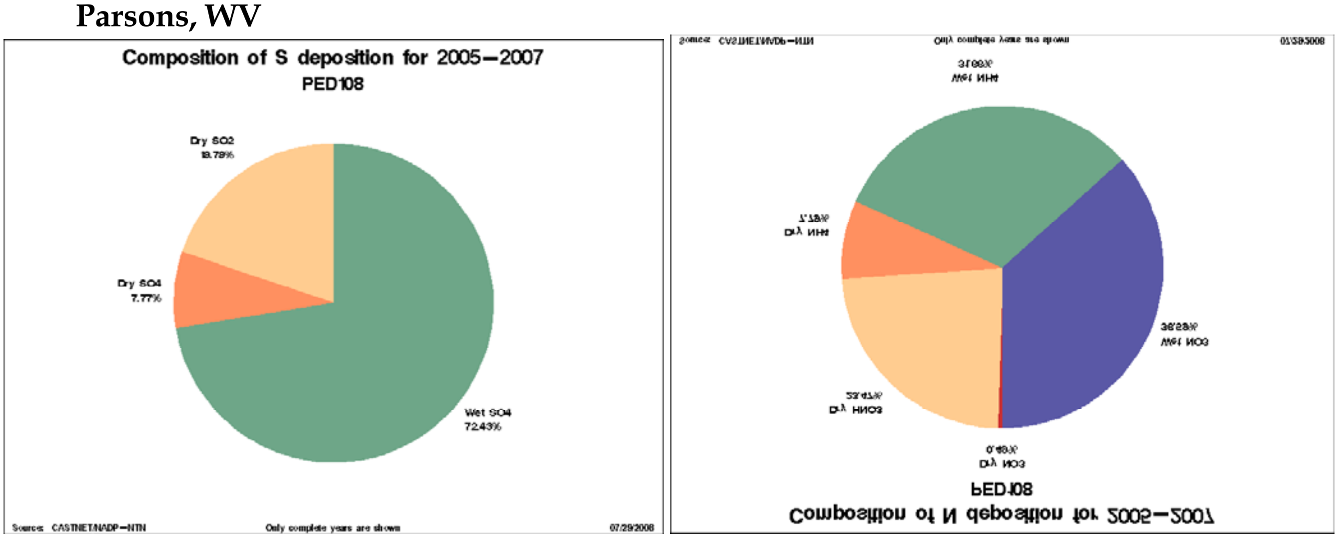
The numbers for the study area concerning dry deposition do not meet Garlands' hypothesis of 50%, but they do exhibit large amounts of $S0_2$ being deposited in the areas with more complex terrain features. Therefore, it can be safely assumed that complex terrain has a direct effect on dry deposition. Padgett and Minnich (2008) noted that dry deposition is more pronounced during the summer months. Moreover, the location of the study streams on the western slope of the park is also upwind and closer to the primary sources of atmospheric deposition (e.g. coal fired power plants in the Ohio Valley) (Lynch and Dise, 1985).



Big Meadows (SNP)



Parsons, WV



Prince Edward, VA

Figure 3.3 Dry Deposition is represented by the orange, yellow, and red [Expand caption. Indicate CASTNET source, etc.]

Study Groups Mean Precipitation (Inches) Winter 2003-Winter 2008

Location	Parsons, WV	JMU	Big Meadows	Charlottesville
Winter 2003	27.36	18.38	31.81	34.93
Spring 2003	32.51	33.07	43.7	43.89
Summer 2003	41.08	50.92	47.65	54.69
Fall 2003	38.29	40.01	60.98	47.97
Winter 2004	28.37	14.68	30.42	21.57
Spring 2004	44.73	25.59	36.12	26.61
Summer 2004	51.97	35.66	34.87	33.44
Fall 2004	26.52	37.79	78.59	37.31
Winter 2005	25.54	13.74	22.23	23.67
Spring 2005	29.13	17.54	26.94	24.55
Summer 2005	24.6	27.88	35.32	30.71
Fall 2005	24.59	23.82	52.83	30.21
Winter 2006	28.02	17.1	31.67	22.71
Spring 2006	29.21	11.06	18.54	9.36
Summer 2006	58.63	31.26	39.73	28.28
Fall 2006	25.78	41.27	68.53	58.13
Winter 2007	25.63	15.85	21.01	18.12
Spring 2007	29.74	22.63	27.23	23.34
Summer 2007	45.8	28.31	36.07	27.77
Fall 2007	25.06	13.7	19.73	16.47
Winter 2008	37.77	14.83	20.57	16.23
5-Year Precip. Mean	**33.35**	**25.48**	**37.36**	**30.00**

Table 3.2 [You need to provide a caption]

Study Groups Mean Deposition (Weighted Mean Concentrations) Winter 2003-Winter 2008

Location	Parsons		JMU		Big Meadows		Charlottesville	
Pollutant	**NOX**	**SOX**	**NOX**	**SOX**	**NOX**	**SOX**	**NOX**	**SOX**
Winter 2003	1.338	0.954	0.793	0.846	0.393	0.408	1.366	1.32
Spring 2003	1.312	1.866	0.99	1.196	0.819	1.192	1.127	1.502
Summer 2003	1.068	2.326	0.952	1.83	0.923	1.626	0.904	1.681
Fall 2003	0.623	1.111	0.422	0.667	0.321	0.668	0.523	0.781
Winter 2004	1.172	0.824	0.78	1.086	0.391	0.623	1.015	1.18
Spring 2004	1.123	1.613	1.169	1.362	1.237	1.672	1.211	1.567
Summer 2004	0.926	2.74	0.984	1.813	0.798	1.594	1.012	2.013
Fall 2004	0.673	0.97	0.41	0.632	0.312	0.729	0.655	1.051
Winter 2005	1.124	1.126	0.72	0.634	0.504	0.573	0.91	0.817
Spring 2005	1.15	1.515	1.52	2.226	1.083	1.677	1.947	2.541
Summer 2005	0.967	2.82	0.869	1.884	0.634	1.373	0.955	2.27
Fall 2005	1.045	1.612	0.512	0.713	0.446	0.96	0.499	0.888
Winter 2006	1.065	1.022	1.055	1.061	0.764	0.763	1.163	1.268
Spring 2006	1.607	2.276	1.073	1.693	1.082	1.592	1.632	2.269
Summer 2006	0.83	2.452	0.615	1.008	0.575	1.197	0.72	1.393
Fall 2006	0.796	1.335	0.488	0.713	0.378	0.598	0.649	0.935
Winter 2007	1.251	1.139	0.765	0.86	0.337	0.596	1.071	1.28
Spring 2007	1.006	1.417	0.852	1.114	1.641	2.414	1.482	2.112
Summer 2007	0.959	2.639	0.998	1.597	0.858	1.805	1.153	2.138
Fall 2007	0.951	1.505	0.791	0.907	1.589	2.076	0.767	0.94
Winter 2008	0.761	0.998	0.629	0.996	0.391	0.592	0.981	1.423
%-Year Mean Wet Deposition	**1.036**	**1.631**	**0.828**	**1.183**	**0.737**	**1.178**	**1.035**	**1.494**

Table 3.3 [You need to provide a caption] Modify the title above?

4. Discussion

The Virginia Department of Environmental Quality (DEQ) has listed seven streams within the Shenandoah National Park as impaired for acidity per the water quality standards set forth by the United States Environmental Protection Agency (EPA). The DEQ has also noted the cause of the acidity to be from atmospheric deposition. Moreover, Webb et al. found similar results in their study included in the VWRRC report (Younis, 2005). Both of these studies exhibit some correlation with atmospheric deposition orographic lifting and the rain shadow effect.

The effect of orographic lifting on Shenandoah National Park is fairly pronounced after analyzing the corresponding literature and climatic data. The driving force of weather is seasonal and corresponds with the warm moist ocean derived from the Gulf Stream in the summer months (Gawtry and Stenger, 2007) and the cold air masses coming from the northwest in the winter months (Abraham, 2008). This results in the western side of the park (The Shenandoah Valley) being almost constantly in the rain shadow (Grymes, 2008). Furthermore, when moisture does develop on the western edge of the park it due to the orographic lifting that occurs (Abraham, 2008) (See Figure 3.1). This is due to the orographic lift from air moving up on the Blue Ridge and is forced upward to an area of lower pressure. Then it expands, cools, and condenses and thus cloud formation will occur when the dewpoint is reached. The type of cloud formation will depend on the moisture content and on the stability of the air. The slope and height of the terrain and the strength of the wind component that produces the upslope flow also will have an effect (MacDonald and Peppler, 2003). All of which has a categorical effect on the acid deposition. Jones and Choularton (1988) noted that atmospheric deposition driven by orographic precipitation is more pronounce in large-scale topography, as found in Shenandoah National Park. Furthermore, Dore et al. (2006) found that atmospheric pollutants increase cloud condensation by acting as nuclei in droplet formation . Rosenfield et al. (2007) found that orographic effects can also decrease the amount of precipitation (wet deposition), but increase the holding capacity of the clouds further increasing deposition through occult and/or dry deposition.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.1 Notice the gap where the valley exists and the formation of cloud where Shenandoah National Park lies

In addition to moisture developing on the western edge, as noted earlier, the location of the streams that were deemed impaired by the Virginia DEQ where in deep valleys ranging from 300′ to 700′ from the surrounding crests (See figure 2.1) (Appendix). These locations when paired with the corresponding orographic lift create microclimates (Gawtry and Stenger, 2007) and a phenomenon known as valley fog. Valley fog forms as cooler air falls to the valley floor and the moisture in the air reaches the dew point (See Figure 3.2).

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are needed to see this picture.

Figure 3.2 **Diagram of Valley Fog Formation**

Studies have been performed on similar geographies concerning atmospheric deposition. Lavoie and Bradley (2002) found that cloud water deposition could be four times more acidic than bulk precipitation. Furthermore, Aleksic et al. (2009) noted cloud water deposition to be 14 to 28 times more than normal precipitation. In addition to this Menon *et al.* (2000) found that most atmospheric sulfate production occurs in clouds. Coe et al. (1991) also noted that the highest concentration of occult deposition was found on the lee side of the mountain. Cloud deposition, otherwise known as occult deposition is extremely difficult to quantify and Aleksic et al. (2009) stated that to achieve accurate deposition concentrations cloud water must be further analyzed.

Figure 3.3 **Photo of Valley Fog in Shenandoah National Park and surrounding region. Believed to be looking westward at sunrise.**

Nevertheless, cloud deposition can be substantial as seen in some cases, particularly at high- elevation sites that are immersed in clouds more than 25% of the time. The percent of total S deposition contributed by cloud deposition has been estimated to range from near zero for lower-elevation sites to over 50% at higher elevation (Cosby et al., 2006). Johnson et al. (2000) found that acidic deposition increased significantly with elevation. The CASTNET data exhibits similar trends. However, atmospheric deposition is extremely variable due to variations in meteorology, air chemistry, and topography (Lovett et al., 1997). Thus further displaying the possible role orographic lifting has concerning atmospheric deposition. Although it must be noted that estimates of atmospheric deposition within complex mountainous terrain are merely crude approximations (Weathers et al., 2000).

5. Conclusion

My data illustrates a distinct water quality issue concerning the western slope of Shenandoah National Park (SNP). Furthermore, through the research presented above there are several potential contributors to the acidification of some of the headwater streams located within SNP. This acidification has been in the form of both episodic and chronic acidification and a variety of for these conditions exists.

The research objective aimed to demonstrate that orographic lifting and other associated patterns had a decided effect on the stream's water quality regarding pH. The Virginia DEQ has listed the cause of the particular streams as atmospheric deposition and it certainly appears that orographic climate effects affect the depositional rates. Nevertheless, it must be noted that the south district waters are chronically acidified due to the bedrock and soil make up being the likely sources of acidification. This was corroborated by the field analysis performed in this study. Although the bedrock and soil noted in the north district contained much higher ANC, in previous samples by the USGS two of these streams were designated as impaired for pH. The field analysis of these sites confirmed these geologic and the soil properties as well. However, the two streams in the north district did not exhibit a pH for impairment during the field analysis. This in effect displayed their acid neutralization capabilities.

Due to this anomalous relationship it is clear that not only the soil can be deemed responsible for the acidification. This is likely where the DEQ decided upon atmospheric deposition as the culprit for the pH impairment. Thus, the preceding research demonstrates the variety of effects that orographic lifting has on atmospheric deposition. Furthermore, it also displays how certain effects associated with orographic patterns exacerbate deposition of certain acid forming compounds. Therefore, it can be inferred that the orographic effects associated with SNP have an influence on the parks water quality.

Nevertheless, due to the extreme variability associated with climatic patterns within SNP and other complex mountainous terrains, as well as depositional rates for particular locations, it still remains to be seen the extent that an orographic climate might have on a particular geography. More *in situ* studies of microclimatic patterns would better exhibit the effects associated with orographic patterns within SNP. Evidence in previous studies displayed how the orographic effect in higher elevations enhanced deposition due to increased rainfall and cloud cover (Weathers et al., 2000). Moreover, the synergistic relationship between the poor ANC soils and the deposition concentrations must not be overlooked because the evidence is clear that this acts as a detriment to the water quality within SNP.

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