Vernal Pool Mapping and Geomorphology in the Appalachian Mountains of Pennsylvania

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ABSTRACT

Vernal pools are small seasonally-ponded wetlands that provide crucial habitat for amphibian reproduction and support trophic levels beyond their boundaries. The Ridge and Valley physiographic province in Pennsylvania is known to have vernal pools, but a regional inventory and geomorphology assessment is needed. My research is split into two independent parts focusing on the higher elevation areas of this region to determine vernal pool distribution and characteristics. Vernal pools were mapped using a LiDAR based suitability model and leaf-off aerial imagery interpretation. Four terrain rasters derived from a 1-meter DEM (modified wind modified wind exposure, terrain surface convexity, topographic position index, and a multiresolution index of valley bottom flatness) were used in the suitability model. An analysis of variance (ANOVA) and Tukey's HSD test found a significant difference using the model between terrestrial (non-wetland) habitat and vernal pools. Photo interpretation and field surveying lead to an inventory of 1011 vernal pools. Geomorphology was assessed from 13 variables to determine the best for vernal pool prediction. Three variables were significant for the occurrence and frequency of vernal pools; saddles with higher surface area, 0.6 to 1.5 kilometers between the summits of parallel ridgelines, and the presence of periglacial related solifluction. Vernal pool distribution is greater than previously known and they occur in predictable settings.

Further research should focus on how and where vernal pools form, their impact on water quality, role in forest ecology, and ways to legally protect them at the state level.

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GENERAL ABSTRACT

Vernal pools are seasonally-ponded wetlands that are very important for amphibian reproduction. The Appalachian Mountains of Pennsylvania are known to have vernal pools, but comprehensive inventory is lacking. My research consists of two parts that focus on the higher elevation areas and assess the distribution and qualities of the vernal pools. Vernal pools were mapped using a LiDAR based suitability model and leaf-off aerial imagery interpretation. Statistical analysis was completed to prove that there was a significant difference in terrain morphology between non-wetland habitat and vernal pools. This research resulted in a total inventory of 1011 vernal pools. Results found that vernal pools were likely occur in landscape positions with higher surface area, 0.6 to 1.5 kilometers between the summits of parallel ridgelines, and the presence of topographic features indicative of glacial processes. Vernal pools are much more abundant than previously known and they occur in predictable settings. Further research could focus on the formation of vernal pools, impact on water quality, role in forest ecology, and ways to legally protect them at the state level.

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My education was only possible because of the GI Bill and other educational benefits for veterans. I am grateful for the opportunities I have had to serve my country abroad through the military and domestically with environmental science. Any contribution to science that I can accomplish is in honor of my fellow service members who made the ultimate sacrifice and were never able to pursue a life of their own choosing.

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1. Introduction

Vernal pools are small ephemeral wetlands that provided critical habitat for amphibian reproduction and development (Zedler, 2003). Isolation and seasonal drying prevent fish from establishing in vernal pools causing a reduction in predation pressure. Vernal pools in the Ridge and Valley physiographic province of the Appalachian Mountains in Pennsylvania often occur in homogenous upland forests alongside or above headwater streams. Their biodiversity and nutrient cycling are much higher than the surrounding terrestrial habitat with respect to relative size (Capps et al., 2014). Vernal pools can vary significantly from year to year and from one another in proximity with respect to hydrology and their support of ecological functions (Semlitsch, 2000). At a regional scale, vernal pools share five characteristics in the northeastern United States: 1) Geographic isolation from surface waters, 2) forested setting, 3) shallow depth and small surface area, 4) seasonal desiccation, and 5) support of wetland obligate species (Colburn, 2004). Higher elevation areas of the Pennsylvania Ridge and Valley have documented vernal pools, but a regional inventory and assessment of their geomorphology has not been conducted. Understanding the distribution and characteristics of vernal pools will be important for future ecological and watershed research.

Pennsylvania provides an extraordinary opportunity to study vernal pool variation, distribution, geomorphology, and ecology. Research in the Ridge and Valley region is lacking, and considerable data gaps exist in current vernal pool mapping projects. Apart from the scientific opportunities, Pennsylvania is one of the few states to offer legal protections for isolated wetlands. Obstacles for development from regulations and the extreme terrain of the ridgelines have permitted vernal pools to persist despite wide scale anthropogenic encroachment in the valleys below. Vernal pool research in the Ridge and Valley will help advance the understanding of headwater hydrology, soil genesis, the influence of shale and other surficial lithologies on wetland abundance, impact of past periglacial climates on wetland formation, and biodiversity. Current legal protections within the state do not consider the biological functions of an isolated wetland, but rather set a size threshold of 0.02 ha to receive jurisdictional protection (Commonwealth of Pennsylvania, 2018). The continued existence of these unique features in Pennsylvania should be based upon their scientific and ecological value, not a surface area measurement.

The distribution, geomorphologic setting, and full ecological value of vernal pools in the Ridge and Valley of Pennsylvania is not fully understood. Two approaches were used in assessing vernal pools in the region; 1) a geospatial process to discriminate vernal pools from terrestrial habitat and a regional inventory using photo interpretation of aerial imagery and 2) combining geospatial analysis with field sampling to articulate vernal pool geomorphology and site physical conditions. Based on the available literature about the value of vernal pools and the lack of research in the Ridge and Valley of Pennsylvania, the objectives of my study are:

1.1 Objectives

1. Landscape Suitability Model Development

   Determine which terrain metrics derived from a 1-m digital elevation model (DEM) can distinguish locations that contain a vernal pool.

   Hyp1 (0): Terrain metrics are not able to reliably discern vernal pools from terrestrial habitat.

   Hyp1 (alt): One or more terrain metrics are capable of discerning vernal pools from terrestrial habitat.

2. Geomorphology Study

   Characterize the geomorphology and lithology of saddles to predict locations where vernal pools are most likely to occur.

   Hyp2 (0): Saddles with or without vernal pools will not have a discernable difference in geomorphological variables.

   Hyp2 (alt): Saddle geomorphology is a significant component in whether vernal pools are present or not.

3. Inventory of Site Physical Conditions

   Survey 36 vernal pools in higher elevations to establish a baseline inventory of site soil, hydrology, and vegetation characteristics.

2. Literature Review

2.1 Vernal Pools Defined

Vernal pools are found globally under a variety of conditions (Keeley and Zedler, 1998). For example, both California and the northeastern United States contain vernal pools that support amphibian reproduction and experience similar seasonal hydrology, but these regions have vastly different temperature and moisture regimes (Schlising and Sanders, 1982). The term "vernal pool" does not have a single strict scientific definition and is best viewed within a regional context. In the northeastern United States, vernal pools have five general attributes: 1) Woodland setting, 2) isolation from surface waters, 3) small size, 4) seasonal hydrology trends, and 5) the support of unique biological communities (Colburn, 2004). An accepted method of categorizing vernal pools specifically is by their surficial geology and landscape position.

The northeastern U.S. is separated into sub-regions based on geology and vernal pools are then classified by their hydrogeomorphic conditions. Parent material is an important factor in soil development because it affects nutrient availability, hydraulic conductivity, weathering rates, landscape formation, and other processes (Schaetzl and Anderson, 2005). The sub-region containing central Pennsylvania is underlain primarily by siltstone, shale, carbonates, and sandstone from the Paleozoic Era. The individual rate and period of weathering for each lithology type influences the geomorphology that vernal pools form upon. Rheinhardt and Hollands (2007) adapted a hydrogeomorphic wetland classification approach to sort vernal pools into five classes; depression, slope, flats, riverine, and anthropogenic. Depressions are the class of interest for this research and are often found isolated alongside or above headwater streams.

Vernal pools at higher elevations in the Pennsylvania Ridge and Valley are isolated from other surface waters unless large flooding events occur. Isolation has a profound impact on the character of these wetlands. Fish cannot establish in vernal pools because of the seasonal drying and disconnection from the stream network. Amphibian reproduction success improves considerably without fish predation (Zedler, 2003). Remoteness can also be detrimental by hindering the genetic dispersion of species, which can be exacerbated by habitat fragmentation (Homan et al., 2004). Vernal pools are also vulnerable to degradation because of their shallow depth and small surface area.

Vernal pools are small and typically under forest cover making them exceptionally difficult to map and assess them via remote sensing methods. Many remote sensing platforms do not have the resolution or ability to penetrate canopy cover to detect vernal pools in the landscape. This hinders the ability of conservation groups and government agencies to provide jurisdictional protection. The physical dimensions of vernal pools, while an impediment to management, are important in how they function. Shallow depths and small surface areas allow the water column to readily turn over from the wind. The physical action of turnover replenishes dissolved oxygen and rapidly warms the water column as spring approaches. In summer, the shallow inundated basins dry from evaporation and plant transpiration (Colburn, 2004). The seasonal patterns of water movement are fundamental for the functions of vernal pools along with the fauna and flora they support.

Ephemeral wetland hydrology is closely tied to regional precipitation levels. Water balances for vernal pools are complex and often include a mixture of inputs. Vernal pools receive water from surface runoff, ground water, or combinations of both (Zedler, 2003). Snowpack is a principal component of the water budget for vernal pools. During the spring thaw vernal pools fill from surface runoff and groundwater that has been able to recharge from snow melt (Schneider and Frost, 1996). Hydrologic inputs differ for each pool by magnitude and type. Variation helps determine which flora and fauna species occur in the wetland with some preferring one temporal period of inundation over another (Zedler, 2003). Inundation fluctuate throughout the year within an individual wetland and between nearby pools. Figure. 1 shows two vernal pools 30 meters apart photographed on the 20th of June 2016 exhibiting different stages in their seasonal hydrology. Vernal pool (a) is inundated with tadpoles present while (b) is only supporting hydrophytic vegetation. Altering pool hydrology in any way can severely change its functionality, which may occur from nearby development and the effects of climate change. Land cover and use are important factors governing the hydrology and nutrient cycling of vernal pools (Capps et al., 2014).

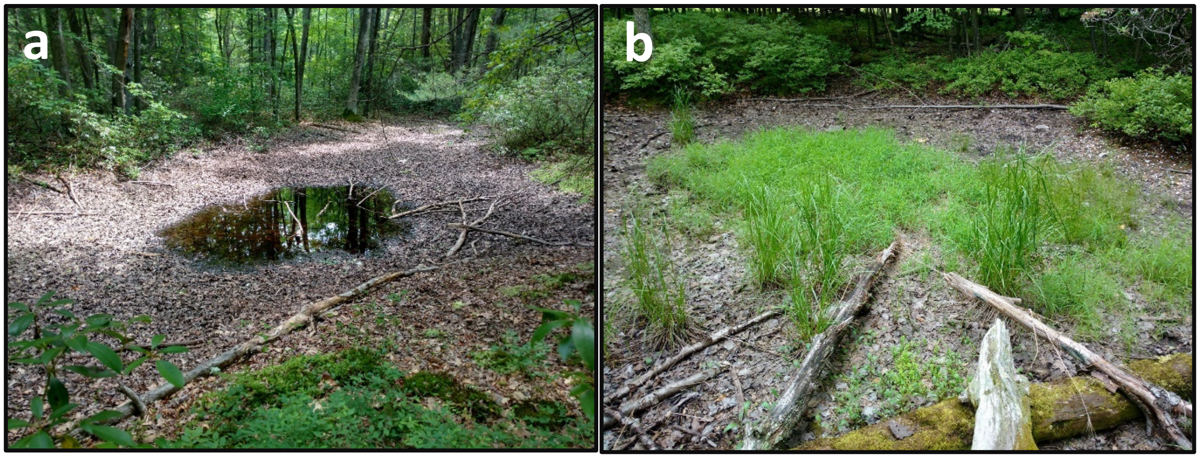

Figure. 1. Two vernal pools 30 meters from one another were photographed on the 20th of June 2016. The basin in image (a) has standing water with tadpoles and the one in image (b) is dry and supporting wetland vegetation. The duration of seasonal ponding is unique to each vernal pool. Photographed by the author in 2016.

Forest is the dominant land cover for higher elevation vernal pools in the Pennsylvania Ridge and Valley. Land cover strongly influences nutrient cycling, ecology, thermal and moisture properties, and functionality. Evapotranspiration demands from trees during the growing season draw extensively on the water table around vernal pools. Inundation levels fluctuate and usually recede below the soil surface as the hotter days of summer ensue and plant transpiration increases. Canopy closure indirectly influences inundation by limiting the effective incoming solar radiation and subsequent rate of evaporation (Colburn, 2004). Korfel et al. (2010) found that biomass and species richness increased under denser forest and canopy cover. The degree of sunlight reaching the pool controls the water temperature, which affects the dissolved oxygen content and the environmental cues organisms use to develop. As autumn arrives, the timing, type, and magnitude of detritus deposition can determine which macroinvertebrates inhabit a vernal pool (Binckley et al., 2010). Water levels begin to rise in the fall season as vegetation goes dormant and transpiration is reduced (Calhoun and deMaynadier, 2008). Evidence of these five regional vernal pool characteristics and their interactions can be found preserved in the soil.

2.1.1 Wetland Definitions and Hydric Soils

The National Wetlands Inventory was the catalyst for the development of the Cowardin et al. (1979) classification system and its definition of wetlands:

> "As lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. For purposes of this classification wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes, (2) the substrate is predominantly undrained hydric soil, and (3) the substrate is non-soil and is saturated with water or covered by shallow water at some time during the growing season of each year.

The jurisdictional definition of wetlands in the United State is given under the Clean Water Act (CWA) with criteria not to be confused with classification, which will be covered in section 2.3. Guidance from the National Resources Conservation Service further describes hydric soils by establishing soil indicators based upon location and soil texture. Hydrologic conditions for hydric soils require saturated conditions of 14 or more consecutive days or a water table no more than 30 cm below the soil surface in the growing seasons for at least five out of ten years (USACE, 2012). Variation to this standard is in place for differing soil textures. These conditions alter the soil profile leading to the reduction and mobilization of certain elements (e.g. Fe and Mn) by microbes, the accumulation of carbon, and the translocation of certain mobilized materials (USDA-NRCS, 2010).

Microbial respiration in non-hydric soils use oxygen as the final electron receptor. When soils become anoxic, microbes' resort to alternative electron acceptors. Development of reducing conditions in soil requires saturation to exclude atmospheric oxygen, have available carbon for the microbes to consume, an active microbial population, and limited dissolved oxygen content (Vepraskas et al., 2001). When oxygen is not available alternate acceptors are utilized in various elemental species; nitrogen, manganese, iron, sulfur, and carbon dioxide. The rate of reduction and the compounds used are dependent upon the length of saturation and the availability of the individual constituents (Tokarz and Urban, 2015). Hydric soils typically undergo a color change (reduced chroma) from the redoximorphic process and the weathering of parent material. Regional lithology, land cover, and geomorphology are important factors influencing the development of vernal pool soils.

2.2 Periglacial Origins of Vernal Pools

Vernal pools can be difficult to attribute to a specific genetic origin. The Pennsylvania Ridge and Valley has been farmed, mined, and logged repeatedly for decades causing some anthropogenic wetlands to form. Natural vernal pool formation has been attributed to processes occurring during periods of periglacial climates with the last glacial retreat in the Wisconsin Stage just over 10,000 years ago (Colburn, 2004). Glaciation has advanced into Pennsylvania several times during the Pliocene, but not into the central part of the state. Evidence of past glacial advances is incomplete because of the destructive nature of this phenomenon. A full accounting of glacial advances and retreats during the Pliocene is not fully known, but from the available evidence it is known that the Pennsylvania Ridge and Valley experienced repeated periglacial climates and loess deposition (Rutter, 2012). The position of the Ridge and Valley at the boundary of the glacial extent heavily influenced how the landscape weathered and what legacy features can be found.

Across the region there is evidence that many soil and landscape features were formed under periglacial conditions (Gardner et al., 1991). The Wisconsinan glaciation (11,000 – 35,000 years ago) advanced into northern Pennsylvania while south in the Ridge and Valley there was a periglacial climate for approximately 2,000 years. During this period vegetation was not as abundant and strong winds deposited loess over the landscape. The deposited loess migrated to low spots in the landscape and altered the soil permeability (Rheinhardt and Hollands, 2007). Ben Marsh (1987) speculated that several vernal pools located in the Ridge and Valley of Pennsylvania were remnants of periglacial formations called "pingo'es". These features form by the upwelling of ground water and its subsequent freezing upon contact with the permafrost layer. Elevated ice mounds formed and blocked colluvium from depositing in that location, which upon thawing left a depression behind. Garner Run is an area with vernal pools in the region that was found to have permafrost related solifluction, ice-driven creep, and mass wasting from freeze-thaw. Solifluction is the downslope movement of seasonally thawed soil due to an underlying freeze/thaw process. It is observable in terrain modeling by lobes that run parallel with one another perpendicular to the gradient. Ripples and waves are observable in the landscape and can impound surface water (Davis, 2001). Del Vecchio et al. (2018) found that in the ridgeline sandstone landscape of the Pennsylvania Ridge and Valley periglacial climate processes were the dominate instrument of sediment introduction and down slope movement. These processes were driven by a periglacial climate, but the effect of aspect is also important.

The rate of thaw, movement, and permafrost feature formation can vary considerably on south versus north-facing aspects (Leffingwell, 1915).

2.3 Wetland Status, Trends, and Protections

Wetlands are in decline in the United States with an estimated loss of 53% from the 1780s to 1980s accounting for more than 100 million acres. The functionality of the remaining wetlands has been degraded by the introduction of invasive organisms and the effects of climate change (Zedler and Kercher, 2005). Climate change puts vernal pools in an increasingly vulnerable position because of the potential alterations in their hydrology (Dahl and Stedman 2013). Changes in the length and chronology of inundation, temperature, and precipitation levels will directly affect the phenology of many amphibians and macroinvertebrates (Green, 2017). Amphibians are in decline with an extinction rate 200 times greater than indicated in the fossil record (USGS, 2015). The effects of vernal pool loss and degradation will extend into the terrestrial habitat by affecting the food chain. Preventing the loss of vernal pools requires adequate legal protections that reflect their ecologic value and not just size.

Vernal pools are typically not considered jurisdictional wetlands under the CWA because of their isolation from other surface waters. Legal protections are afforded nationally under section 404 of the CWA and administered by the U.S. Army Corps of Engineers (USACE) with collaboration from the Environmental Protection Agency (EPA) and the U.S. Fish and Wildlife Service (USFWS). Jurisdictional wetlands are determined at the federal level through four criteria that include the presence of saturated conditions close to the soil surface, hydrophytic vegetation, hydric soil at or near the surface, and a significant nexus to navigable waters of the United States (USACE, 2012). Vernal pools are often excluded from federal protection because they do not satisfy the fourth criteria because of their isolation and often undetermined ground water connections (Colburn, 2004).

The CWA is a federal statute serving as a baseline for environmental standards, and states often expand upon this law with their own legislation. Pennsylvania has state level protections for isolated wetlands through the Dams Safety and Encroachments Act (Commonwealth of Pennsylvania, 2018). The statute sets a minimum size of 0.02 ha for protection and does not outright eliminate wetland destruction. Entities wishing to alter or develop an isolated wetland must first obtain a permit from the state environmental agency (Lutz, 2010). The regulatory agency is given wide latitude in affording protection and issuing permits. The regulatory system requires potential impactors to first avoid the disturbance, minimize the impact, and as a last resort replace, the wetland loss at a ratio determined by the Pennsylvania Dept. of Environmental Protection. A terrestrial buffer zone should be considered because numerous studies have shown that protecting the wetland or enacting an obstacle to disturbance is not sufficient to minimize degradation.

Research conducted by Veysey et al. (2011) examined the distribution and abundance of amphibian species for 49 vernal pools in New Hampshire. Results showed that preserving the core habitat, the vernal pool and a limited buffer area, was not enough in preventing reduced vernal pool functionality. Road density within a km of the wetland was a strong indicator of amphibian egg mass abundance. Areas with lower road densities experience less habitat fragmentation and higher egg mass counts. Forest fragmentation from roads and other infrastructure can severely impact amphibian communities by modifying vernal pool hydrology and habitat connectedness. Some states have sought to protect these wetlands with mandatory buffer zones and other best management practices. The Massachusetts Wetland Protection Act is an example of legislation that requires a buffer zone of 30 m from amphibian breeding locations. The law was found to be inadequate to address conservation concerns in a study by Homan et al. (2004). Spotted salamanders and wood frogs were being affected by the loss of nearby terrestrial habitat at distances much greater than 30 m from the pool. Vernal pools are sensitive ecological refuges that need legal protection beyond their high-water line. The first step towards protection and conservation is a thorough mapping inventory and assessment of vernal pools within an area of interest.

2.4 Wetland Mapping Projects

Mapping wetlands is challenging because they occupy a position as a transitionary landscape between terrestrial and aquatic habitats and the zone of change between the two can be diffuse for many features. Vernal pools further complicate this with their small size, isolation, and placement under dense forest cover. Lang et al. (2009) explains how most issues in wetland remote sensing stem from the spatial and spectral resolutions of a dataset and their ability to reflect the wetland type of interest. Passive and active remote sensing systems must make tradeoffs with respect to resolution to meet cost and technology limitations. Wetland mapping has followed the evolution of remote sensing with countless sensors and techniques used over time.

Effectively mapping wetlands relies upon establishing a set of data standards, using proven methodology, and collaborating with relevant stakeholders. Many sectors of the economy rely on accurate wetland maps from insurance companies assessing flooding risk to environmental managers identifying resources. Often, organizations have to rely on cost efficient methods to identify wetlands using open-source data and software because of limited financial resources. Two programs serve as examples in wetland and vernal pool specific mapping that have adapted to new technics and funding limitations; the National Wetland Inventory (NWI) and the North Atlantic Vernal Pool Data Cooperative.

2.4.1 National Wetland Inventory

Wetland inventories by the federal government began in the early part of the 20th century. The Department of Agriculture sought to identify locations to drain for development and agriculture. Many farmers considered wetlands a waste of potentially arable land, and by extension so did the federal government (Hefner and Storrs, 1994). It wasn't until 1954 that the USFWS conducted a national wetland survey with conservation related objectives. The initial inventory provided insight into the benefits of wetlands, and out of this project grew an interest in further mapping. The National Wetland Inventory was established in 1974 with the goal of providing scientific information on the conditions and extent of the nation's wetlands (Wilen, 1990).

The inventory was tasked with imposing "boundaries on natural ecosystems for the purposes of inventory, evaluation, and management". The first step was to establish an agreed upon system of wetland classification. In 1975, four wetland ecologists started development on what would become the *Classification of Wetlands and Deepwater Habitats of the United States*. Cowardin et al. (1979) provided a hierarchical system of wetland classification that was applicable across several regions. Wetlands were classified in order of their system, subsystem, class, subclass, and any necessary modifiers (Cowardin et al., 1979). After extensive field testing and revision the Cowardin classification system was adopted by the U.S. Fish and Wildlife Service in 1980 (Wilen, 1990).

The operational objectives of the NWI were to map the nation's wetlands and report on their status periodically. In 1986, these objectives were codified with the passage of the Emergency Wetlands Resource Act (Wilen, 1990). Under this legislation the Secretary of the Interior was tasked, through the USFWS, to provide a map of the wetlands in the United States. The inventory was intended to be updated and supplemented with a report on trends every ten years. Changes to the program have occurred over time with modifications in the policy expectations and the methodology used in the mapping process.

Maps for the NWI were initially produced by interpreting mid to high altitude aerial imagery at scales of 1:130,000 or larger then transferred to 1:24,000 scale base maps (USFWS, 2018). As the project grew and newer methodologies emerged the Federal Geographic Data Committee (FGDC) developed a series of wetland mapping standards with the most recent update as of July 2009. The Wetland Mapping Standards publication covers how data should be obtained, evaluated, and submitted for inclusion into the inventory (FGDC, 2009). Guidelines seek to ensure quality control for the imagery used, classification methods, data accuracy, and wetland verification. Imagery coming from aerial and spaceborne platforms would ideally have a 1-meter or better spatial resolution. Incorporation of near-infrared, leaf-off, and finer scaled imagery is preferred and may be essential to achieve desired levels of accuracy. The accuracy and quality control of this program directly impacts countless real-world activities.

Mapping accuracy is evaluated by measuring the errors of omission and commission. Errors of commission occur when a feature is incorrectly classified as a certain category and is known as a false positive. Errors of omission, conversely, occur when a feature is incorrectly left out of a specific category (FGDC, 2009). Commission rates in wetland mapping tend to be low while omission rates are usually high. A study in the Blue Ridge physiographic region of

Virginia found an omission rate of 85% (Wright and Gallant, 2007). The NWI has consistently shown to be conservative in identifying wetlands trending towards higher omission rates.

The NWI has been in operation for over 40 years now and has proven to be a valuable resource. The program currently deals with data gaps, limitations in detecting small wetlands, and reliable funding. Challenges of climate change and wetland degradation necessitate more investment in this dataset as a principle component of the National Spatial Data Infrastructure. Understanding the distribution of wetlands across the U.S. will become crucial as problems with sea level rise, loss of biodiversity, and flooding increase.

2.4.2 North Atlantic Vernal Pool Data Cooperative

Vernal pool inventories have been undertaken across the northeastern U.S., most notably in New Jersey (Lathrop at al., 2005) and Massachusetts (Wu et al., 2014). The North Atlantic Vernal Pool Data Cooperative was founded on the premise of improving vernal pool awareness by creating regional inventories and utilizing remote sensing. The project is funded by the North Atlantic Landscape Conservation Cooperative and spans across 12 governmental boundaries; Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Nova Scotia Canada, Pennsylvania, Quebec Canada, Vermont, and Virginia (Faccio et al., 2016).

The initiative started in January of 2014 with the goal of seeking contributors from the private sector, non-governmental organizations, and governmental entities through a vernal pool mapping workshop. Subsequent workshops and collaborations have led to a submission of 61,331 vernal pools observations. Out of this total, 20.9% of the records have been field verified and a list of 48,523 potential sites remain (Faccio et al., 2016). The program has built a set of mapping standards and best management practices for anyone to adopt. Data management and security is a big part of these standards because vernal pools are sensitive. The project addresses location data by establishing three levels of access: Level 1 for unrestricted data, level 2 for visualizations only, and level 3 for completely restricted information. Access levels were established with input from each contributor, but the metadata structure was provided by project managers. Metadata and supplemental table formats were given to participants to help with the collection and organization of their data.

The cooperative approach of this project has been instrumental in its impact and future utility. Vernal pool mapping efforts need to adopt interdisciplinary and community-based tactics to mitigate the ebb and flow of traditional funding sources. Embedded in the final report is a comprehensive breakdown of the organizational network and methodology freely available for others to replicate. Options are provided for researchers to find the best approach for their purposes.

2.5 Wetland Remote Sensing using LiDAR

When the USFWS first conducted wetland surveys in 1954, the available remote sensing data was limited to aerial photography (USFWS, 2018). The advent of multispectral imagery and aerial mounted light detection and ranging (LiDAR) systems have changed the way in which environmental information is collected. Active systems such as LiDAR emit energy that interacts with the earth's surface before returning to the sensor. This is very useful in terrain modeling, but the platform can be limited by low repeatability and cost. Resolution limitations are common issues with detecting narrow ecological gradients, especially as seasonality affects wetland hydrology (Lang et al., 2009). Wetlands can be considered "moving targets" in remote sensing because of their role as a transitionary landscape (Gallant, 2015).

LiDAR is a remote sensing technique that uses pulses of light to derive information about the earth's surface. Data is collected with x, y, z coordinates that represent a 3-dimensional position in space. The timing of the emission and return, angle of incidence, and the exact location of the sensor as measured by the inertial measurement unit and GPS determine these spatial coordinates (Gillrich et al., 2014). Measurement accuracy can vary by sensor with a spatial resolution of 15 cm under ideal conditions and capability, but typically between 26 to 153 cm (Hodgson and Bresnahan, 2004).

Terrain information from LiDAR has been used extensively in wetland mapping (Lang et al., 2013; Wu et al., 2014; and Wu and Lane, 2016). Topography provides information on surface flow routing in the landscape and the intensity of the LiDAR returns can indicate the presence of a water body (Lang and McCarty, 2009). Wu and Lane (2016) assessed wetland extents and water storage capacities using LiDAR intensity data and digital elevation models in the Prairie Pothole Region of North America. In eastern Massachusetts, Wu et al. (2014) were able to detect potential vernal pools using Stochastic Depression Analysis. The study found 8,733 potential pools through an iterative process assessing the probability of a grid cell containing a depression. Both studies used LiDAR and aerial imagery to verify the quality of information contained in the other dataset. The LiDAR data used in this research has already shown to be effective in detecting hydric soils. Fink and Drohan (2016) used the same LiDAR dataset employed in this research to build a logistical regression model that accurately predicted 73% of the non-hydric soils and 67% of the hydric soils from their validation dataset. The topographic attributes LiDAR measures can persist through time as the vegetation in the landscape grows, is logged, or otherwise changes in a way that would traditionally affect the accuracy of using aerial imagery.

Undulating landscapes, like the Pennsylvania Ridge and Valley, have highly variable local topography. Digital elevation models are used to explain the land surface by creating terrain raster products of the primary and secondary topographic attributes. A raster is a geospatial file that contains information in a single cell arranged in a grid. Primary topographic attributes include, but are not limited to, an area's slope, elevation, aspect, plan and profile curvature, flow-path length, upslope contributing area, and catchment area. Secondary attributes are derived from two or more primary attributes. Kayastha (2013) was able to discriminate wetlands in Virginia using multiple primary and secondary topographic attributes to include; slope, aspect, plan curvature, profile curvature, topographic position index, and multiple methods of topographic wetness index. Topographic Wetness Index (TWI) is a widely used secondary attribute that considers the ways in which surface flow can accumulate in the landscape (Wilson and Gallant, 2000). Using methods described by Beven and Kirkby (1979) TWI is calculated as (**Equation.1**):

Equation. 1: $TWI=\ln(\alpha/\tan\beta)$

Where: α is the upslope contributing area in m^2, and β represents the slope in percentage

Topographic wetness index has been used extensively to map and predict soil moisture in the landscape (Buchanan et al., 2014; Grabs et al., 2009; Hofmeister et al., 2016; Kayastha, 2013; Liang and Chan, 2017; and Maduako et al., 2017). Approaches in estimating TWI diverge when the concept of upslope contributing area is considered. The formula assumes that soil transmissivity is constant so the selected flow routing method in the contributing area is important for determining the overall index value (Lang, 2013). Constraining the flow-routing methods to those available in SAGA-GIS software there are four versions of interest; flow tracing, mass-flux, recursive, and top-down (Conrad et al., 2015).

Topography significantly affects the rate and distribution of flow-routing in the landscape. The TWI has been calculated using over 400 unique formulations that consider a DEM's resolution, elevation precision, flow direction and slope equation, smoothing, and the inclusion of soil properties (Buchanan et al., 2014). Information in a DEM is stored in a gird format with values for elevation set for each cell. Estimations are calculated from grid values using two approaches, single-direction and multiple-direction (Sørensen et al., 2006). The single-direction method distributes flow from the center-cell to its downslope neighbor. The multiple-direction method, in contrast, partitions the flow value to numerous downslope cells (Erskine et al., 2006). Flow-tracing is a method that determines values on a per-pixel basis in a DEM with calculations ending when a sink or the end of the grid is encountered. Recursive flow accumulation processes flow upwards through all the connected cells until the whole DEM has been covered. The top-down approach processes the DEM downwards from the highest to lowest cell (Conrad et al., 2015). Mass-flux is a method still under development in the SAGA-GIS software that divides a grid cell into quarters to calculate flow. Slope and the interpolation of neighbor cells governs how flow is routed in the landscape (Gruber and Peckham, 2008). Software such as SAGA-GIS and ArcGIS provide users with a large toolkit to examine the topography of wetlands.

3. Materials and Methods

3.1 Study Area

The Appalachian Mountain Section (AMS) is a 11,940 km^2 geologic subdivision of the Ridge and Valley physiographic province of the Appalachian Mountains of Pennsylvania. The focus for much of the research was constrained to the AMS to address issues with data management and processing. This region resides within Major Land Resource Area 147 (MLRA), the Northern Appalachian Ridges and Valleys (USDA-NRCS, 2006). Ridge summits and shoulders are frequently underlain by resistant sandstone and conglomerate bedrock, while lower side slopes and the valleys are underlain by less resistant shale and carbonates (DCNR, 2018). Development has been limited along the ridges due to their steep relief, low soil fertility, undulating topography, and shallow soils. Higher elevation zones in the AMS are of interest because of their isolation, dominant forest cover, and abundance of headwater streams (Figure. 2). Many of the ridgelines are in public land administered by the Pennsylvania Game Commission, Bureau of Forestry, and Department of Conservation and Natural Resources. Research can be done more readily in these areas than on private property because of access.

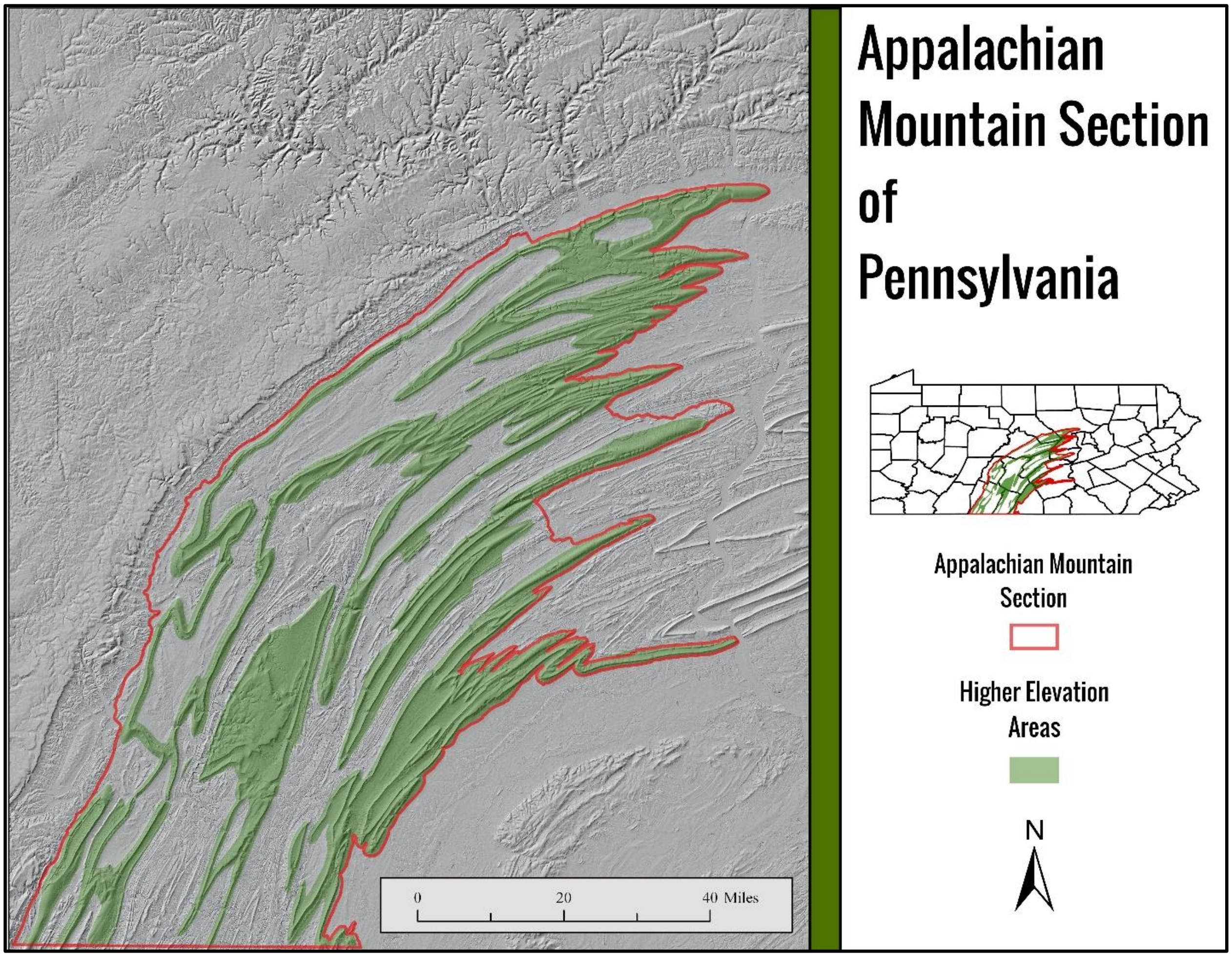

Figure. 2. Hillshade map of the higher elevation study area within the Appalachian Mountain Section of Pennsylvania.

Climatic conditions in MLRA 147 consist of an average annual temperature of 7 to 14 °C with approximately 180 days without freezing. Annual precipitation ranges from 122 to 177 cm with higher rates in the northern part of the region. Moisture and temperature regimes fluctuate throughout the resource area and are affected by elevation and latitude (USDA-NRCS, 2006). Forest structure and ecology are known to be influenced by elevation gradients and aspect (Jung et al., 2014).

In the AMS, higher elevation zones were identified using county digital elevation model (DEM) mosaics (Figure. 3) (DCNR, 2008). County elevation data was visualized using the standard deviation for symbology classes to show elevation relative to the nearby area. Higher elevation zones were manually digitized in ArcGIS Pro. The higher elevation area of interest (AOI) has constrained wetland resources along the ridgelines and a high amount of forest cover compared with the entire AMS. The percentage of forest cover was above 90% for the AOI compared to 70% for the whole AMS (Table 1) (Multi-Resolution Land Characteristics Consortium, 2011). Levels of agriculture and development were considerably lower in the AOI highlighting the impediments from the terrain and soil fertility. The NWI data for the region shows that the dominant Cowardin system wetland class present in the AOI is riverine (wetlands and deepwater habitats contained within a channel except areas with higher salinity or dominated by emergent vegetation) (Cowardin et al., 1979). In the NWI the riverine class primarily represents surface hydrology flow lines. Vernal pools are often found in saddles alongside or above headwater streams, and frequently classified as forested/shrub wetlands, the next dominant class at 17.4% behind riverine at 70.3% (Table 2).

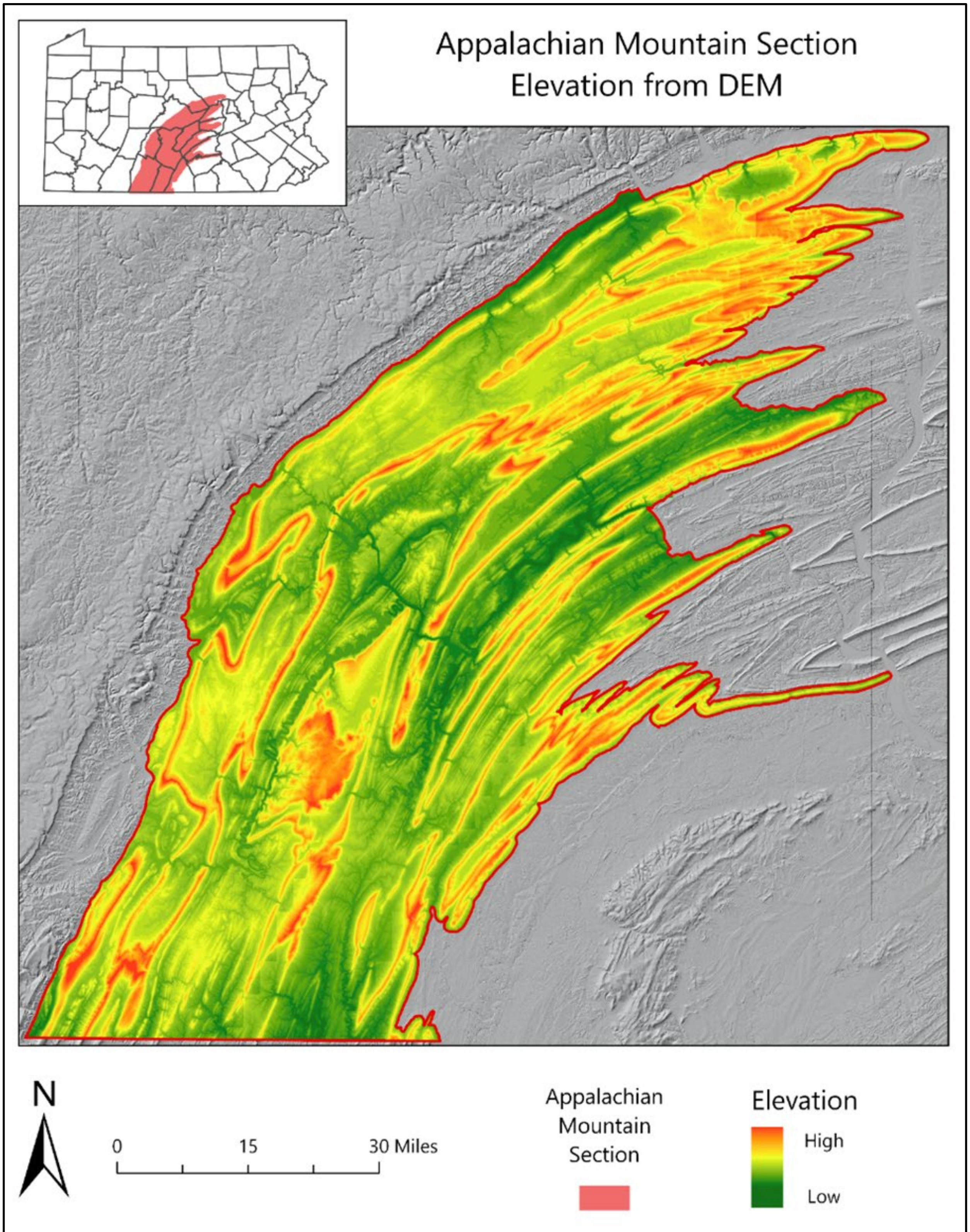

Figure. 3. Elevation data in the Appalachian Mountain Section of Pennsylvania is visualized using county mosaics of digital elevation models.

Table 1. Landcover for the Appalachian Mountain Section and the higher elevation zones from the 2011 National Land Cover Database. Classes are represented individually and in categories by their area and percent.

Landcover Class	Higher Elevation Zones Hectare	Higher Elevation Zones Percent Cover	Appalachian Mountain Section Hectare	Appalachian Mountain Section Percent Cover
Developed, Open Space	19,137	3.11%	59,647	4.98%
Developed, Low Intensity	2,437	0.40%	19,016	1.59%
Developed, Medium Intensity	510	0.08%	5,632	0.47%
Developed, High Intensity	84	0.01%	2,034	0.17%
Subtotal:	**22,167**	**3.60%**	**86,329**	**7.21%**
Pasture/Hay	21,476	3.49%	132,348	11.06%
Cultivated Crops	8,842	1.44%	102,875	8.60%
Barren Land	551	0.09%	1,094	0.09%
Subtotal:	**30,869**	**5.01%**	**236,317**	**19.75%**
Deciduous Forest	493,469	80.10%	764,377	63.88%
Mixed Forest	37,661	6.11%	47,997	4.01%
Evergreen Forest	29,927	4.86%	50,712	4.24%
Shrub/Scrub	400	0.06%	750	0.06%
Grassland/Herbaceous	575	0.09%	1,085	0.09%
Subtotal:	**562,031**	**91.23%**	**864,921**	**72.28%**
Open Water	1,002	0.16%	8,778	0.73%
Woody Wetlands	19	0.00%	209	0.02%
Emergent Herbaceous Wetlands	2	0.00%	34	0.00%
Subtotal:	**1,023**	**0.17%**	**9,020**	**0.75%**
Total:	616,090		1,196,588	

Table 2. The wetland distribution for the Appalachian Mountain Section and higher elevation zones from the 2009 National Wetland Inventory. Wetland types are listed with their count, area, and percent of total wetland resources.

Wetland Class	Higher Elevation Zones Hectare (ha)	Higher Elevation Zones Percent	Appalachian Mountain Section Hectare (ha)	Appalachian Mountain Section Percent
Freshwater Emergent	371	2.66%	810	3.80%
Freshwater Forested/Shrub	2,433	17.43%	3,469	16.27%
Freshwater Pond	522	3.74%	802	3.76%
Lake	824	5.90%	4,796	22.49%
Riverine	9,808	70.27%	11,448	53.68%
Total:	**13,958**		**21,326**	

3.2 Elevation and Ancillary Data

Table 3. The datasets used to inventory, model, and assess vernal pools in the Pennsylvania Appalachian Section of Pennsylvania.

Data	Acquisition Date	Source	Use
LiDAR DEM	2006 - 2008	Pennsylvania Spatial Data Access (PASDA)	Creating Terrain Products
National Wetlands Inventory	2009	U.S. Fish & Wildlife Service	Wetland Locations
National Land Cover Database	2011	USGS	Land Cover Assessment and Modeling
Leaf-off Orthoimagery	2003 - 2008	Pennsylvania Spatial Data Access (PASDA)	Validation of Suspected Sites
Surficial Geology	2001	Pennsylvania Dept. of Natural Resources and Conservation	Parent Material Identification
Vernal Pool Site Data	2015 - 2018	Shale Hills Critical Zone Observatory	Testing & Validation

The PAMAP program was established by the Pennsylvania government and outside collators to provide high-quality LiDAR and leaf-off orthoimagery data for entire commonwealth. These datasets are available online in an open-source repository, the Pennsylvania Spatial Data Access. LiDAR comes in a 1-meter spatial resolution and is available as; point clouds, digital elevation models (DEM), breaklines that represent an abrupt change in the land surface typically used for water and road features, and elevation contours (DCNR, 2008). Flight lines for collecting LiDAR were flown with a 30% overlap and a 1.4 m nominal average point spacing. Accuracy levels for a 95% RMSE were at least 1.5 m for horizontal and 0.2 m in open terrain for vertical (DCNR, 2008). The program has been available for several years now and has demonstrated to be reliable with substantial quality control/assurance protocols. Field verified vernal pool data was incorporated in the geospatial process for model development, validation, and reliable statistical analysis.

Field verified vernal pool data was collected initially from two undergraduate thesis in geosciences at The Pennsylvania State University. In 2016 and 2017 the inventory was expanded during summer research experiences for undergraduates at the Shale Hills Critical Zone Observatory. The field verified data was used in this research for hypothesis testing and validation. The dataset includes the locations of 190 individual vernal pools, 78 saddles with vernal pools present, and 74 saddles inspected with no vernal pools found. Basic data pertaining to site location, presence of amphibians, and whether the vernal pools were listed on the NWI was collected.

3.3 Vernal Pool Mapping and Suitability Modeling

Aerial imagery and LiDAR are often used together to identify and monitor wetlands (Faccio et al., 2016; Fink and Drohan, 2016; Gillrich et al., 2014; Lang and McCarty, 2009; Wu et al., 2014; and Wu and Lane, 2016). The methodology employed and its success depend on the wetland's physical conditions and the datasets resolution. This project mapped vernal pools using manual photo interpretation and a LiDAR based suitability model developed with verified location data. An inventory of vernal pools for the Ridge and Valley was maintained throughout the project with each observation given a level of confidence; Level 1 having been field verified, Level 2 are for pools appearing in multiple dates of imagery, and Level 3 are from a third party. Only field verified data from previous research was used to build and validate the LiDAR suitability model.

Terrain rasters used in the suitability model were created from a 1-meter DEM using ArcGIS Pro (ESRI, 2011) and SAGA-GIS (Conrad et al. 2015). The rasters were chosen based off their potential to detect the flat slope of water, sinks in surface hydrology, and other landscape morphological features indicative of a vernal pool. A total of 62 terrain rasters were chosen for testing based on these criteria (Tables 4 and 5). There were 9 terrain rasters selected from ArcGIS Pro and 53 from SAGA-GIS. Multiple topographic attributes were replicated using different methods of calculation; slope (3), aspect (3), curvature (18), flow accumulation (4), and TWI (4). When generating the 62 rasters the data size and required processing time must be considered. Creating a raster for a large area may cause the software to freeze among other issues.

Table 4. Terrain raster #1 to 31 include multiple approaches for deriving slope, aspect, curvature, and other metrics. Each tool is listed with the software used to create it and the method for its creation.

ID	Metric	Software	Method
1	Slope	ArcGIS Pro	Geodesic
2	Slope	ArcGIS Pro	Planar
3	Slope	SAGA	Zevenbergen & Thorne 1987
4	Aspect	SAGA	Zevenbergen & Thorne 1987
5	Aspect	ArcGIS Pro	Planar
6	Aspect	ArcGIS Pro	Geodesic
7	Curvature	ArcGIS Pro	General
8	Curvature	ArcGIS Pro	Profile
9	Curvature	ArcGIS Pro	Plan
10	General Curvature	SAGA	Zevenbergen & Thorne 1987
11	Profile Curvature	SAGA	Zevenbergen & Thorne 1987
12	Plan Curvature	SAGA	Zevenbergen & Thorne 1987
13	Tangential Curvature	SAGA	Zevenbergen & Thorne 1987
14	Cross Sectional Curvature	SAGA	Zevenbergen & Thorne 1987
15	Flow Line Curvature	SAGA	Zevenbergen & Thorne 1987
16	Longitudinal Curvature	SAGA	Zevenbergen & Thorne 1987
17	Maximal Curvature	SAGA	Zevenbergen & Thorne 1987
18	Minimal Curvature	SAGA	Zevenbergen & Thorne 1988
19	Total Curvature	SAGA	Zevenbergen & Thorne 1989
20	Flow Direction	ArcGIS Pro	D8
21	Wind Exposure	SAGA	Default
22	Vector Ruggedness Measure	SAGA	Circle Search Mode
23	Local Curvature	SAGA	Multiple Flow Direction
24	Upslope Curvature	SAGA	Multiple Flow Direction
25	Local Upslope Curvature	SAGA	Multiple Flow Direction
26	Downslope Curvature	SAGA	Multiple Flow Direction
27	Local Downslope Curvature	SAGA	Multiple Flow Direction
28	Topographic Position Index	SAGA	scale = 50
29	Topographic Position Index	SAGA	scale = 100
30	Terrain Surface Texture	SAGA	Resampling
31	Terrain Surface Concavity	SAGA	8 neighborhood

Table 5. Terrain raster products #32 to 62 include multiple approaches for deriving flow accumulation and TWI. Each tool is listed with the software used to create it and the method for its creation.

ID	Metric	Software	Method
32	Terrain Surface Convexity	SAGA	8 neighborhood
33	Terrain Ruggedness Index	SAGA	Circle Search Mode
34	Slope Height	SAGA	Default
35	Valley Depth	SAGA	Default
36	Normalized Height	SAGA	Default
37	Standardized Height	SAGA	Default
38	Mid-Slope Position	SAGA	Default
39	Real Surface Area	SAGA	Default
40	Multiresolution Index of Valley Bottom Flatness	SAGA	Default
41	Multiresolution Index of Ridge Top Flatness	SAGA	Default
42	Multi-Scale Topographic Position Index (TPI)	SAGA	Default
43	Protection Index	SAGA	Default
44	Positive Openness	SAGA	Default
45	Negative Openness	SAGA	Default
46	Flow Accumulation (limited slope)	SAGA	Default
47	Slope Length	SAGA	Default
48	TWI SAGA	SAGA	Default
49	Melton Ruggedness Number	SAGA	Default
50	Modified Catchment Area	SAGA	Default
51	Maximum Flow Path Length	SAGA	Default
52	LS Factor	SAGA	Default
53	Flow Accumulation (Top-Down)	SAGA	Default
54	Flow Accumulation (Recursive)	SAGA	Default
55	Flow Accumulation (Mass Flux)	SAGA	Default
56	Flow Accumulation (Flow Tracing)	SAGA	Default
57	TWI Flow Accumulation (Top-Down)	SAGA	Default
58	TWI Flow Accumulation (Recursive)	SAGA	Default
59	TWI Flow Accumulation (Mass Flux)	SAGA	Default
60	TWI Flow Accumulation (Flow Tracing)	SAGA	Default
61	Vertical Distance to Channel Network	SAGA	Default
62	Drop Raster	ArcGIS Pro	Default

Study plots were created to minimize data management issues by using the "Kernel Density" tool in ArcGIS Pro. A concern with this approach is the potential bias from spatial correlation. It was assumed that the vernal pools present in these plots were representative of those across the region. The kernel density tool calculates the density of objects found within a defined neighborhood for point or line features. Kernel density rasters were created separately for the field verified vernal pools and areas with none found. These two rasters were then multiplied together using the "Map Algebra" tool to make a density raster of both features combined. Two plots were established 65 km apart using this final raster. Sampling points were split evenly in each plot between vernal pools and terrestrial habitat (Figure. 4). Points were taken for five saddles in each plot with 72 points in plot 1 and 40 in plot 2. Boundaries for each plot were drawn to include the contributing grid cells for the sampling point to ensure the metric calculations receive the necessary information about the landscape. After generating 62 rasters for plots 1 and 2 the "Extract Multiple Values to Points" tool recorded their values into a single shapefile attribute table for the 112 sampling points.

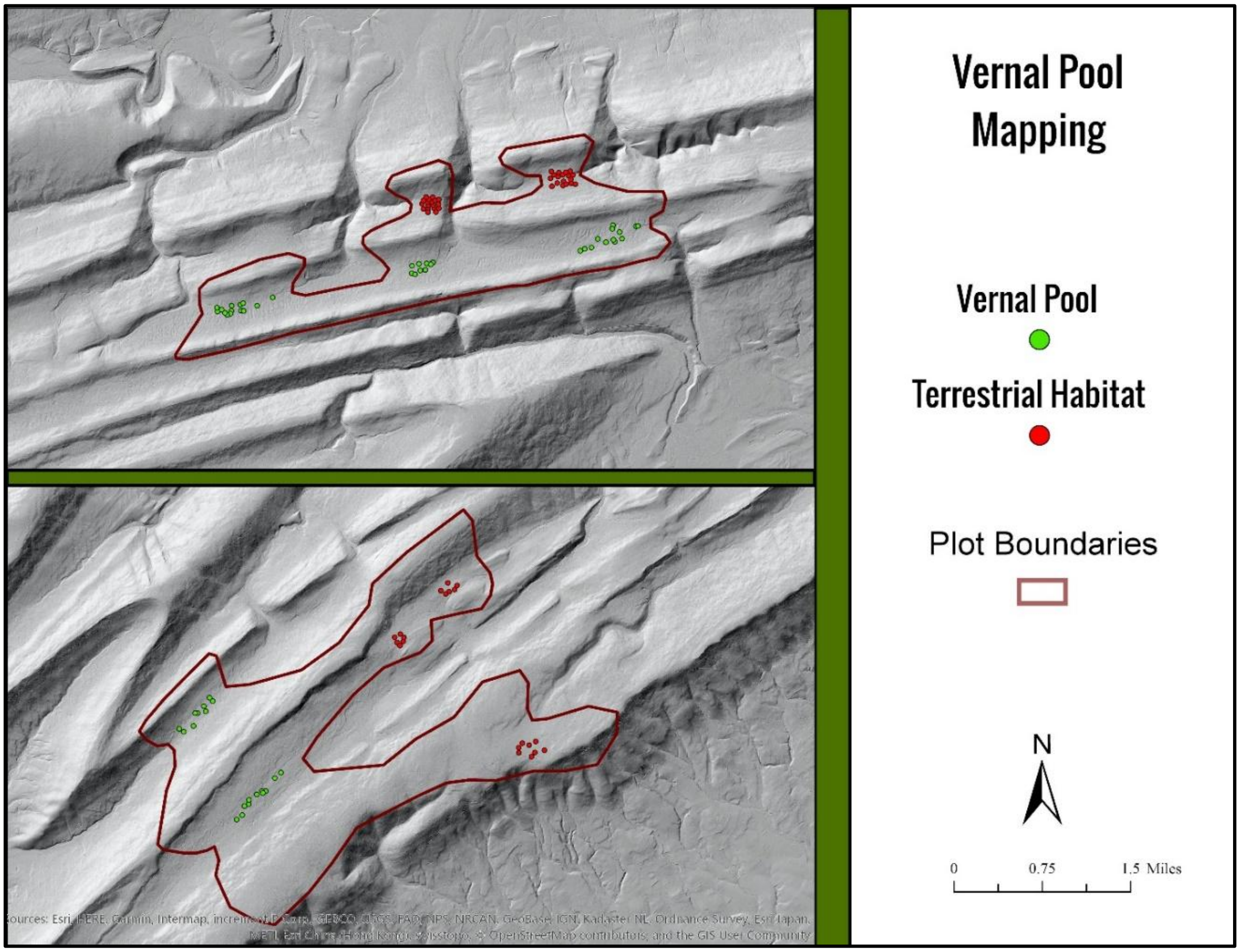

Figure. 4. A map of the plots and sampling points used to find the best terrain metrics for discriminating vernal pools in the landscape from terrestrial habitat. Sampling points were split evenly in each plot between vernal pools and terrestrial habitat. Points were established in five saddles for each plot with 72 points in plot 1 and 40 in plot 2

The .dbf file from the shapefile folder was converted into an open-source .csv table file then loaded into JMP statistical software (JMP, 2018), but R Studio an open-source statistical software, is comparable (RStudio Team, 2015). Statistical analysis yielded four significant variables to use in a vernal pool suitability model. The entire workflow of metric selection, model development, and validation is shown in Figure. 5. The validation process used was done over three plots with 60 sampling points split evenly into three categories; verified vernal pools, vernal pools observed from aerial imagery, and terrestrial (non-wetland) habitat (Figure. 6).

Reliable manual photo interpretation will share the same characteristics of sampling points from field validation. This process (Figure. 5) helps to distinguish between wetlands and terrestrial habitat, but it does not fully explain the landscape variables that can predict vernal pools.

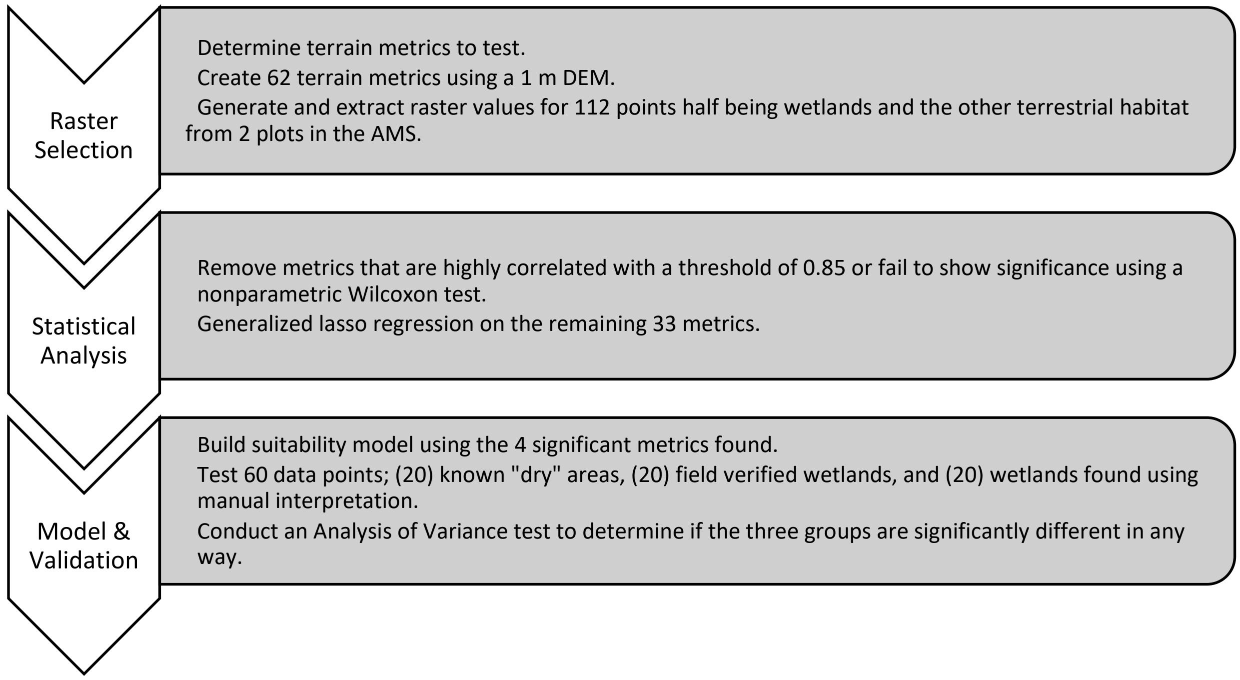

Figure. 5. Workflow for the LiDAR suitability model development and validation. The process is broken down into three parts; raster selection, statistical analysis, and model development and validation.

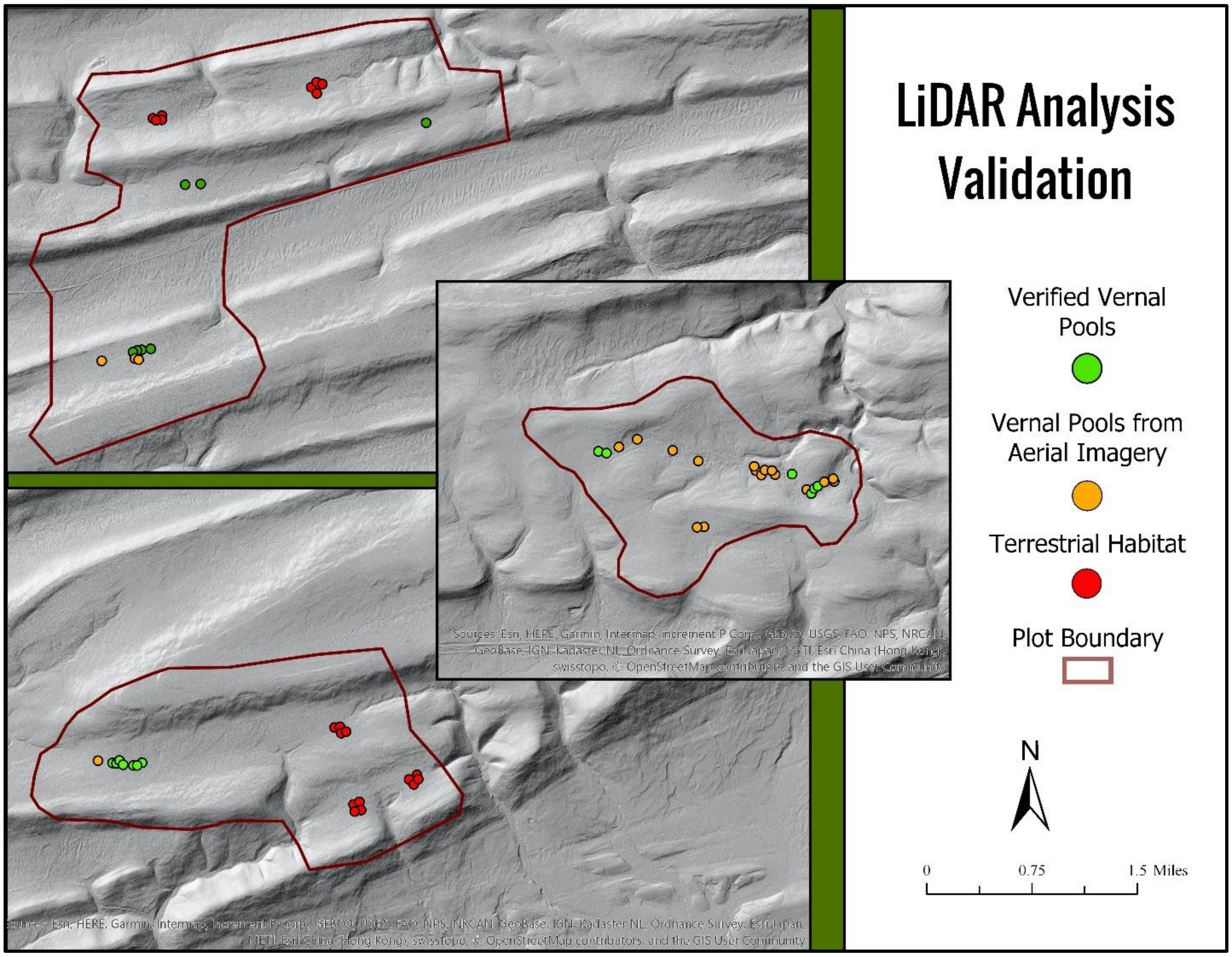

Figure. 6. A map of the three validation plots and sampling points for the LiDAR suitability model. Three categories of sampling points were used to test if vernal pools would be different than terrestrial habitat and to determine the reliability of photo interpretation.

3.4 Vernal Pool Geomorphology

Vernal pools occur across the AMS under natural and manmade conditions. The distribution of natural vernal pools can be predictable when considering their geomorphologic position, the regional legacy of periglacial climates, and lithology. Knowing the landscape positions and conditions common to vernal pools can save resources by helping field surveying target specific areas before a visit. Elevation and landscape information was collected using LiDAR and USGS topographic base maps in ArcGIS Pro (ESRI, 2011). Vernal pools were found to frequently occur in saddle positions among the ridgelines during previous research with the Shale Hills Critical Zone Observatory. Saddles are relatively flat areas between two parallel ridgelines and the start of headwater streams. Field verified data was used to identify 80 saddles throughout the region with sample locations split evenly between those with vernal pools and terrestrial (non-wetland) habitat. Saddles with extensive development, like a major highway, were excluded to prevent bias from anthropogenic disturbance in the analysis.

Thirteen variables were measured manually or observed in LiDAR hillshade for each saddle using ArcGIS Pro. The variables selected were based upon their potential relation to ground and surface hydrology, evidence of permafrost features, thermal loading, and the general physical dimensions of a saddle. Permafrost legacies were recorded when (1) solifluction related features were observed in the hillshade LiDAR. Solifluction lobes are readily apparent using LiDAR hillshade and appear as long running elevated mounds in the landscape running perpendicular to the gradient. Surface hydrology was measured from its start near the saddle to the point of becoming a 2^{nd} order stream by the (2) longest and (3) shortest reaches. Elevation data was collected for the (4) saddle, (5) highest and (6) lowest ridges perpendicular to the saddle, and the (7) difference between the saddle and highest ridge. The azimuth of the (8) highest and (9) lowest ridgelines can affect the incoming solar radiation for a saddle. Physical measurements of the saddle include the (10) distance between the summits of the two parallel ridgelines, saddle (11) width and (12) length, and the (13) saddle area (Figure. 7). Saddle lithology was evaluated for each saddle for a general idea of conditions, but was not statistically assessed because of reliability concerns with the data source. Field surveys were done in combination with the geospatial analysis. Site conditions pertaining to soils, hydrology, and vegetation were recorded to guide the geospatial process and establish a baseline of vernal pools site characteristics within the AOI.

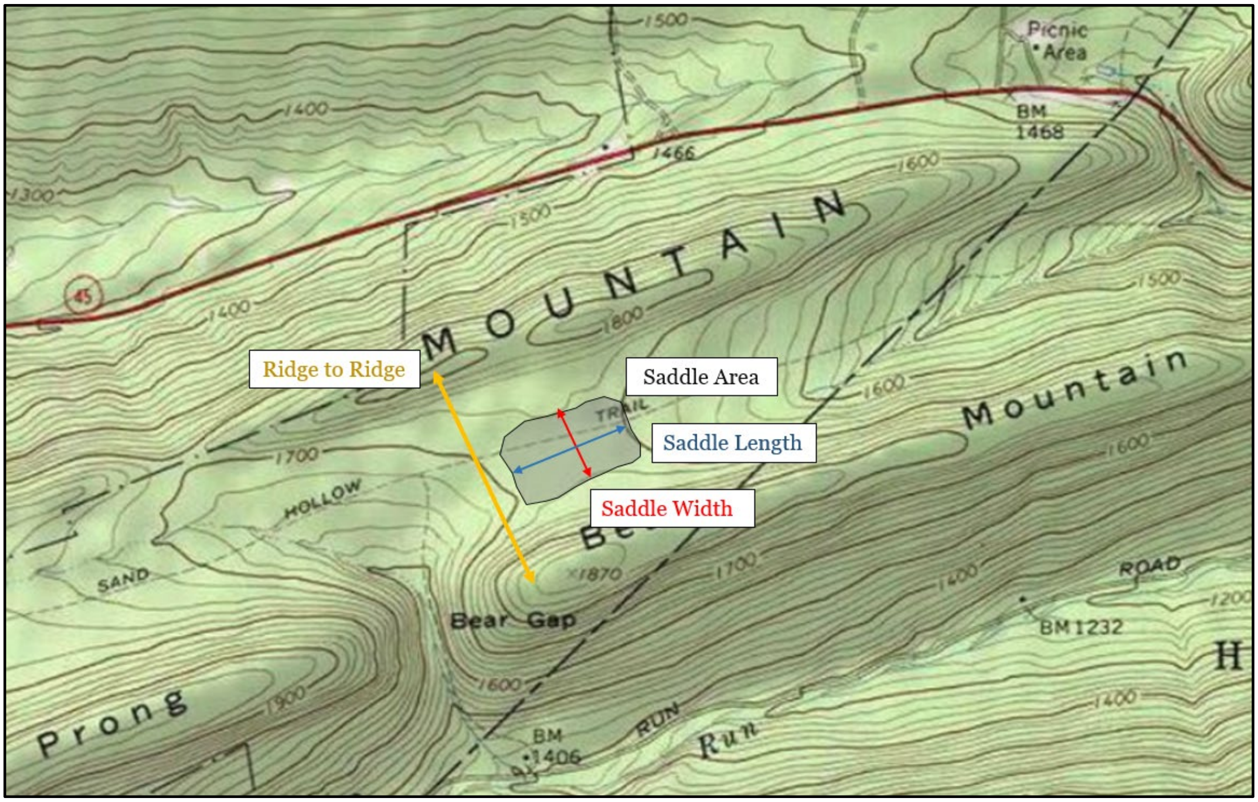

Figure. 7. Physical measurements of a saddle to include (10) the distance from ridge to ridge, saddle (11) width and (12) length, and the area (13) (ESRI, 2011).

3.4.1 Wetland Surveys

Vernal pools were surveyed across the higher elevation AOI with some criteria for site selection. Accessibility and hiking safety were concerns so only sites on public land and within 4 km of a drivable road were chosen. Beyond these conditions 36 vernal pools were selected at random from a list of verified locations and potential pools found in aerial imagery (Figure. 8). Sampling took place from the beginning of June until the start of December 2018 to provide a seasonal perspective, but this did limit amphibian observations for the later dates.

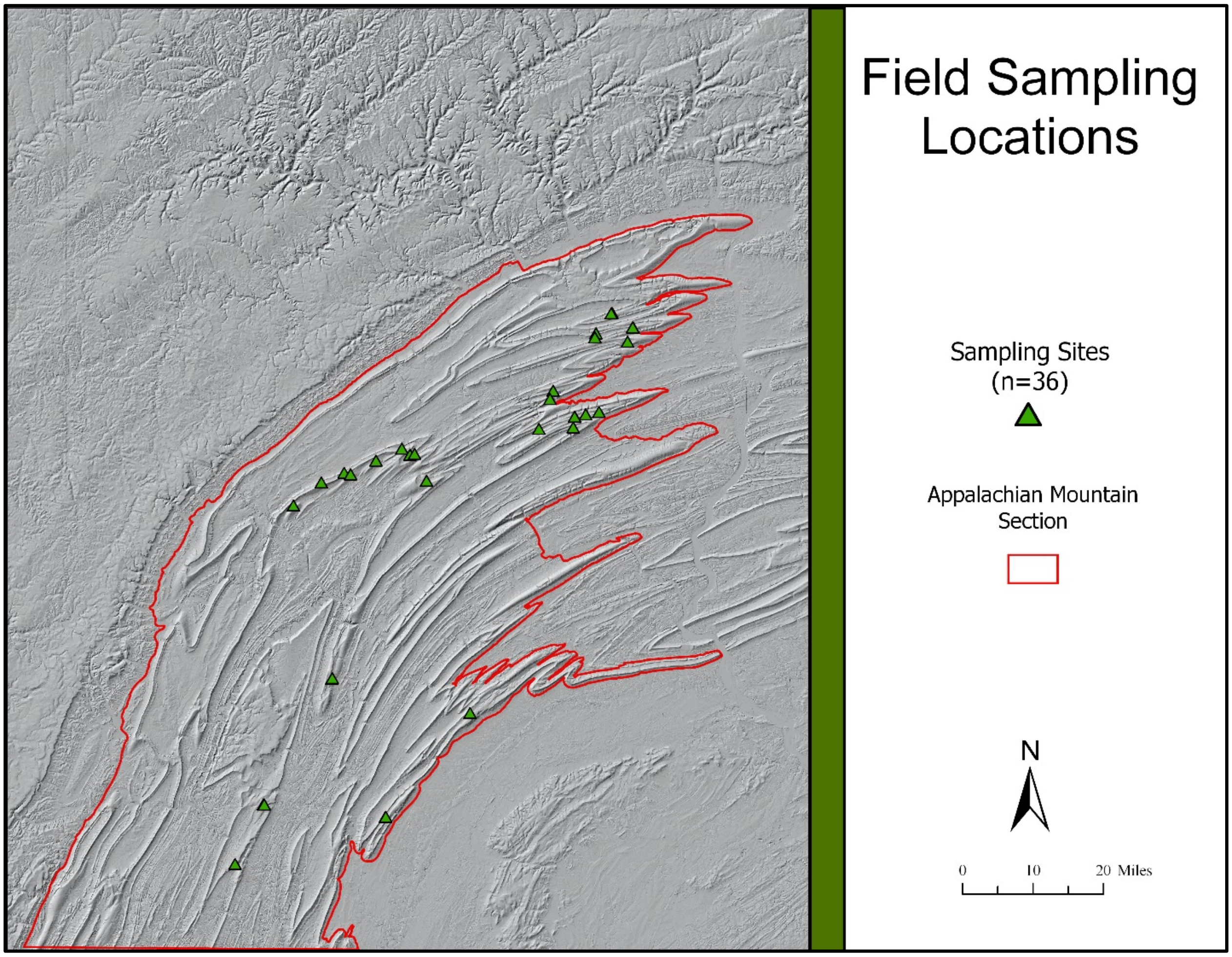

Figure. 8. Sampling locations (n=36) for vernal pools in the Appalachian Mountain Section of Pennsylvania. Sites were surveyed to establish a baseline of soil, vegetation, and hydrologic conditions.

Wetland surveys were done with guidance from the U.S. Army Corps of Engineers Eastern Mountains and Pediment Regional Supplement (USACE, 2012) and the NRCS Hydric Soil Handbook (USDA-NRCS, 2010). The USACE regional manual provides detailed information for the classification and delineation of wetlands. Procedures are covered to evaluate hydrophytic vegetation, soil, and hydrologic variables. Detailed hydric soil indicators and techniques for identification are given in the NRCS handbook.

Vernal pools play significant roles in amphibian reproduction, macroinvertebrate habitat, and sustenance for terrestrial species. Biological information was collected for each site to provide a representative picture of the ecological services and functions throughout the region. Forest cover around a pool provides nutrient input and can hinder its identification from remote sensing. Tree species and local dominance was recorded along with percent openness of the canopy by visual inspection. The purpose of the vegetation survey was not for jurisdictional determination, but for the understanding of what species are present and their potential for modeling using hyperspectral imagery in the future. Fauna was documented for the presence of amphibians in any stage of development and macroinvertebrates. Biologic factors were sampled before the soils to limit turbidity in the wetland.

Soils were sampled in the vernal pool basin by first using a soil probe to determine the variation in texture and color. A hand-auger was used to sample down to a depth of 1 m or to the point of refusal in a representative area. Contents from the auger were laid out in sequence and described by their matrix color, redoximorphic features, texture, lithochromic coloring, depth to weathering rock fragments, and any observations of buried carbon. Textures were described using the NRCS "Texture by Feel" flowchart to maintain consistency in sampling (Thien, 1979).

Hydrologic information was collected by identifying the primary and secondary hydrology indicators present using the USACE wetland delineation form (USACE, 2012) from onsite inspection and/or aerial imagery. Primary indicators are stand-alone evidence and two or more secondary indicators are needed to reliably indicate that wetland hydrology is present.

3.6 Statistical Analysis

Statistical analysis for this research was developed and implemented through collaboration with the Virginia Tech Statistical Applications and Innovations Group. JMP statistical software was used for the entire project because of its familiarity (JMP, 2018). A reliable statistical analysis was developed by approaching each component of the project separately; geospatial modeling and an assessment of the geomorphology.

The LiDAR based suitability model went through multiple layers of statistical analysis and adjustment to be separated into three components; variable screening, selection, and model validation. The start of this process began with 62 raster values for 112 sampling points that were evenly split between terrestrial habitat and vernal pools. Terrain metrics were eliminated in a stepwise process. A correlation matrix was used with a threshold of 0.85 to screen for variables with high correlation. Those exceeding the threshold were then compared using a Wilcoxon signed rank test to determine which was the most significant. The remaining metrics then underwent variable selection using a generalize lasso regression. This technique has shown to be effective in selecting environmental variables (Zeiger and Hubbart, 2018; Huang et al., 2010; Yue and Loh, 2015). Lasso regression is a powerful nonparametric approach because it shrinks the effects of non-significant variables to find the few that have the most influence (Tibshirani, 1996). Four terrain metrics remained after this step to move forward with model development and validation.

When terrain metrics are produced their values are often very different from one another in scale and meaning. One of the four metrics recorded values in an 8-bit digital number while another gave a metric-specific index value. All four terrain metrics were normalized for comparison between a value of 0 and 1. A suitability model was built to maximize the separation between vernal pools and terrestrial habitat in a way that is repeatable by environmental managers. The final terrain rasters were generated and put in to an equation using the "Map Algebra" tool in ArcGIS Pro. Values were then extracted for each sampling point and loaded into JMP. An analysis of variance (ANOVA) and Tukey's Honest Significant Difference test were used to determine significant differences and separation between the two vernal pool groups and terrestrial habitat. Normality assumptions were evaluated using normal quantile plots for each of the 3 sampling point types.

In the geomorphology assessment, variables recorded for each of the 80 sites were put through a similar process as the suitability model. Variables were first screened for correlation then analyzed using a generalized lasso regression. A 14th factor concerning lithology was evaluated using just a box-and-whisker plot to understand how vernal pool frequency related to geology due to concerns over data accuracy. Development of the statistical approaches used showed and supported the iterative nature of combining geospatial data and an understanding of landscape morphology.

4. Results and Discussion

4.1 Vernal Pool Mapping

The extent of the suitability modeling and geomorphology assessment was limited to just the higher elevation zones within the AMS, but any vernal pools observed in the entire Ridge and Valley was compiled into a master shapefile and given a level of confidence. There were 1011 pools found in the Ridge and Valley; 224 field verified (Level 1), 774 from photo interpretation (Level 2), and 13 from a third party (Level 3). Of the 1011 vernal pools identified, only 477 were listed on the NWI. In the higher elevation AOI 733 vernal pools were identified. The spatial density of vernal pools in Figure. 9 reflects locations that were investigated and not necessarily their natural distribution. The LiDAR suitability model could potentially expand this inventory if applied to the entire Ridge and Valley.

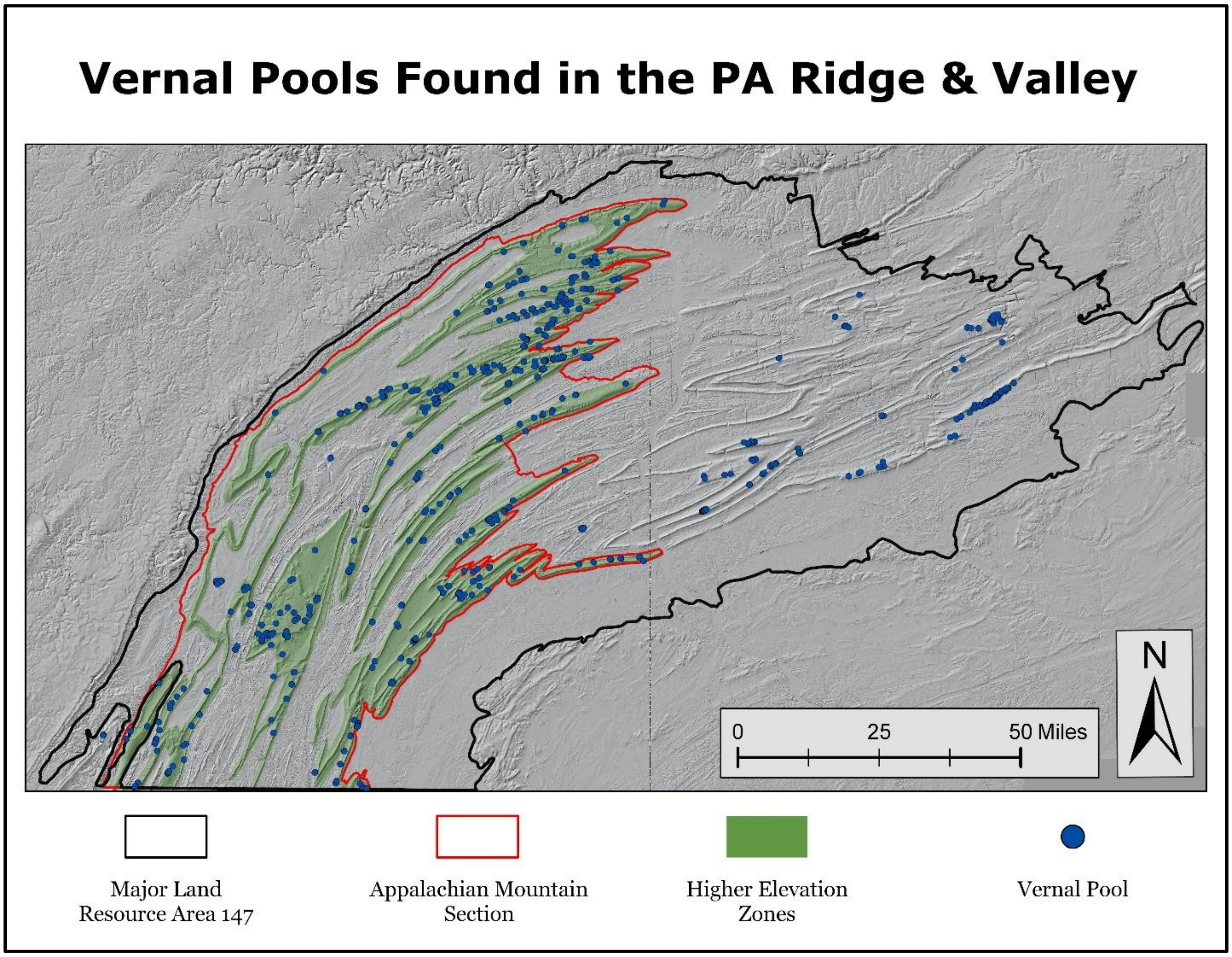

Figure. 9. A map of the 1011 vernal pools found in the Pennsylvania Ridge and Valley. The AMS geologic subdivision and higher elevation AOI is shown as well.

4.1.1 Suitability Modeling

Four metrics were found to be significant from the stepwise statistical process using screening and variable selection with a generalized lasso regression. These include a (1) modified wind exposure under default software settings ($\chi 2 < 0.0001$), (2) terrain surface convexity using an eight neighborhood cell distribution ($\chi 2 = 0.0005$), (3) topographic position index (TPI) with a scale set to 50 ($\chi 2 = 0.1029$), and (4) the multiresolution index of valley bottom flatness (MRVBF) ($\chi 2 = 0.0316$). The wind exposure tool was modified because it only incorporates terrain and not the influence of vegetative cover. The metric provides a dimensionless index with values above 1 being exposed to wind and below being shadowed. Terrain surface convexity yields positive values for convex surfaces and negative for concave features. Topographic position index is the representation of a central pixel compared with the mean of its nearby neighbors. Multiresolution index of valley bottom flatness is valuable in mapping depositional areas because it identifies valley bottoms (Conrad et al., 2015). The raster values for the four terrain metrics were normalized and displayed as box and whisker plots to determine the separation trends between the terrestrial habitat and the wetland groups (Figure. 10). Vernal pool groups had lower values for wind exposure, TPI, terrain surface convexity, but higher values for MRVBF. An equation was put together using the box and whisker plots to maximize separation and produce a suitability equation. The intention was to make this repeatable by environmental managers, but the model could be improved with advanced mathematical analysis. The suitability model will produce higher values for areas likely to be terrestrial habitat and lower values for likely vernal pools (**Equation. 2**):

Equation. 2: Suitability = (TPI +Wind Exposure + Terrain Surface Convexity) – MRVBF

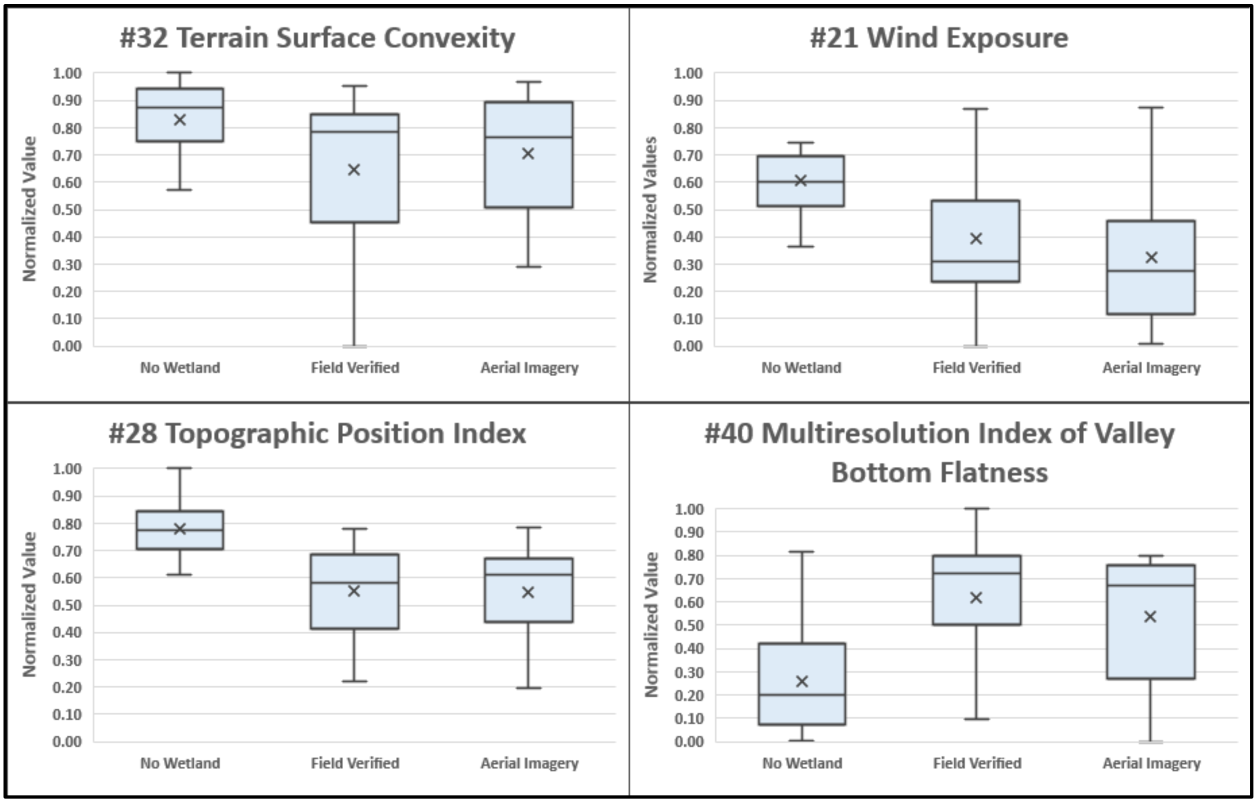

Figure. 10. Box and whisker plot of the normalized values of terrain surface convexity, wind exposure, topographic position index, and the multiresolution index of valley bottom flatness. The mean values for each group are shown with an X.

The model was validated using 60 sampling points consisting of three categories. The ANOVA determined there was an overall significant difference between the classes (Figure. 11). Tukey's Honest Significance Difference test determined differences between each of the classes. Manual photo interpretation was found not to be significantly different in the model response than the field verified vernal pools. Between the two classes of vernal pools there was no significant difference with $\chi 2 = 0.9164$. When each vernal pool class was compared with terrestrial habitat there was a significant difference with $\chi 2 < 0.0001$. The normal quantile plot shows that the sampling points follow a normal distribution. The results of the metric selection, model development, and validation show that LiDAR derived terrain metrics are effective in discerning vernal pools from terrestrial habitat.

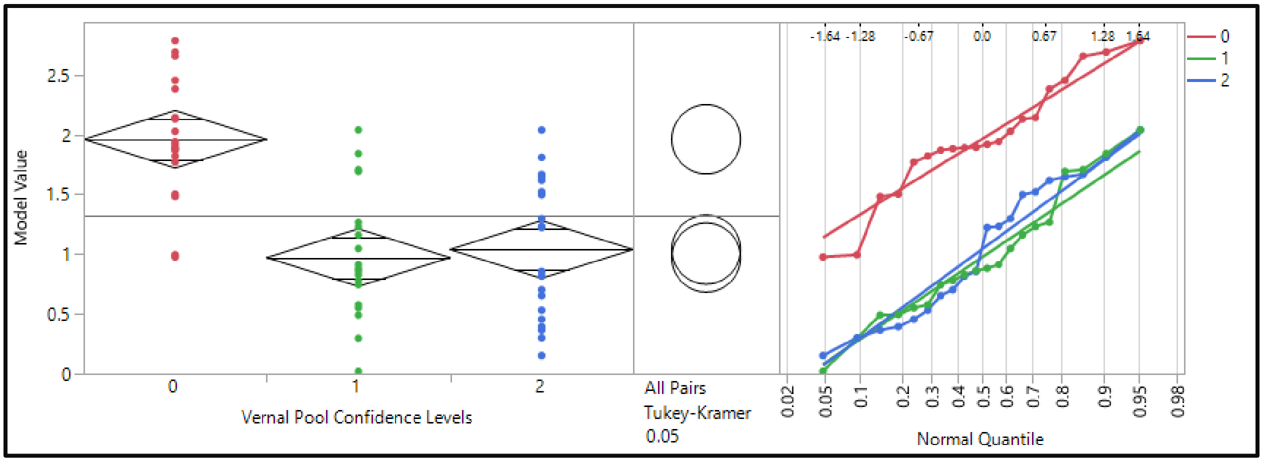

Figure. 11. Graph of ANOVA and contrast results for three groups for model validation; 0 for terrestrial habitat, 1 for field verified wetlands, and 2 for wetlands observed in aerial imagery.

The development and validation of this model was done through a mixture of open-source and commercial software. The suitability model was effective, but there are significant sources of error that could be improved upon. Higher resolution LiDAR and a better mathematically-developed suitability equation could further improve accuracy. Separating and discerning vernal pools will always have some limitations via using remote sensing because of dense evergreen cover and their small size. The mapping approaches used in this research can all be accomplished with free software, which is important for organizations operating under limited fiscal resources.

4.2 Vernal Pool Geomorphology

Vernal pools were found to occur frequently in saddles with specific lithologic and geomorphological attributes. The surficial geology of all 1011 wetlands inventoried was gathered using the statewide geology shapefile, which does have considerable error. Geology information was created on a landscape scale so the frequency of vernal pools per lithology type should be viewed as a generalization and not an exact distribution; 471 on sandstone, 342 on shale, 53 on quartzite, 68 on limestone, 39 on calcareous shale, 29 on dolomite, and one on an argillaceous sandstone. The localized presence of shale inclusions along mapped sandstone units should be studied further in-situ. Vernal pool abundance with relation to surficial lithology was displayed via box and whisker plots for the 80 saddles selected (Figure. 12). It appears that vernal pools can form with varying frequency on different lithologies, but when over shale, there is a considerable increase in abundance. The shale formation, structure, and depth of overlain unconsolidated material needs to be evaluated using field analysis to better understand vernal pool hydrology. Multiple shale saddles had 10 or more vernal pools creating complex wetland systems above or directly alongside the start of the headwater hydrology. Lithology seems to shape the magnitude of vernal pool occurrence, but the geomorphology of a saddle attests to the potential for occurrence.

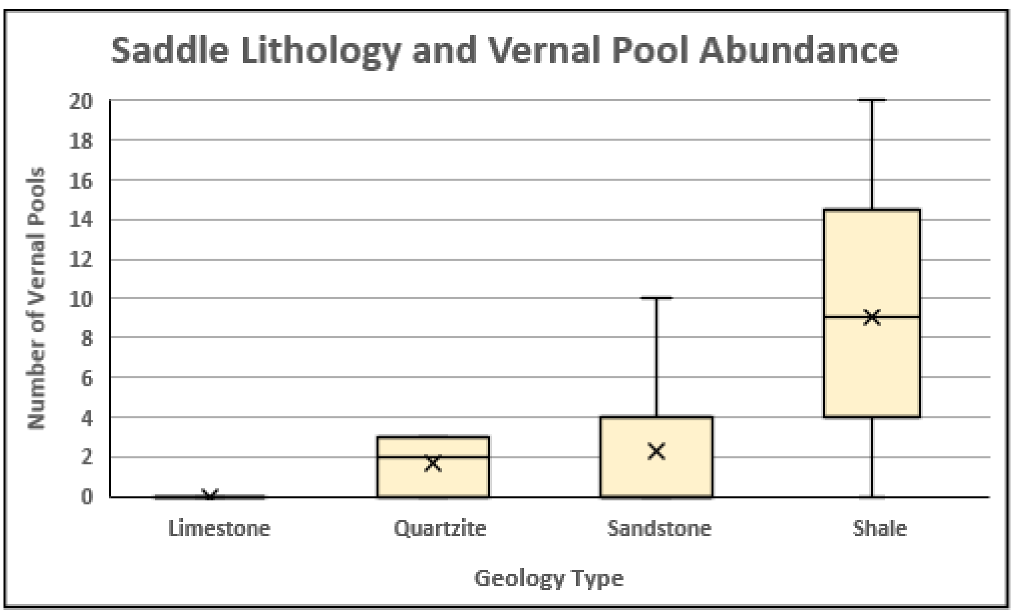

Figure. 12. The number of vernal pools in a single saddle according to the sites lithology for 80 saddles in the Appalachian Mountain Section.

Three variables were found to be significant using a generalized lasso regression for selection, with two related to the physical dimensions of the saddle and the third associated with legacy periglacial soil processes. The saddle area was found to be significant ($\chi 2 < 0.0001$) with more vernal pools expected as the saddle area increases (Figure. 13). Vernal pools range in size, but surface area differences are not dramatic with an average of 420 m^2. Larger saddles can support 10 to 20 vernal pools, which are often aligned in a near linear path between the two headwater streams. The distance between the summits of the two parallel ridgelines ($\chi 2 = 0.0154$) is an important feature when considering vernal pool hydrology. This distance reflects the catchment area that can feed surface and ground water to the vernal pool. Vernal pools appear to occur most often when the distance is between 0.6 and 1.5 km (Figure. 14). The effect of periglacial related solifluction ($\chi 2 < 0.0001$) was observed throughout the region during photo interpretation and in the statistical analysis. Vernal pools were often found right along periglacial features in a saddle or along the hillside (Figure. 15). When solifluction is present vernal pools are more likely to occur (Figure. 16). The accompanying field surveys provide a regional baseline of site physical conditions.

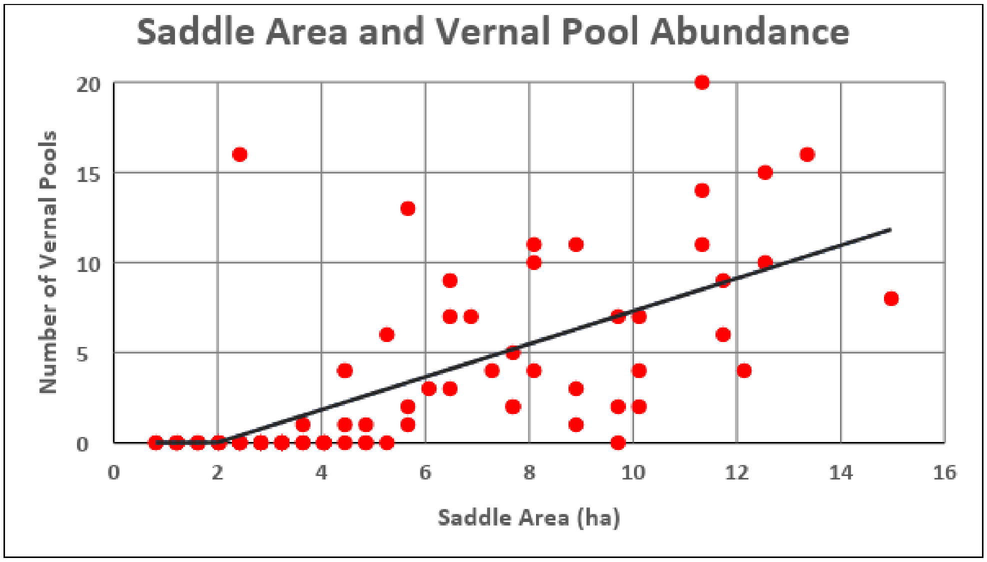

Figure. 13. The distribution of vernal pools according to the saddle area for 80 sites. A linear trend line shows that as area increases so does the frequency of vernal pools.

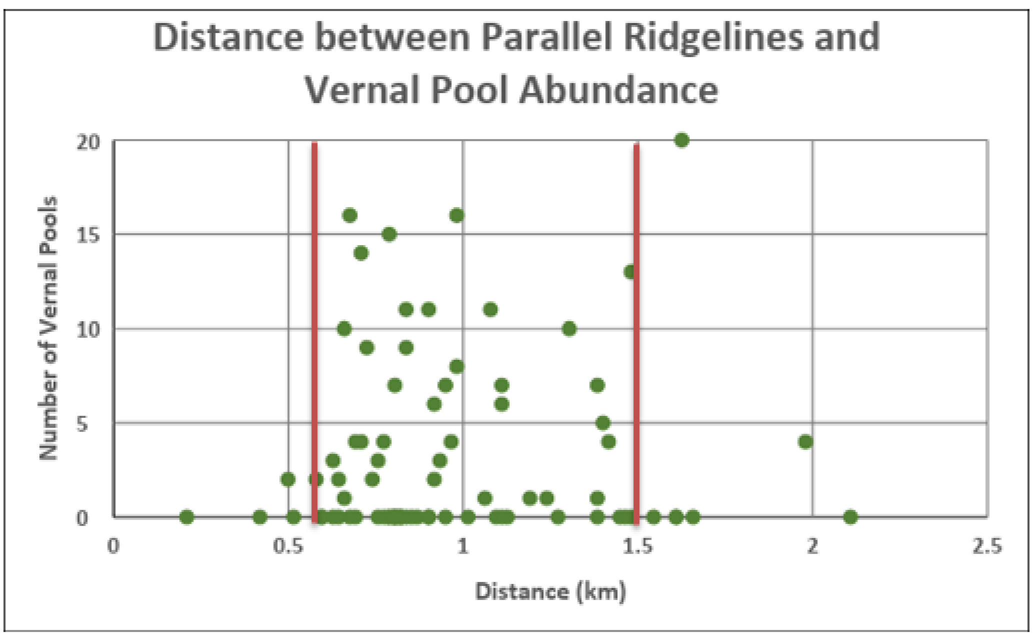

Figure. 14. The distribution of vernal pools by the distance between the summits of parallel ridgelines. Vernal pools appear to occur more often when this distance is between 0.6 and 1.5 km.

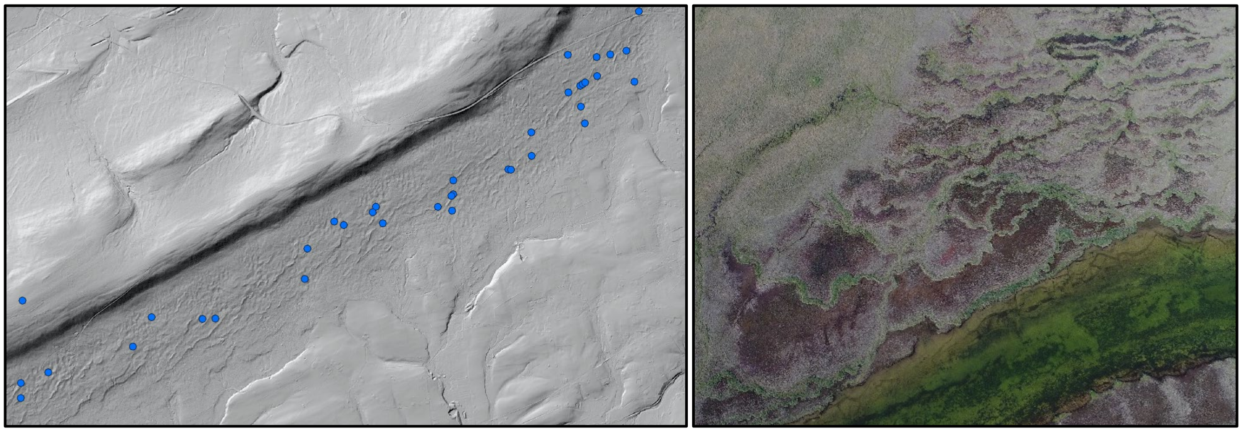

Figure. 15. An image of solifluction along a hillside in Pennsylvania (a) using LiDAR hillshade compared with an image of solifluction taken in Alaska (b) along the Dalton hwy. Dots in image (a) represent vernal pools and can be seen occurring right along the solifluction.

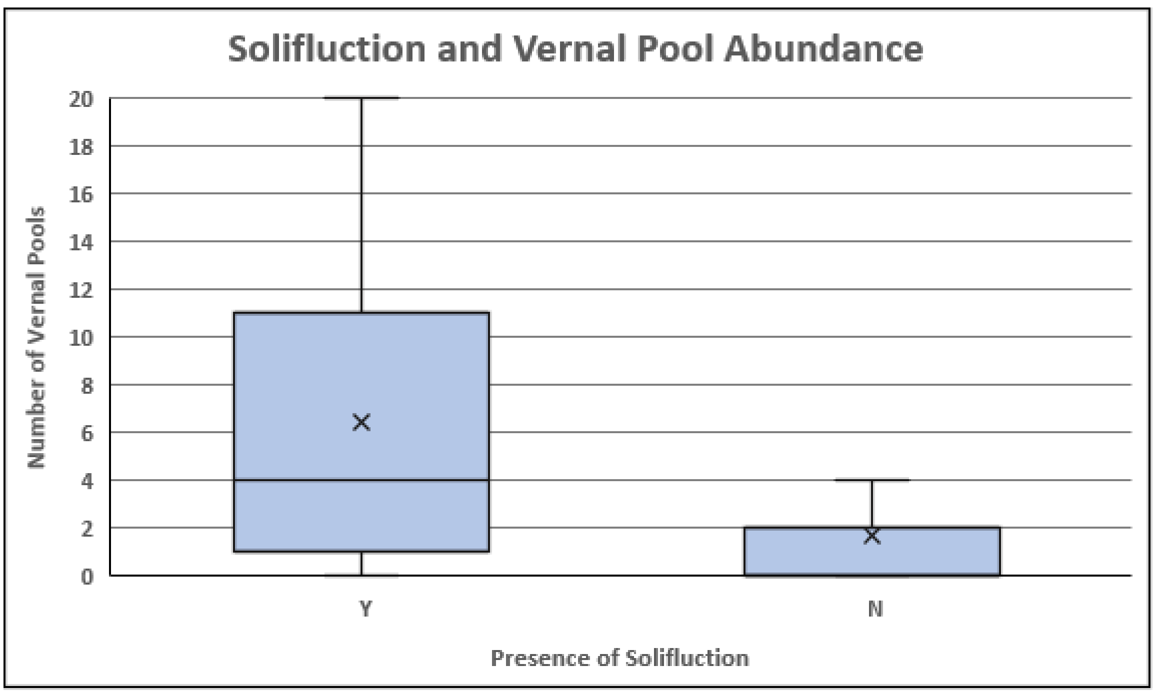

Figure. 16. A box and whisker plot of the distribution of vernal pools in the presence of solifluction. Wetland frequency increases when solifluction is observed.

4.2.1 Wetland Surveys

Vernal pool services and functions are unique in the upland terrestrial habitat. The 36 sites surveyed were chosen to reflect the variation in these ecological roles to gain a regional baseline of vernal pool characteristics. A total of 16 tree species were observed with a dominant presence of blackgum (*Nyssa sylvatica L.*), red maple (*Acer rubrum L.*), and sweet birch (*Betula lenta L.*). Every site except one had blackgum present, which could be used in suitability modeling if high spatial-resolution hyperspectral imagery were available. Canopy openness was estimated to be 36% on average, illustrating the difficulty of finding these wetlands without leaf-off imagery. Fauna for each wetland was noted through observations, but this data is not fully reflective of actual abundance because amphibians can be difficult to find and some pools were surveyed outside of the normal amphibian breeding season. Half of the 36 vernal pools were found to have amphibian egg masses, tadpoles, salamanders, and/or multiple macroinvertebrate species. An accurate survey of vernal pool fauna must coincide with the specific phenophase in which organisms use the habitat.

Hydrology is a key factor governing the biology of vernal pools and was assessed using USACE hydrology indicators (USACE, 2012). A total of 258 primary and 98 secondary indicators were observed. The three most common were **A1** surface water (primary), **D2** geomorphic position (secondary), and **C4** presence of reduced iron (primary). The presence of surface waters (**A1**) was typically the first indicator observed when approaching a site. Many pools stayed inundated throughout the season with only three observed dry during mid-July. According to the National Climatic Data Center the precipitation for Pennsylvania during 2018 was 66 cm above average. Inundation levels naturally vary from year to year and are reflective of precipitation patterns. Vernal pools are depressional wetlands (**D2**) by nature. Of the 200 sites I have personally visited for field validation, vernal pools were observed to be shallow elliptical basins with a depth between 0.5 to 1.5 m below the basin rim. The presence of reduced iron (**C4**) in the uppermost 30 cm was found in 33 sites by observing a change in soil color after exposure to the atmosphere. The seasonal inundation of vernal pools appears to cause high amounts of variation in redoximorphic features throughout the soil profile. Unlike wetlands that stay inundated all year vernal pools experience extended dry periods during the summer. During these periods, oxygen can permeate the soil profile allowing for the re-oxidation of iron and formation of concentrations and other redoximorphic features.

Soil descriptions were made at each wetland to a depth of 1 meter or the point of auger refusal by unconsolidated rocks or bedrock. Auger refusal limited describing soils for two of 36 sites at 50 cm, 11 of 36 at 75 cm, and 21 of 36 at 100 cm. Weathered colluvium increased substantially at depth and included different rock types. Dark red lithochromic coloring was frequently observed with colors such as 10 R 4/8 and 10 R 5/4. Lithochromic coloring was observed in areas with weakly cemented or completely weathered sandstone material. The depth to rock fragments ranged from 3 to 81 cm with an average of 40 cm. There were three sites that no rock fragments were encountered. The most common soil textures were sapric organic at 0 cm, clay loam at 25 and 50 cm, sandy clay loam at 75 cm, and clay loam at 100 cm (Table 6). Soil matrix and redoximorphic colors were collected and are listed in Tables 7 and 8 in the Appendix. The surrounding ridgelines were primarily composed of sandstone. The deposition of loess and finer materials into basins occurred because these features occupy the lowest position in the landscape (Rheinhardt and Hollands, 2007). As finer materials collect in the basin, permeability is reduced and is further magnified when on shale lithology.

Table 6. Soil texture for all 36 sites to a depth of 1 meter or auger refusal.

Soil Texture, depth in cm																					
Site	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
1	O	O	O	O	O	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
2	O	O	O	O	O	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL
3	O	O	O	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL
4	O	O	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal
5	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
6	O	SCL	SCL	SCL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
7	O	O	O	O	O	O	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	L	L	L
8	O	O	O	O	O	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SCL	SCL	SCL	SCL	SCL	SCL
9	O	O	O	O	CL	CL	CL	CL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL
10	O	O	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
11	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
12	O	O	O	CL	CL	CL	CL	SL	SL	SL	SL	SL	SL	SL	SL	SL	Refusal	Refusal	Refusal	Refusal	Refusal
13	O	O	O	O	SCL	SCL	SCL	SCL	SL	SL	SL	SL	SL	SL	SL	SL	SL	Refusal	Refusal	Refusal	Refusal
14	O	O	O	SiL	SiL	SiL	CL	CL	CL	CL	CL	CL	CL	CL	CL	SCL	SCL	Refusal	Refusal	Refusal	Refusal
15	O	O	O	O	SiL	SiL	SiL	SiL	SiL	SiL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	Refusal	Refusal	Refusal
16	O	O	O	O	O	O	SL	SL	SL	SL	SL	SL	SL	SL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
17	O	O	CL	CL	CL	CL	CL	CL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	Refusal	Refusal	Refusal	Refusal	Refusal
18	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL
19	O	O	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	Refusal	Refusal	Refusal
20	O	O	O	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL
21	O	O	O	O	O	CL	CL	CL	CL	CL	C	C	C	C	C	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
22	O	O	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	C	C	C	C	C	C
23	SL	SL	SL	SL	SL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
24	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL
25	O	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL
26	O	O	O	LS	LS	LS	LS	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
27	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
28	O	O	O	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SCL	SCL	SCL	SCL	SCL
29	O	O	O	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SiCL	SL	SL	SL	SL	SL	Refusal	Refusal	Refusal	Refusal	Refusal
30	O	O	O	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SL	SL	SL	SL	SL	SL
31	O	O	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL	SL
32	O	O	O	CL	CL	CL	CL	CL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	SCL	Refusal	Refusal	Refusal	Refusal
33	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
34	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	C	C	C	C	C	C	C	C	C	C
35	O	O	O	O	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal	Refusal	Refusal
36	O	O	O	O	O	O	SiCL	SiCL	SiCL	SiCL	SiCL	CL	CL	CL	CL	CL	CL	CL	Refusal	Refusal	Refusal

5. Conclusions

Vernal pools are a dominant wetland class in the higher elevations of the Pennsylvania Appalachian Mountain Section of the Ridge and Valley province. Their presence is critical for amphibian reproduction and supporting terrestrial trophic levels. A comprehensive inventory and understanding of vernal pool geomorphology will give future research the methods and locations to study vernal pools in greater detail.

The value of vernal pools become readily apparent in spring as they are teeming with amphibian and other wetland dependent fauna. Protecting vernal pools starts with first detecting them in the landscape using GIS and field surveying. The benefits of how this project approached inventorying and assessing vernal pools comes from the open-source nature of the data and software. The steps laid out in the methodology can be repeated by conservation groups and land managers with a reasonable understanding of geospatial data and software. As remote sensing data improves in resolution and access, many more vernal pools will be added to the more than 1,000 found in this study.

Objectives were met for modeling suitable areas for vernal pools to occur in the landscape and assessing their geomorphology. The alternative hypothesis was accepted for the suitability modeling because four terrain metrics were found to be significant in discerning vernal pools from terrestrial habitat. The alternative hypothesis was also accepted for the geomorphological assessment since three variables were found to predict the presence of vernal pools.

The results of the project help explain the factors that caused vernal pools to form in the AMS. The geomorphology along the ridgelines, past periglacial climate, and underlying shale lithology cause vernal pools to form in predictable locations. Evidence from this research shows that the legacy of periglacial features and the undeveloped nature of the ridgelines have allowed vernal pools to persist throughout time. Solifluction and other ice formations occur frequently throughout this region, which has undergone repetitive periglacial climates. Many vernal pools were found residing right along these features and when combined with shale lithology their frequency increases dramatically. The prevalence of periglacial features alongside vernal pools should be further examined proceeding south along the Ridge and Valley to see how far and to what magnitude this legacy extends.

Results from this research shed just a glimpse of the distribution and diversity of vernal pools along the Ridge and Valley. Further research needs to be conducted to better inventory vernal pools along with studying their formation. Most importantly, federal and state laws must be changed to effectively conserve vernal pools that function as biological refuges and reside at the origin of surface hydrology with unknown impacts on water quality. As precipitation and moisture regimes change from climate change more research is needed to determine how vernal pool hydrology and functionality may be altered. Pennsylvania has an abundant distribution of vernal pools and with adequate legal protections and conservation they can be passed down to future generations as part of a collective environmental heritage

Appendix

Table 7. Soil matrix color to a depth of 1 meter or auger refusal for 36 sites.

Matrix color, depth in cm																					
Site #	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
1						7.5 YR 3/1	7.5 YR 3/1	7.5 YR 3/1	7.5 YR 3/1	2.5 YR 7/1	2.5 YR 7/1	2.5 YR 7/1	2.5 YR 7/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
2						10 YR 6/1	10 YR 6/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1
3								10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1
4							10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	Refusal	Refusal
5					10 Y 7/1	10 Y 7/1	10 Y 7/1	10 Y 7/1	10 Y 7/1	10 Y 7/1	10 Y 7/1	10 Y 7/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
6		5 Y 6/1	5 Y 6/1	5 Y 6/1	2.5 YR 7/1	2.5 YR 7/1	2.5 YR 7/1	2.5 YR 7/1	2.5 YR 7/1	2.5 YR 7/1	2.5 YR 7/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
7							2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	5 Y 5/1	5 Y 5/1	5 Y 5/1
8						7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1
9					7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1
10							7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
11				10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
12				10 Y 5/1	10 Y 5/1	10 Y 5/1	10 Y 5/1	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	Refusal	Refusal	Refusal	Refusal	Refusal
13					7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	7.5 YR 5/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	Refusal	Refusal	Refusal	Refusal
14				10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	Refusal	Refusal	Refusal	Refusal
15					5 YR 4/1	5 YR 4/1	5 YR 4/1	5 YR 4/1	10 YR 7/6	10 YR 7/6	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	Refusal	Refusal	Refusal
16							10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
17			10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 7/6	10 YR 7/6	10 YR 7/6	10 YR 7/6	10 YR 7/6	10 YR 7/6	10 YR 7/6	10 YR 7/6	Refusal	Refusal	Refusal	Refusal	Refusal
18			Hemic	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8
19			10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	5 GY 7/1	Refusal	Refusal
20								7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1
21						10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
22			10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 4/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1
23	10 YR 4/2	10 YR 4/2	10 YR 5/6	10 YR 5/6	10 YR 5/6	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
24					7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1	7.5 YR 4/1
25						10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1
26				10 YR 5/2	10 YR 5/2	10 YR 5/2	10 YR 5/2	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
27					10 YR 4/1	10 YR 4/1	10 YR 4/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	2.5 Y 5/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
28				10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	5 G 6/1	5 G 6/1	5 G 6/1	5 G 6/1	5 G 6/1
29				2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	2.5 Y 6/1	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	Refusal	Refusal	Refusal	Refusal	Refusal
30				10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8
31			10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8
32				10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	10 YR 5/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	2.5 Y 7/1	Refusal	Refusal	Refusal	Refusal
33					10 YR 4/1	10 YR 4/1	10 YR 4/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
34				10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	10 YR 6/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1
35					7.5 YR 6/1	7.5 YR 6/1	7.5 YR 6/1	7.5 YR 6/1	7.5 YR 6/1	7.5 YR 6/1	7.5 YR 6/1	7.5 YR 6/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	Refusal	Refusal	Refusal	Refusal	Refusal
36							7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	7.5 YR 7/1	10 YR 6/2	10 YR 6/2	10 YR 6/2	10 YR 6/2	10 YR 6/2	10 YR 6/2	10 YR 6/2	Refusal	Refusal	Refusal

Table 8. Soil redoximorphic feature color to a depth of 1 meter or auger refusal for 36 sites.

Redoximorphic Features, depth in cm																					
Site #	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
1						5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	2.5 YR 5/4	2.5 YR 5/4	2.5 YR 5/4	2.5 YR 5/4	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
2						10 YR 6/8	10 YR 6/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8
3												5 YR 4/6	5 YR 4/6	5 YR 4/6	5 YR 4/6	5 YR 4/6	5 YR 4/6	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8	7.5 YR 5/8
4							10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	Refusal	Refusal
5					10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
6		10 YR 6/8	10 YR 6/8	10 YR 6/8	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
7							7.5 YR 4/6	7.5 YR 4/6	7.5 YR 4/6	7.5 YR 4/6	7.5 YR 4/6	7.5 YR 4/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6			
8						10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8
9					10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8
10												10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
11																Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
12				2.5 Y 7/8	2.5 Y 7/8	2.5 Y 7/8	2.5 Y 7/8	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	Redusal	Redusal	Redusal	Redusal	Redusal
13					10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	Refusal	Refusal	Refusal	Refusal
14				10 YR 6/6	10 YR 6/6	10 YR 6/6	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	5 YR 5/8	Refusal	Refusal	Refusal	Refusal
15									10 Y 2.5/1	10 Y 2.5/1	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	Refusal	Refusal	Refusal
16							10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
17			10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8									Refusal	Refusal	Refusal	Refusal	Refusal
18				5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	5 Y 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1
19									5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	5 Y 7/8	Refusal	Refusal
20								10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6
21						10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8						Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
22			10 YR 6/6	10 YR 6/6	10 YR 6/6	10 YR 6/6	10 YR 6/6	10 YR 6/6													
23			10 YR 7/1	10 YR 7/1	10 YR 7/1	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
24					7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6	7.5 YR 5/6
25						7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6	7.5 YR 6/6
26								Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
27													Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
28				10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 4/6	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8	7.5 YR 6/8
29												10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	Refusal	Refusal	Refusal	Refusal	Refusal
30				2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	2.5 YR 5/6	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1
31			10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1	10 YR 7/1
32				7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	10 YR 7/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	Refusal	Refusal	Refusal	Refusal
33					10 YR 6/8	10 YR 6/8	10 YR 6/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	7.5 YR 7/8	Refusal	Refusal	Refusal	Refusal	Refusal	Refusal
34				7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6	7.5 YR 7/6
35					10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 6/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	10 YR 7/8	Refusal	Refusal	Refusal	Refusal	Refusal
36							10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	10 YR 5/8	Refusal	Refusal	Refusal

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