

Article

Deeper Vernal Pools Persist under Drought: The Value of Depth for Ephemeral Wetland Resilience

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Abstract: Vernal pools are temporary wetlands that form during winter and spring and are common in glacially scoured crystalline bedrock regions of the northeastern United States. These habitats support many organisms, including threatened and endangered amphibians. However, increasingly severe droughts associated with climate change are causing pools to dry earlier and remain dry longer, threatening the ecological functions of these ephemeral ecosystems. Additional research is therefore needed to identify characteristics associated with drought resilience. The objective of this study was to identify vernal pool characteristics associated with persistence during drought and to evaluate whether readily measurable field attributes may serve as indicators of drought resilience. Ecohydrological dynamics, hillslope flow pathways, and hydroperiod characteristics were examined across vernal pools experiencing drought conditions. Phase I used field surveys to assess relationships between pool characteristics and amphibian breeding effort. Phase II used *in situ* sensor clusters to explore the influence of hydrologic flow pathways on pool stability. Phase III quantified relationships between pool depth and seasonal water retention. Initial findings suggest pool characteristics, specifically depth and size, were consistently associated with indicators of drought resilience across the study phases. These relationships highlight the value of maximum depth as a practical indicator for conservation prioritization, although additional work is needed to evaluate its importance relative to other physical, hydrologic, chemical, and landscape factors. By identifying characteristics associated with longer hydroperiods and greater biological persistence, this study provides information that may assist conservation practitioners in prioritizing vernal pools for monitoring and protection under increasingly variable climatic conditions.

Keywords: Climate Change; Remote Sensing; Hydroperiod; Amphibian; Conservation; Ponds; Marshlands

1. Introduction

The effects of climate change and drought can be seen in environments across the earth [1]. Changes in weather patterns and temperatures have altered the functionality of different types of ecosystems [2]. Species that once inhabited certain areas are now unable to survive in these locations. In addition, locations that were once terrestrial ecosystems are becoming aquatic, whereas elsewhere, aquatic ecosystems are transitioning into terrestrial ecosystems as enhanced drought shifts hydrologic regimes and displaces mesic ecosystems with xeric ones [3]. Wetlands take up “about 6% of the earth’s surface area” [4], however, this number is decreasing due to their vulnerability to natural and human factors. Vernal pools are temporary, seasonal wetlands that are abundant in the northeast United States. These pools are also referred to as ephemeral wetlands [5]. Vernal pools follow an annual cycle of

wet and dry periods [6]. Vernal pools are unique in that they are geographically and hydrologically isolated from other wetlands [7]. During the wet winter months, vernal pools will fill due to precipitation and flooding and stay wet through the spring. As the temperature begins to rise as the seasons turn to summer, the water will evaporate and enter a dry period. In most years, the wet phase will last at least 2 months; however, it is common for a vernal pool to remain in the wet phase for 4 months [8,9]. The soil remains wet for approximately 1–3 months followed by a dry period that lasts 5–8 months [8,9].

The primary way in which a vernal pool is formed is through precipitation [10]; however, they are also formed due to melting snow and ice [7], surface water runoff, and groundwater. A vernal pool's pathway for water sourcing can be referred to as the hillslope flow pathway. Throughout a vernal pool's wet season, the water levels do not stay consistent. Rainfall and drought cause fluctuations in water level [8,11]. Hydroperiod refers to the duration of time a vernal pool is inundated with water and can be used to assess these seasonal fluctuations in water levels. One of the potentially detrimental changes that has been observed in the climate is the increase in drought conditions. Droughts are not only increasing in severity and frequency, but areas that were not previously prone to drought are now becoming "drought-sensitive" [12]. Wetlands are the most vulnerable ecosystems regarding climate change [13]; the hydroperiod of a vernal pool can be unpredictable [10]. Drought is one of the main threats to vernal pools, as it alters the stability of the wetlands themselves, the wellbeing of the organisms that inhabit them, and it reduces their adaptive capacity to future disturbances [14]. Dry periods are becoming longer, and the amount of precipitation received during both the wet and dry seasons is becoming erratic and highly variable [15]. It is not uncommon for there to be a dry period in the middle of a vernal pool's wet season due to a drought during the winter. With "increasing droughts and shifts in precipitation timing" [16], vernal pools may fill and dry up multiple times during one wet season [8]. This inconsistent behavior can interfere with the amphibian life cycle [16] if a pool dries up before larvae can metamorphose into terrestrial forms that are ready to leave the pools and live in the surrounding upland habitat. Additionally, a vernal pool may fill up during a period where the pool is typically dry. This can have negative effects since the dry season is a time of terrestrial plant growth [17]. The refilling of a vernal pool at this time may result in the destruction of the plant species that inhabit the area. For example, some perennial grass species that live on the border of vernal pools can tolerate living and functioning in moist soil but are not adapted to germinate when submerged in water [18].

Vernal pools are popular breeding grounds for many species, including amphibians and invertebrates [19]. Studies show that amphibians, such as Wood Frogs and *Ambystoma* salamanders, will travel from upland forests to vernal pools to reproduce [20,21]. Despite their dependence on these ephemeral wetlands, the impacts of drought and environmental drying on amphibians remain relatively understudied, including Wood Frog species that rely on ephemeral wetlands for reproduction [22]. Some species of invertebrates, such as fairy shrimp [23], will live their entire life in a vernal pool. The ephemeral nature of vernal pools, as well as their isolation are main contributors to their importance. Both factors help vernal pools to remain unoccupied by predators, such as fish, which leads to a greater chance of reproductive success for amphibians [20,21]. Predatory fish cannot survive well in the cyclical pattern of wet and dry seasons. The hydrology of a vernal pool, especially in the wet period, directly impacts the productivity of the organisms who inhabit the area [24]. Without these wetlands, many amphibian species would be at risk of extinction due to a lack of breeding location. Pool morphology, land management, and soil type are all factors that affect pool inundation patterns. Grazing has been suggested as a method of increasing water retention by creating microdepressions, which furthers the potential of vernal pools as ecological refugia [25]. Vernal pools have many additional environmental benefits; they help to clean polluted water, store water from floods and melts, replenish groundwater supply, and store carbon in order to prevent it from entering the earth's atmosphere [26]. The biodiversity in temporary aquatic environments, such as vernal pools, is comparable to that of permanent aquatic environments [27]. These wetlands are one of the few remaining ecosystems that are dominated by native plant species and are a critical home for rare and endemic species [28]. Throughout the past century, there has been a worldwide decrease in aquatic environments, specifically wetlands [29]. This habitat loss leads to endangered and at-risk species having fewer locations to live in and breed in [30]. This conservation importance is also reflected in New York State's Freshwater Wetlands Act, which classifies a vernal pool known to be productive for amphibian breeding as a wetland of "unusual importance," regardless of size [31]. Lack of habitat may result in a loss of these species, though recent studies show that pools with longer inundation periods may serve as a hydrologic refuge under the increased drought-like conditions [15,32,33].

Remote sensing can be defined as “the science of observing and recording information about objects from a distance, without touching them” [34]. These sensors can be ground, air, or space-based depending on the goals and locations of the study [35]. It is a valuable method of data collection as it is not limited by scientists’ availability and accessibility to sites. The quantity of data that can be recorded by remote sensors far surpasses the amount of data that can be collected by people, as they are capable of cyclically collecting data over periods of time ranging from minutes to years. For example, studies have been done where satellites collect data multiple times each week over the course of decades [34]. Remote sensing is a growing field in the physical sciences; as technology continuously develops, this method of data collection can be applied to a wider range of studies. This method has been used to monitor wetlands [4,36–39]. Due to many wetlands having an ephemeral nature, they can be difficult to identify and locate. Continuous data collection using remote sensors is a useful technique for wetland identification [40]. Further, wetlands are dynamic ecosystems, and the use of remote sensors allows scientists to notice minute changes [4]. Ground-based sensors are becoming a popular option for studying the hydrology and geology of wetlands. There are sensors capable of producing “operational data products for rainfall, river flow, soil moisture, bathymetry, and open water” [41] which are measurements that provide key information to the health of wetlands.

Ground-based sensors are also ideal for forested wetlands as trees may block the view of air and space-based sensors [42]. Furthermore, if a wetland, such as a vernal pool, is undergoing a period of dryness, a sensor that is above the ground may fail to locate an aquatic ecosystem. A continuous collection of data from remote sensors allows for critical warning signs to be observed and caught, however, it also helps scientists to determine what is a real change in the ecosystem and what is a false alarm [43]. There has been more focus on monitoring coastal wetlands with remote sensing than inland wetlands, but both need long-term monitoring [36]. It is important to have information on the location and details of these pools for long-term conservation and management strategies [44]. Previous studies have examined hydrological variables to understand vernal pool and wetland water features, but many have limitations. Some focus only on basin shape or precipitation and do not account for hillslope or ground-water contributions, which can strongly influence pool stability [7]. Others rely on short-term observations or remote sensing data that may not capture the full range of seasonal hydrology. Hydrologic connectivity has been shown to play an important role in wetland function, yet the specific flow pathways that sustain vernal pools are not well understood [10]. Most existing monitoring has also focused on coastal or open wetlands, leaving forested inland vernal pools understudied. There is limited process-based understanding of how hillslope and subsurface flow affect vernal pool stability, especially in forested areas where canopy cover limits remote sensing. Continuous ground-based monitoring can help fill this gap by tracking water levels and flow contributions to better understand why some pools hold water longer than others and how these patterns may shift with changing climate conditions. Data collected through sensors is a key tool in supporting ideas presented to policymakers [34]. Wetland health assessments can raise public awareness of wetland conditions and gain support in asking policy makers to implement sustainable policies to protect and restore the health of the wetland ecosystems [39]. As a rapidly changing climate alters the pattern of the vernal pool’s annual wet and dry cycles, the hillslope flow pathways dominating the filling of each vernal pool may also change. It is generally unknown what flow pathways are dominant in these pools, and how this hydrologic functioning, along with pool morphology, allows some vernal pools to maintain a more stable hydroperiod, remain more resilient to drought, and support greater amphibian reproductive success than others.

In this study, different hydrological and ecological variables were measured and analyzed, with the assistance of both manual surveys and in-situ hydrologic sensors, to better understand the hydroperiods of vernal pools and how they relate to amphibian conservation. The main objective of the study was to identify physical and hydrologic characteristics associated with vernal pool persistence during drought and evaluate whether readily measurable field attributes could serve as useful indicators of drought resilience for conservation planning. Proximally adjacent vernal pools with a similar lithology were compared to see why they differ across a hydroperiod spectrum leading to variance in water retention and amphibian breeding success. When identified, these factors can then provide a useful framework for identifying and prioritizing certain vernal pools for conservation and management actions across diverse landscape and funding contexts. This study was done in three distinct phases. Phase I focused on studying the ecohydrological characteristics of 30 vernal pools to determine the predictors of amphibian breeding success and resilience against drought. Phase II used remote hydrology sensors to identify the hillslope flow pathways of five vernal pools with varying histories of drought resistance. Phase III quantified the relationship between pool

depth and water retention, to further analyze how pools are responding to drought. Together, these phases were intended to assess whether readily measurable pool characteristics are associated with ecological and hydrologic indicators of resilience.

2. Materials and Methods

A multi-phase study was conducted to investigate drought resilience in vernal pools in the Hudson Valley area of New York. Each phase of data collection, which occurred from 2021–2025, targeted a component of water retention and drought resilience in vernal pools. The methods reflect the chronological development of this research.

2.1. Study Design

This study was conducted in three phases to evaluate the hydrology and drought resilience of vernal pools. Phase I (2021–2023) examined the pools ecohydrological characteristics as it relates to amphibian breeding success. Phase II (2023–2024) assessed the effect of varying hillslope flow pathways on pool stability (**Figure 1**). Phase III (2025) quantified the relationship between pool depth and water retention. Collectively, this phased approach allowed for the assessment of vernal pools ecological and physical responses to drought.



Figure 1. This conceptual figure depicting how hillslope flow pathways impact vernal pools. On left a pool fills from surface water runoff; on right a pool fills via groundwater seepage up through subsurface flow pathways along fractures, roots, and the soil matrix [45].

2.2. Regional Study Site

This study took place on both private and protected, public land in Dutchess and Ulster County, New York, United States (**Figure 2**). The study was conducted on 12 different properties of wetland and forest ranging from 29–348 hectares. These sites exist in high relief complex terrain of glacially scoured, folded, and faulted metamorphic bedrock, but of a small enough absolute scale to not be considered mountains. Elevations at the sites ranged from 67 to 122 m above sea level. The land is owned by Scenic Hudson, a non-profit environmental organization and land trust in the Hudson Valley area in New York. Vernal pools can be found throughout the properties.



Figure 2. This map depicts the general location of the study sites in Dutchess and Ulster County, New York State, USA. Exact locations are intentionally vague due to species poaching concerns.

2.3. Phase I: Ecohydrology

2.3.1. Amphibian Egg-Mass Monitoring

In this study, amphibian breeding effort is determined based on the amount of egg mass deposits located within a pool. Specific pools at each site were chosen based on which pools have consistent amphibian egg mass data and were wet during the 2023 late spring survey period. All sites are located within the Hudson River watershed in New York State which is considered a highly productive amphibian breeding region with a high concentration of vernal pools [46]. To assess breeding effort of vernal-pool obligate amphibian species, egg-mass data as part of a long-term monitoring program (Scenic Hudson, unpublished data). From 2017–2023, vernal wetland surveys took place in February–May to quantify breeding effort by wood frogs (*Lithobates sylvaticus*), spotted salamanders (*Ambystoma maculatum*) and the Jefferson’s/blue-spotted salamander species complex (*Ambystoma jeffersonianum*, *Ambystoma laterale*, and hybrids). Vernal habitats included intermittent woodland pools; small, intermittently flooded forested wetlands, and relict human-made pools. All habitats periodically dry completely and lack fish. Surveys consisted of a trained surveyor walking each wetland’s margin and counting individual egg-masses using polarized sunglasses to reduce glare and improve visibility. Veteran surveyors benchmarked new surveyors to ensure minimal variation among observers. Two different surveyors visited each wetland at least twice, and usually three times each year. Phase I analysis includes all *Ambystoma* egg-masses pooled into a single count due to uncertainty in egg-mass identification in the field. Some pools surveyed for this study did not have consistent egg mass data due to being dry some years. Analysis only includes pools that were wet all 6 years ($n = 25$).

2.3.2. Physical Measurements

Specific pools at each site were chosen based on which pools have consistent amphibian egg mass data and were wet during the 2023 late spring survey period. In total, 30 pools were surveyed for physical and chemical properties. The physical characteristics of 30 vernal pools were measured at 1-m increments on a longitudinal transect (i.e., a transect along the longest axis of the pool). These characteristics include substrate and surface temperature (°C), canopy coverage (%), and depth (m) (**Table 1**). A “SpotOn 34” temperature probe measured substrate and surface temperature. A Forestry Suppliers spherical densiometer measured canopy coverage and a meter stick measured depth. At the end of each transect, trees considered within a variable radius plot according to a forester’s prism (10 BAF) were identified and their Diameter at Breast Height (DBH) measured using a Forestry Suppliers DBH tape. Area, perimeter, and distance to the nearest road/railroad for each pool were assessed by GIS and used in analysis.

Table 1. All characteristics used in pool surveys.

Transect Variables (Every 1 m along Longitudinal Transect)	Tools/Units
Surface temperature	Temperature probe (°C)
Substrate temperature	Temperature probe (°C)
Emergent vegetation	Species ID
Canopy coverage	Densiometer (%)
Depth	Meter stick (m)
Transect Variables (at Endpoints)	
Trees	Foresters prism/DBH (cm)/Species ID
Shrubs/grasses	Species ID
Aggregated Variables	
SPC	YSI (µS/cm)
Cl	YSI (mg/L)
NO ³⁻	YSI (mg/L)
Turbidity	YSI (NTU)
pH	Indicator strips
Phosphate	Indicator strips (ppm)
DO	YSI (mg/L)
Size (perimeter and area)	GIS (m and m ²)
Distance to road	GIS (ft)

2.3.3. Chemical Measurements

Water quality metrics were taken in one location for each pool on the same day, to ensure consistency with recent weather. Temperature (°C), specific conductivity (µS/cm), chloride (mg/L), nitrate (mg/L), turbidity (NTU),

and dissolved oxygen (mg/L) were all taken using YSI probe Professional Plus. Phosphate and pH were also taken using indicator strips.

2.3.4. Analytical Measurements

25 of 30 pools were wet all 6 years of egg mass data collection and were used in the final analysis. We compared each measured variable to the egg masses for both Wood Frogs and *Ambystoma* Salamanders/m² using correlation matrices. An average maximum count was calculated from the maximum count from each year, which was then used in the analysis. We obtained R- and p-values from the matrices. The analysis for both *Ambystoma* Salamanders and Wood frog eggs used the number of egg masses in a pool normalized to the size (m²) of a pool.

2.4. Phase II: Hillslope Flow Pathways

2.4.1. Field Procedures

Five vernal pools were selected at one study site in Ulster County, New York. The sample size was limited by the availability of dataloggers and therefore sought to capture a representative range of hydroperiods while minimizing other factors such as habitat type (vernal pools vs shrub swamps). Five vernal pools of similar areas were selected to represent a range of hydroperiod extremes, based on visual over several years of intermittent visitation, with some pools remaining wet longer and more frequently than others. Due to the limited sample size (n = 5), this section of the study is exploratory.

Four of the five pools had amphibian egg masses documented across multiple years; the fifth pool was included as one that appeared to have too short a hydroperiod to support breeding. Hereafter, the pools are referred to as: wettest (Vernal Pool W); medium wet (Vernal Pool MW); medium (Vernal Pool M); medium dry (Vernal Pool MD); and driest (Vernal Pool D). Open-source hydrology sensors were installed into each of the pools and programmed to cyclically collect data at set intervals (see next paragraph). The open-source hydrology sensors used for this study were Smart Rocks. Smart Rocks were invented by the OPeNS lab group at Oregon State University and are used to collect data in small streams and bodies of water [47]. The Smart Rocks were deployed by attaching the PVC casing to an acrylic mounting plate and then securing the mounting plate to a rebar. The rebar was hammered into the substrate of the vernal pool, securing the Smart Rock in place. The Smart Rock hovered about 5–10 cm off the substrate, depending on the depth of the vernal pool. Smart Rock sensors are programmed to cyclically collect and store data on temperature (°C), pressure (mbar), electrical conductivity (uS/cm), and turbidity (NTU). To better analyze the results of this study, pressure (mbar) was converted to depth (cm). Constant air pressure was assumed as the analysis was looking at overall seasonal changes throughout a season that are not greatly impacted by small changes in air pressure. Electrical conductivity (uS/cm) and temperature (°C) were converted to total dissolved solids (TDS) (ppm). When the sensors were deployed in Fall 2023 (August 25–November 3, 2023), they were programmed to cyclically collect data every 15 min. During the Spring 2024 (January 19–May 25, 2024) deployment, the frequency of data collection was adjusted to 60-min intervals to lengthen the sensors' battery life. The Smart Rock in Vernal Pool W collected data every 15 min from Fall 2023 through Spring 2024 (August 25, 2023–May 25, 2024) as the sensor was not removed from the pool between data sets. A temperature probe was used to measure the substrate and surface temperatures in a grid pattern in each vernal pool. The measurements were collected each meter along the three secants of each vernal pool in the study (**Figures S15–S20**; see **Supplementary Materials**). The data collected was compared to the rainfall history in the area to see how the vernal pools are impacted by precipitation.

2.4.2. Field Measurements

Quantification of relevant variables was conducted across the vernal pools and the field site generally. Data collection included continuous water temperature sensing, depth measurements using pressure sensing, electrical conductivity to understand total dissolved solids, turbidity, substrate temperature, surface temperature, and precipitation (**Table 2**).

Table 2. Summary of observational measurement types from study site.

Measurement	Measurement Tool	Physiographic Location	Notes
Water Temperature	Open-Source Smart Rock Sensors	Vernal Pools W, MW, M, MD, and D	Data was collected cyclically at intervals ranging from 15 min to 60 min. Used with Electrical Conductivity to calculate TDS.
Pressure	Open-Source Smart Rock Sensors	Vernal Pools W, MW, M, MD, and D	Data was collected cyclically at intervals ranging from 15 min to 60 min. Used to calculate depth.
Electrical Conductivity	Open-Source Smart Rock Sensors	Vernal Pools W, MW, M, MD, and D	Data was collected cyclically at intervals ranging from 15 min to 60 min. Used with Temperature to calculate TDS.
Turbidity	Open-Source Smart Rock Sensors	Vernal Pools W, MW, M, MD, and D	Data was collected cyclically at intervals ranging from 15 min to 60 min.
Substrate Temperature	Temperature Probe	Vernal Pools W, MW, M, MD, and D	The substrate temperature was measured in a three column grid at each meter of the vernal pool.
Surface Temperature	Temperature Probe	Vernal Pools W, MW, M, MD, and D	The surface temperature was measured in a three-column grid at each meter of the vernal pool.
Precipitation	Online rainfall history database for Ulster County, NY [48]	Ulster County, NY	The rainfall in the area surrounding was analyzed.

2.5. Phase III: Hydroperiod

2.5.1. Field Procedures

To collect hydroperiod data, 94 vernal pools ($n = 94$) in Dutchess County and Ulster County, New York were sampled in June and July 2025. Each pool was visited once in June and once in July. In June, a visual assessment was conducted at each pool to identify the expected lowest point of the pool, the current waterline, and the maximum waterline (**Figure 3**). The maximum water line was found based on matted leaves and other evidence of inundation. A CST Berger rotary laser was set on the shore in a level position, ensuring visibility of each measurement site. The laser receiver was secured to a metal graduated ruler. Measurements for the lowest point (cm), current water level (cm), and maximum water level (cm) were recorded. In July, a second round of sampling was done at each pool. If a pool was dry, it was recorded as having a water level of zero before moving to the next. To ensure consistency between sampling rounds, the position of the laser was adjusted so that it accurately matched the lowest point found in June. This confirmed that the same lowest point was used in both rounds. The current water level (cm) for July was measured and recorded.

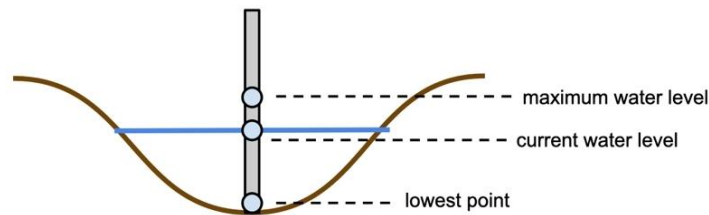


Figure 3. This conceptual figure depicts the theoretical measurement sites at each vernal pool.

2.5.2. Hydrologic Measurements and Analysis

The recorded measurements were used to calculate pool depth at time of measurement and maximum water height, to allow for analysis of water retention dynamics. The maximum water level and lowest point measurements were used to calculate the depth of each pool. The depth calculation and current water level measurements were used to find the June water height and July water height. The change in water height in each pool was then calculated, as a percentage of its original depth, so that the overall change in water levels and how it relates to pool depth could be assessed. Regressions were used to assess the relationships between the variables.

3. Results

3.1. Phase I: Ecohydrology

Standard linear regressions were used to accomplish the goals of this exploratory phase. The p -value and R -statistic for variables with a p -value of less than 0.2 are shown in **Table 3** for Wood Frogs and **Table 4** for *Ambystoma*

Salamanders. pH was found to have a p -value of 0.058 for wood frogs (**Table 3**) and 0.138 for salamanders (**Table 4**) but was not included in any further analysis due to low variability in the results, with all pools having a pH of 4 or 5. This finding should be studied at a wider range of pH levels before determining its significance to amphibian reproduction. Laboratory and in situ experiments have previously found *Ambystoma* Salamanders and Wood Frogs to best survive at $\text{pH} > 4.2$ and < 6 [49].

Table 3. Variables associated with Wood Frog egg mass counts at a $p < 0.2$ threshold.

p -Value	R-Statistic	Variable
0.058	-0.384	pH
0.127	0.313	<i>Ambystoma</i> Salamander Eggs/m ²
0.137	0.306	Average Depth

Table 4. Variables associated with *Ambystoma* Salamander egg mass counts at a $p < 0.2$ threshold.

p -Value	R-Statistic	Variable
0.053	0.392	Average Depth
0.127	0.313	Wood Frog Eggs/m ²
0.129	0.312	NO ₃ ⁻
0.138	-0.305	pH
0.162	-0.289	Turbidity

Aside from pH (addressed above), the lowest p -value included in the analysis for Wood Frogs was *Ambystoma* Salamander eggs/m² with a p -value of 0.127 (**Table 3**) and average depth with a p -value of 0.137 (**Table 3**). The lowest p -values for *Ambystoma* Salamanders were average depth of a pool with a p -value of 0.053 (**Table 4**) and Wood Frog eggs/m² with a p -value of 0.127 (**Table 4**). **Table 4** shows the characteristics that are most closely associated with average depth at a significance level of $p < 0.5$.

The most closely associated variable with average depth was the number of *Ambystoma* Salamander eggs/m² followed by the range in substrate temperature within a pool with a p -value of 0.094 (**Table 5**). Average depth was examined in association with *Ambystoma* Salamander eggs/m² (**Figure 4**) and with the Wood Frog eggs/m² (**Figure 5**). Range in substrate temperature was examined with *Ambystoma* Salamander eggs/m² (**Figure 6**), and **Figure 7** shows the direct association between the two species. A high p -value threshold was used to examine possible connections between ecohydrological variables and amphibian breeding, these results from Phase I should be considered exploratory.

Table 5. Variables associated with average depth ($p < 0.5$).

p -Value	R-Statistic	Variable
0.053	0.392	<i>Ambystoma</i> Salamander Eggs/m ²
0.094	0.342	Range Substrate Temp
0.147	0.306	Wood Frog Eggs/m ²
0.248	-0.24	Cl
0.273	-0.228	Surface Temp
0.294	-0.218	Turbidity
0.329	-0.204	SPC
0.347	0.196	DO
0.431	-0.165	GIS Area
0.437	0.163	Maximum Substrate Temp

3.2. Phase II: Hillslope Flow Pathways

Pressure data was collected by the Smart Rock hydrology sensors from Fall 2023 to Spring 2024 and converted to depth. The following graphs depict the depth data of the five vernal pools that were highlighted in this phase of the study. Because only five pools were intensively monitored, results from Phase II should be considered exploratory. In Phase II, Vernal Pool W has historically been the wettest pool in the area; however, it is also the largest pool in both width and depth at about 24 m across its longest axis and a meter deep during the wet season. Conversely, Vernal Pool D has historically been the driest and smallest pool at about 9 m long and 0.2 m deep during the wet season. The majority of the vernal pools in between follow a consistent wetting and drying pattern. Vernal Pool

MW is about 9 m across, 0.4 m deep. Vernal Pool M is about 15 m across, 0.6 m deep. Vernal Pool MD is about 13 m long, 0.4 m deep.

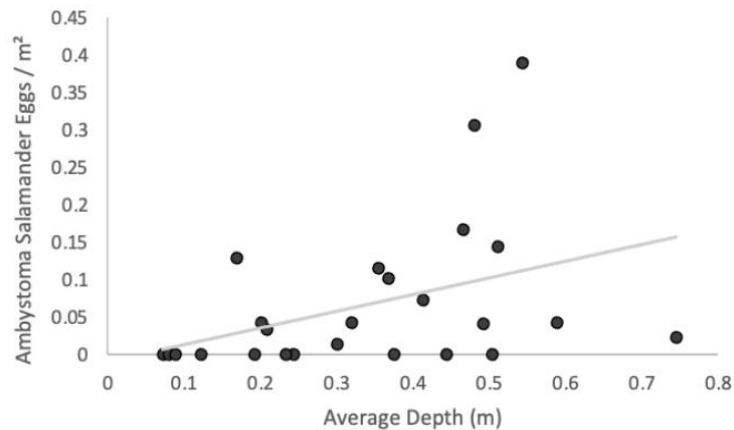


Figure 4. The average depth of a pool has a positive association with the number of *Ambystoma* Salamander eggs found within that pool.

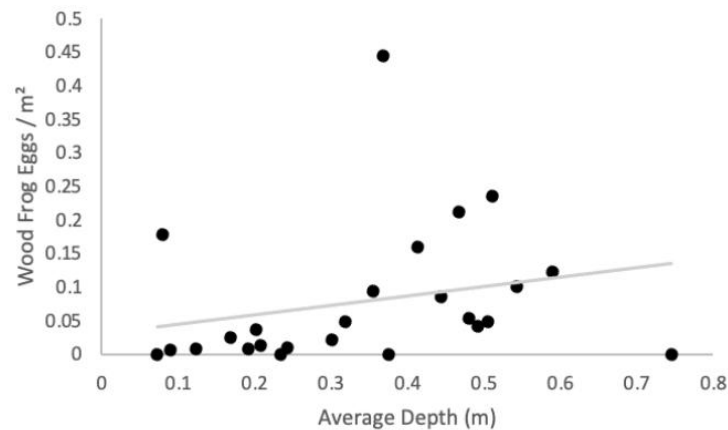


Figure 5. The amount of Wood Frog eggs found in a pool was also positively associated with the average depth of a pool.

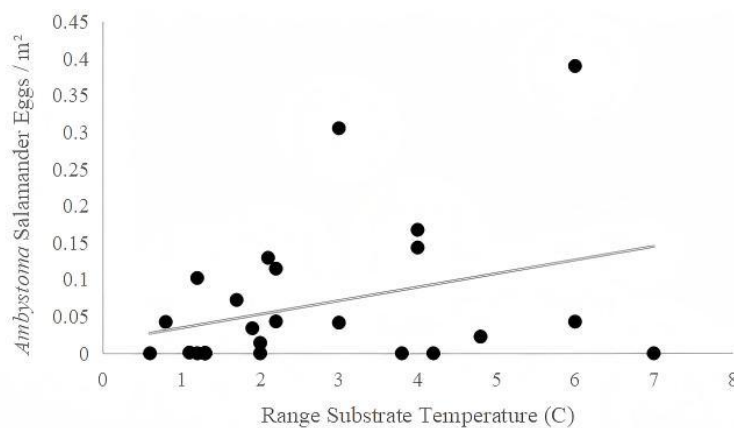


Figure 6. A positive association was found between the range in substrate temperature within a pool, and the amount of *Ambystoma* Salamander eggs. The p -value of this association is 0.448 and is associated with the average depth of the pools with a p -value of 0.094.

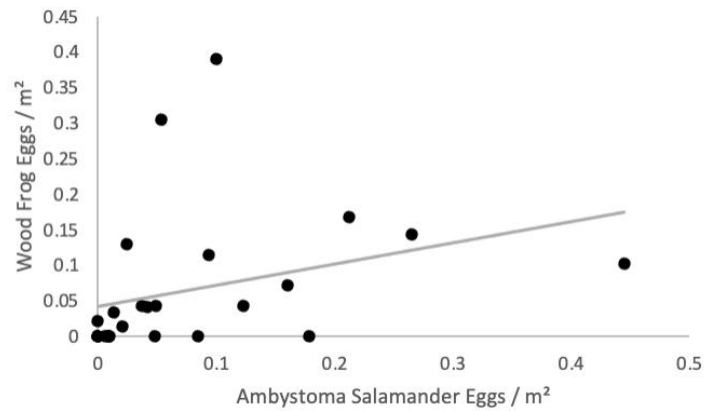


Figure 7. The relationship shown between the amount of Wood Frog eggs and the amount of *Ambystoma* Salamander eggs in a pool is also positive. The p -value of this association is 0.127.

3.2.1. Depth Data: August 25–November 3, 2023

Continuous measurements of water pressure were converted into depth estimates for individual vernal pools from August 25 through November 3, 2023. Data are presented here to highlight unique events and patterns relevant to the larger interpretation of the processes dominating different pools and across pools generally discussed in our findings (Figures 8–11).

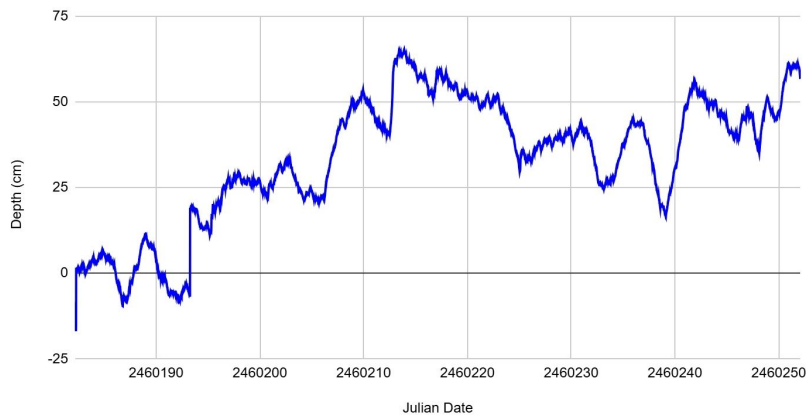


Figure 8. Recorded Depths (cm) of Vernal Pool W During Fall 2023: This graph shows the depth of Vernal Pool W recorded every 15 min from August 25–November 3, 2023.

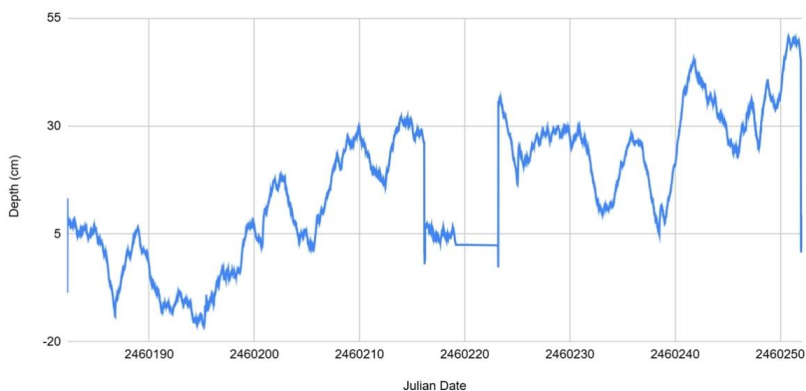


Figure 9. Recorded Depths (cm) of Vernal Pool MW During Fall 2023: This graph shows the depth of Vernal Pool MW recorded every 15 min from August 25–November 3, 2023.

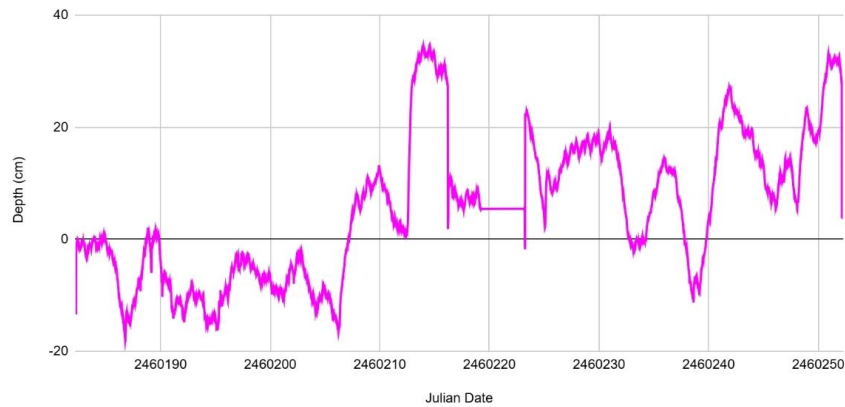


Figure 10. Recorded Depths (cm) of Vernal Pool MD During Fall 2023: This graph shows the depth of Vernal Pool MD recorded every 15 min from August 25–November 3, 2023.

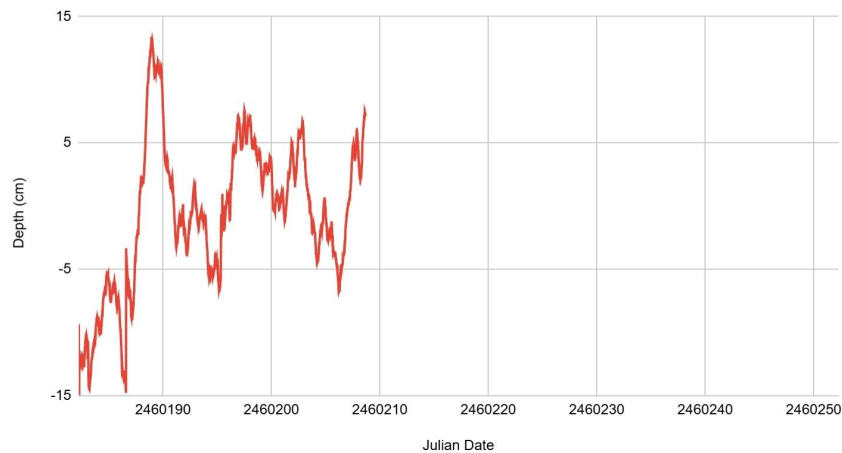


Figure 11. Recorded Depths (cm) of Vernal Pool D During Fall 2023: This graph shows the depth of Vernal Pool D recorded every 15 min from August 25–November 3, 2023. Due to technical errors, the sensor stopped recording depth data around September 21, 2023.

3.2.2. Depth Data: January 19–May 25, 2024

Additional continuous pressure data was also recorded from the timeframe of January 19 through May 25, 2024; interpretation of depth changes over this timeframe is highlighted (**Figures 12–14**).

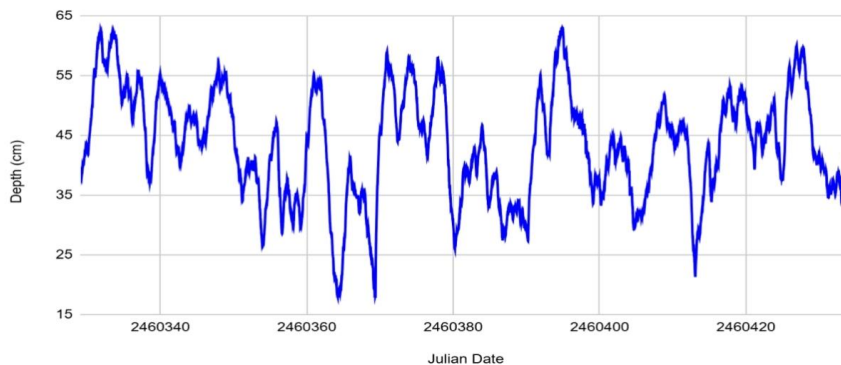


Figure 12. Recorded Depths (cm) of Vernal Pool W during Spring 2024: This graph shows the depth of Vernal Pool W recorded every 15 min from January 19–May 25, 2024.

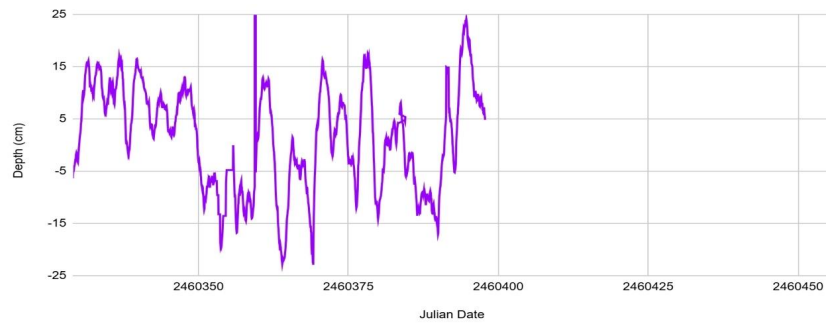


Figure 13. Recorded Depths (cm) of Vernal Pool M during Spring 2024: This graph shows the depth of Vernal Pool M recorded every 60 min from January 19–May 25, 2024.

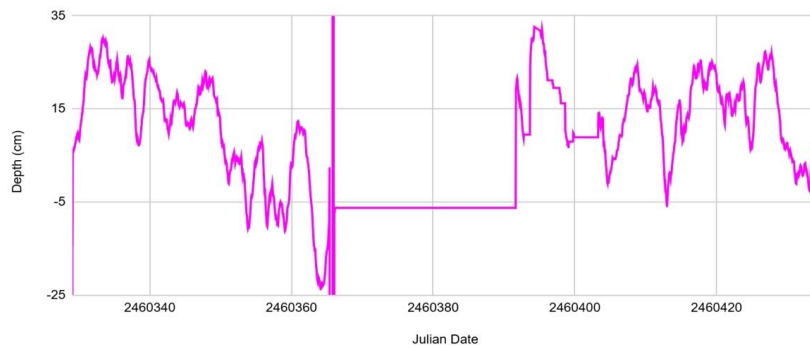


Figure 14. Recorded Depths (cm) of Vernal Pool MD during Spring 2024: This graph shows the depth of Vernal Pool MD recorded every 60 min from January 19–May 25, 2024.

3.2.3. Example of Combined Data Collected in Vernal Pools via Smart Rock Sensors

The following **Figure 15** compares the depth, total dissolved solids, and turbidity data of Vernal Pool W.

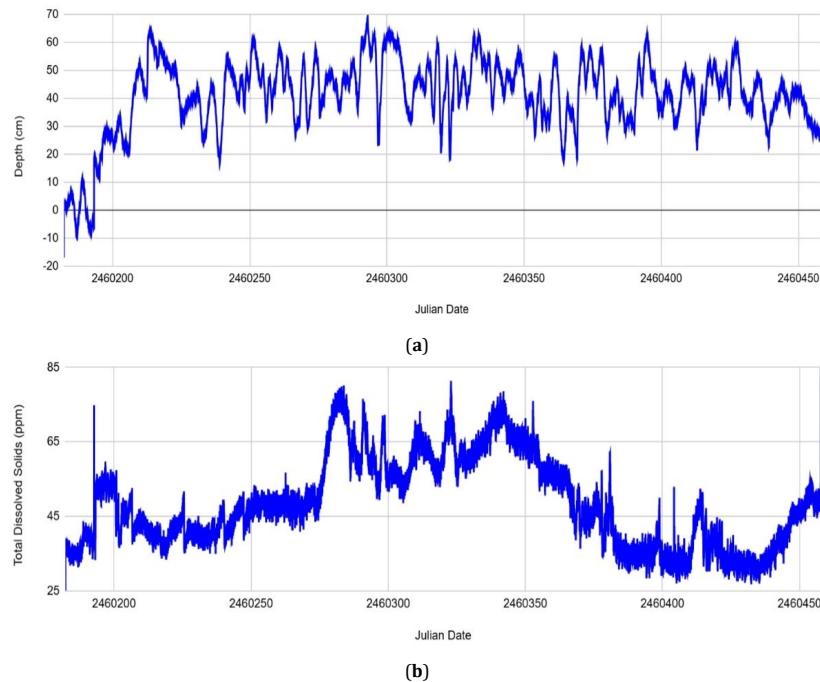


Figure 15. *Cont.*

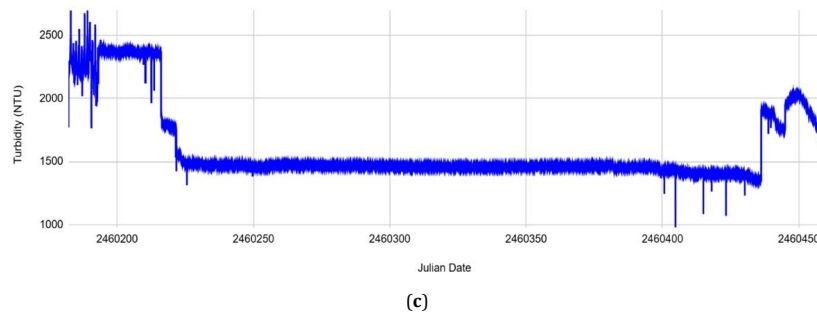


Figure 15. (a) Recorded Depth (cm), (b) TDS (ppm), and (c) Turbidity (NTU) of Vernal Pool W from Fall 2023 to Spring 2024: Data recorded every 15 min from August 25, 2023–May 25, 2024.

3.2.4. Coefficient of Variation

The coefficient of variation was calculated for each depth dataset for the 5 vernal pools assessed in Phase II to better understand how consistent the depth variations are when normalizing for overall depth (**Table 6**). This allows for a relativist look at how consistent water depths are in pools across varying regimes of hillslope flow pathways, despite some pools being much shallower or much deeper in absolute depth. Because a variety of flow pathways were discovered to be dominant in the different pools, varying from deeper subsurface, shallow subsurface, and overland flow, and no one type was consistent in its hydrologic control across them all, this caused variables of most types (e.g., TDS, turbidity, etc.) to fluctuate in some pools, while remaining unchanged in others, if that particular pathway influencing that variable was absent there. Therefore, it was decided depth was the only hydrologic variable of importance to be appropriate for statistical comparison, as its dataset is present similarly at all pools for most time periods, with present variations at all 5 pools. The coefficient of variation was chosen as a normalized comparison format because it is calculated by dividing the standard deviation of a dataset by the mean and then multiplying by 100 to convert the value into a percentage. It “represents the ratio between the standard deviation and the mean” [50]. A higher CV means that the standard deviation of the data set is larger and, therefore, more of the data values are further away from the mean. A lower CV means that the standard deviation is smaller, and more of the data collected is closer to the mean value. A lower CV shows that a data set has less variability, when normalized by the mean of each dataset. This shows which pools are more variable or heterogeneous in depth over time, and which are more consistent or homogeneous, and normalized by their absolute depths.

$$CV = \left(\frac{\sigma}{\mu} \right) \times 100$$

Table 6. Coefficient of Variation of Draw-Down Depth (Maximum Depth to Last Recorded Depth).

Vernal Pool	Date	Coefficient of Variation
Wettest (W)	August 25–November 3, 2023	9.9
Wettest (W)	January 19–May 25, 2024	24.9
Medium Wet (MW)	August 25–November 3, 2023	100.9
Medium (M)	January 19–May 25, 2024	94.3
Medium Dry (MD)	August 25–November 3, 2023	66.9
Medium Dry (MD)	January 19–May 25, 2024	101.1
Dry (D)	August 25–September 21, 2023	41.1

3.2.5. Results Summary: Hydrologic Behavior

Detailed descriptions of the above figures are summarized below in specific subsections, additional **Supplementary Materials Figures S1–S20** also share further findings of interest to some readers.

(1) Depth

The depth in the pools at the wetter end of the spectrum of the five studied in Phase II had a more stable rise throughout the wet season, suggesting a stronger connection to subsurface flow pathways. When comparing the depth data to the rainfall data, there is a clear qualitative relationship between an increase in depth during precipitation events in the wetter pools, such as Vernal Pool W, suggesting shallower, more rapid hillslope flow

pathways connecting the pool to precipitation. Vernal Pool W did not experience complete drying during the wet season (**Figures 8, 12, and 15a**). The graphs of the vernal pools at the drier end of the spectrum had more rapidly changing spikes and dips, suggesting less connection to subsurface hillslope flow pathways, and more reliance on overland flow, or very shallow, rapid sub-surface flow. These drier pools, such as Vernal Pools M (**Figure 13**), MD (**Figures 10 and 14**), and D (**Figure 11**), also go through multiple cycles of fully drying out during the wet season. Although the way the depths of the pools react to precipitation events is similar overall, the wetter pools did not hit a depth of 0 cm; therefore, their behavior is less extreme and likely more connected to deeper flow pathways of water in the hillslope that connect precipitation to surface water residing in the pools.

(2) Total Dissolved Solids (TDS)

TDS usually increases during precipitation events due to an increase in minerals and sediments entering the pool from surface runoff and infiltration [51]. During the Fall 2023 Smart Rock deployment, the TDS levels in Vernal Pool W remained steady with small spikes occurring near precipitation events (**Figure S1**; see **Supplementary Materials**). Some of the drier pools experienced large drops in TDS when there was less precipitation, and then large spikes in TDS to compensate when precipitation occurred and refilled the pool. Rainfall has a greater impact on the TDS of the drier pools because there is less water in the pools, causing the sediment to be more concentrated in the pool. During the Spring 2024 Smart Rock deployment, the consistent TDS recordings in Vernal Pools M and MD may be due to the pools freezing (**Figures S10 and S11**; see **Supplementary Materials**). If this is the case, then the large spikes in TDS in these pools may represent a snow melt event. Vernal Pool W may not have frozen all the way due to it being much larger and deeper than the other 2 pools and therefore would not have felt the impacts of the freezing and melting as strongly (**Figure S9**; see **Supplementary Materials**).

(3) Turbidity

Similarly to TDS, the changes in turbidity are more prominent in the drier pools due to the pools being shallower and drying out and filling back up. In both Fall 2023 and Spring 2024, Vernal Pools MD (**Figures S7 and S14**; see **Supplementary Materials**) and D (**Figure S8**; see **Supplementary Materials**) had the most chaotic graphs for turbidity. During the Fall, Vernal Pool W was stable until around the end of September when there was a sudden drop in turbidity before the data stabilized again (**Figure S5**; see **Supplementary Materials**). This may be explained by the sensor tipping over and settling into the sediment at the bottom of the pool. During Spring 2024, Vernal Pool W had an overall trend of a decrease in turbidity throughout the period of data collection (**Figure S12**; see **Supplementary Materials**). This aligns with snowmelt increasing the depth of the pool causing the water to become more diluted.

3.3. Phase III: Hydroperiod

Maximum pool depth and monthly water height measurements were taken at 94 pools ($n = 94$) and analyzed for their correlations. The following graphs depict the depth, water height, and water retention data for each of the pools in this phase of the study (**Figures 16 and 17**).

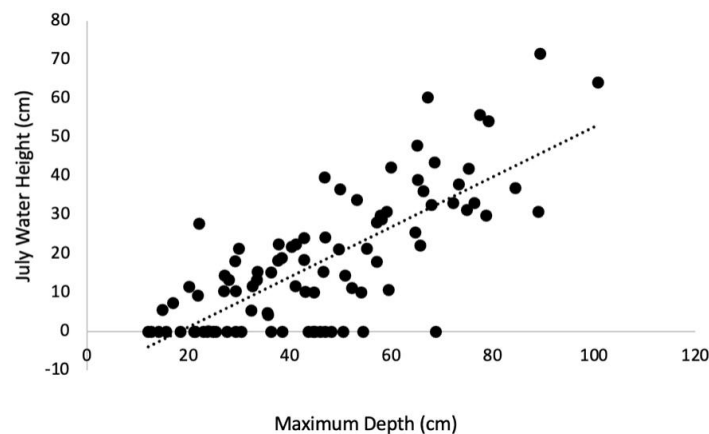


Figure 16. The maximum depth of each vernal pool is positively associated with July water height ($\beta = 0.65$, 95% CI: 0.53–0.76, $p < 0.001$, $R^2 = 0.75$, $y = 0.65x - 11.83$).

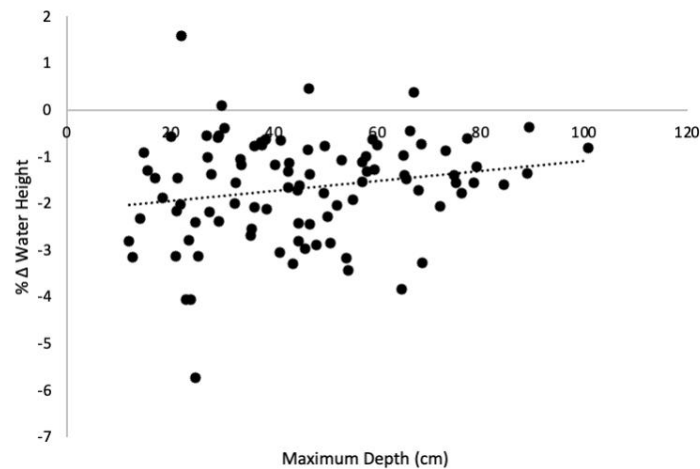


Figure 17. Slight association of maximum depth and percent change in water height ($\beta = 0.011$, 95% CI: -0.00042 – 0.022 , $p = 0.059$, $R^2 = 0.038$, $y = 0.011x - 2.2$).

4. Discussion

4.1. Overview of Findings

Across the three phases of this study, pool depth was the variable most consistently associated with indicators of drought resilience, including amphibian breeding effort, hydroperiod length, and water retention during seasonal drying. While the relationship between greater depth and increased water storage capacity is ecologically intuitive, the consistency of this association across multiple datasets suggests that depth may serve as a useful indicator of vernal pool persistence during drought conditions. This finding is consistent with Brooks (2005) [7], who identified basin morphology, particularly pool depth and storage capacity, as key controls on hydroperiod persistence in seasonal forest pools. Likewise, Cartwright et al. (2021) [15] identified hydrologically persistent vernal pools as important climate refugia for amphibian reproduction under increasing drought, highlighting the conservation value of pools that retain water longer. The suggestion from these findings is valuable information for creating a conservation management plan. Rather than basing conservation plans on the hydrologic inputs of vernal pools, which can be challenging due to the difficulty of assessing hydrology without field study of each unique small pool, plans can instead rely on more easily measured physical characteristics, such as maximum pool depth and area. The identification of deeper pools as being consistently associated with drought resilience may help land managers prioritize naturally persistent vernal pools for conservation and monitoring. Additional experimental research is needed before management actions that alter pool morphology, such as deepening or expanding pools, can be recommended.

Results from Phase I, specifically **Figures 4** and **5**, showed positive associations between pool depth and breeding effort for both *Ambystoma* Salamander eggs and Wood Frog eggs. Phase II of this study looked at the question of whether hillslope flow pathways may contribute to a pool's stability during drought conditions. Qualitative observations indicated that pools were influenced by a variety of hillslope flow pathways and hydrologic conditions. Some pools presented relatively stable water levels, while others experience rapid fluctuations in depth and water quality metrics, suggesting that multiple hydrologic processes contribute to pool dynamics. However, no single hillslope flow pathway consistently distinguished wetter pools from drier pools across all sites. Evidence of this can be seen in **Figures 8** and **11**. **Figure 8** depicts the depth of Vernal Pool W during Fall 2023 and **Figure 11** depicts the recorded depths of Vernal Pool D. The depth in Vernal Pool W is stable with very few sporadic spikes whereas the depth of Vernal Pool D is very inconsistent. In this case, it can be qualitatively observed that Vernal Pool W is less affected by outside elements, such as surface water, due to an additional water source entering the pool. Furthermore, the turbidity data in **Figures S5–S8** and **S12–S14** also display evidence of multiple flow pathways. The turbidity of the drier pools (**Figures S7, S8** and **S14**) was more varied than that of the wetter pools (**Figures S5, S6** and **S12**). This is likely due to more surface water entering the drier pools. However, despite these observations, pool size and depth showed more consistent associations with persistent metrics than the hydrologic pathway indi-

cators evaluated in this study. All the vernal pools that were studied behaved and operated similarly hydrologically despite their differing hillslope flow pathways. A key difference between the wetter and drier pools is that the wet pools have a higher maximum depth and they do not reach a depth of zero (i.e., dry down) during the wet season. Similarly, Phase III findings highlight the importance of depth in the overall hydroperiod of vernal pools. **Figures 16 and 17** show that pools with a greater maximum depth had higher water levels in July and lost less overall water, compared to shallow pools. As stated, the pools with greater depths likely did not reach dry down, as they retained more water to begin with. This reinforces the idea that depth is a key factor in vernal pool stability during drought. Together, these findings indicate that depth is a practical and readily measurable characteristic associated with drought resilience. Because depth can be assessed rapidly in the field without intensive hydrologic monitoring, it may provide a useful screening metric for identifying pools with greater conservation potential.

This study was designed to identify associations among pool characteristics and drought responses rather than to determine the relative importance of all potential drivers of resilience. Multiple physical, chemical, hydrologic, and landscape variables were measured, but their independent effects were not evaluated simultaneously. The identification of size and depth as the most consistent field-measurable characteristics associated with drought resilience is an important discovery in the context of conservation strategies under a changing climate as it shows that pools that are larger and have the capacity to hold more water are more resistant to altering drought conditions. Hydrological and geological factors, such as hillslope flow pathways, did not have the uniform influence over vernal pool stability that was originally anticipated at the start of this study. From a management perspective, these findings suggest that basic topographic and bathymetric measurements may provide a straight-forward first step for prioritizing vernal pools for monitoring, protection, and restoration under increasingly variable climatic conditions. With more effective management strategies in place, amphibian populations can be better conserved under enhanced drought and changing climate.

Jointly, the three phases of this study provide complementary evidence regarding vernal pool persistence under drought conditions. Phase I demonstrated that deeper pools generally supported greater amphibian breeding efforts, highlighting the ecological significance of hydroperiod stability. Phase II explored hydrologic behavior within a subset of pools and suggested that multiple flow pathways and hydrologic processes may contribute to differences in pool persistence. Phase III expanded the analysis across a larger network of pools and showed that deeper pools consistently retained water longer during seasonal drying. Combined, these findings suggest that while the mechanisms governing drought resilience are likely multifaceted, pool depth emerged as the most consistent and readily measurable characteristic associated with ecological and hydrologic persistence across the study. These findings contribute to a growing body of research demonstrating that physical basin characteristics influence wetland resilience under changing climatic conditions [14,17]. As drought frequency and intensity continue to increase, identifying naturally persistent vernal pools may provide an effective strategy for prioritizing conservation efforts. Further, depth may provide a practical starting point for conservation prioritization and monitoring efforts, allowing managers to identify pools with greater potential to persist through drought while more detailed investigations of hydrologic connectivity, water chemistry, and landscape influences continue to refine understanding of vernal pool resilience.

4.2. Coefficient of Variation, CV

Vernal Pool W was found to have the lowest CV values for draw-down depth at 9.9 and 24.9 during Fall 2023 and Spring 2024, respectively. These values show that Vernal Pool W has the least amount of variation in the data collected and therefore has the most stable depth. Vernal Pool W is consistently the deepest vernal pool in this study. This lower CV suggests stronger connections with more stable sources of water from deeper groundwater sources, suggesting overall depth and water level stability may go hand-in-hand for some of the deepest pools. The CV values for the draw-down depth of the most common type of vernal pools in the middle of the spectrum (Vernal Pool MW, M, and MD) are around 100, with Vernal Pool MD having a slightly lower CV during Fall 2023. This data shows that these three vernal pools all have more variation in their depth values; they are less consistent in their depth and, therefore, in their stability, hence the name “vernal” pool to describe them. Though, despite having a variety of actual depths, the variation in depth is relatively consistent across pool types in this middle dry-wet range of all the most common pool types, suggesting that the main buffer to pool drying for a normal vernal pool may indeed just be overall total depth, since the hillslope flow pathways and processes feeding these pools result

in similar amounts of up and down height variation across the seasonal change. Finally, Vernal Pool D, the driest pool studied, has lower CV values for draw-down depth at 41.1 during Fall 2023, similar to the low values observed for the wettest pool, Vernal Pool W. This value shows that there is less variation in depth data than the majority of vernal pools in the middle of the wet-dry gradient in this study. These CV values for the vernal pools' depth variation support the idea that the physical characteristics of a vernal pool (ex. depth, volume) are more important to a pool's stability than the hydrological make-up of the pool's hillslope flow pathways and inputs, except for pools that are near-perennially wet or consistently dry.

4.3. Comparison to Other Studies and Possible Error

A previous study was done that compared vernal pools to beaver-created ponds [52]. Due to the semi-permanent nature of beaver ponds, they have similar qualities to seasonal vernal pools. In this previous study the densities of wood frog egg masses were compared to the density of spotted salamander egg masses [52]. The study focused on 65 vernal pools and 37 semi-permanent beaver ponds over 3 years [52]. It was found that the wood frog egg mass densities were similar in both ecosystems, however, the spotted salamanders had 4 times as many egg masses in vernal pools [52]. In the northeastern United States, there has been an increase in beaver populations. With the evidence of beaver ponds being used by amphibians for similar purposes to vernal pools, beaver ponds may be a suitable substitute for vernal pools in the future. More research is needed to confirm viability of metapopulations of vernal pool obligate amphibians in beaver ponds.

Previous studies explain how the location in which a vernal pool forms impacts groundwater availability. Therefore, vernal pools do not all have equal access to groundwater [53]. One study describes how vernal pools with a clay-rich soil base have different physical and chemical hydrology than vernal pools with a hardpan soil base [28]. The soil concentration, the way in which water becomes groundwater, and the geology underneath a vernal pool all impact the movement of water between the ground and the surface [54]. Recent work has shown that basin morphology is a primary driver of hydroperiod in small, isolated wetlands, supporting the importance of pool shape and depth in ascertaining pool resilience [55]. Physical and chemical hydrology also have an impact on which species predominantly live in the ecosystem [54]. Although this study did not find much noticeable evidence of groundwater increasing a vernal pool's stability, except in the deepest of pools, increased access to groundwater may still be beneficial to the stability of vernal pools for some of these most consistently wet and deepest vernal pools (i.e., near-perennial pools).

This study was limited by several factors, including a small sample size, the accuracy of the Smart Rock sensors, and a short period of data collection. Another limitation of this study was the inclusion of only pools that were wet for the entire study period in the statistical analysis of Phase I, creating a potential bias towards more persistent pools. It would also be valuable to repeat this study with sensors deployed over a longer timeframe to observe how vernal pool hydrology changes across seasonal transitions throughout multiple years. Additionally, incorporating a method to more accurately track hillslope throughfall at site specific levels would allow for more accurate comparisons of how the hydrology and flow pathways of vernal pools respond to increased surface and groundwater inputs. Future studies incorporating larger sample sizes, longer monitoring periods, and multivariable statistical approaches will be important for evaluating the independent contributions of depth, hydrologic connectivity, water chemistry, and landscape setting to vernal pool persistence under a changing climate.

5. Conclusions

This study evaluated ecological, hydrologic, and hydroperiod characteristics associated with drought resilience in vernal pools across three complementary phases of investigation. Across all phases, deeper pools were consistently associated with greater amphibian breeding effort, longer hydroperiods, and greater water retention during seasonal drying. These relationships suggest that pool depth may serve as a useful and readily measurable indicator of drought resilience for monitoring and for conservation planning in vernal pool ecosystems. However, because this study was observational, these findings should not be interpreted as evidence that pool depth alone determines drought resilience, or that modifying pool depth would necessarily improve ecological outcomes. In some cases, modifying pool depth may lead to alternative ecological and environmental issues.

In Phase I of the study, it was observed that, of all the variables analyzed, the depth of a pool's water showed the

strongest association with amphibian breeding effort, a proxy for populations of these species. The deeper vernal pools were consistently associated with higher amphibian breeding effort, suggesting that these pools may provide environmental conditions more favorable for successful reproduction under drought conditions. This idea was introduced in Phase I of the study and later observed in Phases II and III where physically larger and deeper pools showed increased resilience against drought. The variation in hillslope flow pathways and hydrological variables that were studied in Phase II were more weakly associated with the vernal pool's overall drought stability than pool depth and did not provide evidence that more stable pools have more groundwater access than the majority of normal vernal pools. In Phase III, it was found that pools with greater depths had more water in July and lost less overall water than the shallower pools. This pattern indicates an association between greater pool depth and longer hydroperiods amidst seasonal drying rather than demonstrating a causal relationship. Overall, the stability of each vernal pool was more closely associated with the volume of water that the pool holds, with less regard for the hillslope controls of hydrologic inputs. It is important to understand which characteristics are associated with the stability of these wetland ecosystems as the climate continues to change so land managers can prioritize resilient vernal pools for monitoring and conservation. Although restoration can provide additional vernal pool habitat, restored and natural pools may differ in invertebrate community composition and abundance, highlighting the importance of conserving existing natural pools while considering characteristics associated with greater hydrologic resilience, such as pool depth, in restoration planning [56]. Additional experimental studies are needed before management interventions that alter pool depth can be recommended.

Supplementary Materials

The supporting information can be downloaded at https://ojs.ukscip.com/uploads/2/asset-file/2026/09/asset-file_50f2cca46ec2a6612593348ad8317b60.pdf.

Author Contributions

Conceptualization, A.J.W. and P.Z.K.; methodology, M.G.D., K.M.F., A.J., A.J.W., D.S.S., and P.Z.K.; software, M.G.D. and A.J.; validation, M.G.D., A.J., and K.M.F.; formal analysis, M.G.D., A.J., and K.M.F.; investigation, M.G.D., K.M.F., A.J., A.J.W., D.S.S., and P.Z.K.; resources, P.Z.K., A.J.W., and D.S.S.; data curation, M.G.D. and A.J.; writing—original draft preparation, M.G.D. and A.J.; writing—review and editing, M.G.D., K.M.F., A.J., A.J.W., D.S.S., and P.Z.K.; visualization, M.G.D., A.J., and K.M.F.; supervision, A.J.W. and P.Z.K.; project administration, P.Z.K., A.J.W., and D.S.S.; funding acquisition, P.Z.K. and A.J.W. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

This study involved visual observation of egg masses of wild animals. We did not physically interact with the egg masses in any way, and the egg masses would not have behavior that could be affected by researcher presence (as opposed to adults which might have, for example, stress reactions merely from researcher presence); Adults are not present after laying eggs. Therefore ethical review of the study was not applicable or required.

Informed Consent Statement

Not applicable.

Data Availability Statement

Additional data is available through the **Supplemental Materials** document associated with this publication. Some data has not been made available due to species conservation concerns, but can be provided when appropriate through correspondence with the authors.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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