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Hydrologic Structure and Function of Vernal Pools in South Deerfield, Massachusetts

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Hydrologic structure and function of vernal pools in South Deerfield, Massachusetts

A Thesis Presented

By

CHARLOTTE M. AXTHELM

Submitted to the Graduate School of the
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Environmental Conservation

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ABSTRACT

HYDROLOGIC STRUCTURE AND FUNCTION OF VERNAL POOLS IN SOUTH DEERFIELD, MASSACHUSETTS

SEPTEMBER 2019

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Directed by: Professor Paul K. Barten

Vernal pools are small, ephemeral wetlands lacking an inlet or outlet. These wetlands, also known as seasonal pools, are found in a wide range of biomes, and their characteristics vary based on location. While the vegetation of western U.S. pools, and amphibians of eastern U.S. pools have been extensively studied, many aspects of vernal pools have not been fully characterized. In particular, although the general seasonal wetting and drying cycle is understood qualitatively, few studies have attempted to quantify the hydrological regime of vernal pools in New England. As water level variation drives many, if not all, of the characteristics unique to these systems, more research on this aspect of vernal pool functioning is needed. The primary objective of this study was to gain a better understanding of vernal pool hydrology through the study of a complex of three pools in South Deerfield, MA. The water level in the South Deerfield pools has been monitored since 2009. For this study, the most recently recorded water year (1 October 2017 to 30 September 2018) was used to characterize the water level fluctuations in the Middle Pool. Water level was monitored manually (weekly intervals) and with pressure transducers (4-hour intervals) in permanently installed wells. The effects of precipitation and evapotranspiration on water level were quantified with a water balance analysis. This analysis also estimated changes in storage by estimated inflow from the uplands and outflow via deep seepage. Water level changes in the Middle Pool were consistent with qualitative descriptions and trends described in earlier studies in the region. We found that the countervailing effects of precipitation and evapotranspiration were the primary drivers of water level fluctuations throughout the year. However, the estimate of storage derived as a water balance residual was not representative of water level in the vernal pools. The storage estimate derived for the Middle Pool was more successful at estimating the water level during spring transition, the high water period most important to amphibian breeding.

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CHAPTER 1

INTRODUCTION

Vernal pools are small wetlands with complex hydroperiods involving seasonal wetting and drying cycles, and no surficial hydrologic connections to larger wetland or watershed systems. The lack of surficial connectivity and the non-permanent hydrology both contribute to the perception that vernal pools are less valuable than other wetlands, as well as the idea that vernal pools are isolated. On the contrary, both of these factors make vernal pools unique and essential components of a landscape and have a large effect on the faunal communities they support (Semlitsch and Bodie, 1998; Brooks and Hayashi, 2002). The idea of isolation in the classical sense has also been proven to be outdated in a number of ways (Semlitsch and Bodie, 1998; Snodgrass et al., 2000; Zedler, 2003). For species that use these systems, the complex of wetlands is as important as the individual wetlands, because each component provides a different purpose (Semlitsch and Bodie, 1998). One of the key examples of this is in prairie pothole wetland complexes, where waterfowl use different potholes at different times depending on their life stage (Brown and Dinsmore, 1986). Likewise, many vernal pool-obligate amphibians require the interconnectivity of geographically related wetlands for inter-pool dispersal, genetic diversity at the population scale, as well as for the different resources each site provides (Scott et al., 2013). The importance of these factors, and the understanding of vernal pools as critical landscape features, is becoming better understood, with mounting scientific evidence reinforcing this observation.

The non-permanent, seasonal nature of vernal pool hydrology is also unique. In New England, the essential pattern of wetting and drying aligns with the growing season.

During the summer when evapotranspiration (ET) is strongest, pools are dry and the water level recedes because the water demands are higher than the inputs (Brooks, 2004). From the fall to the early spring, trees are dormant, and precipitation inputs in the form of rain and snowmelt cause the pools to fill (Fig. 1; Brooks 2004).

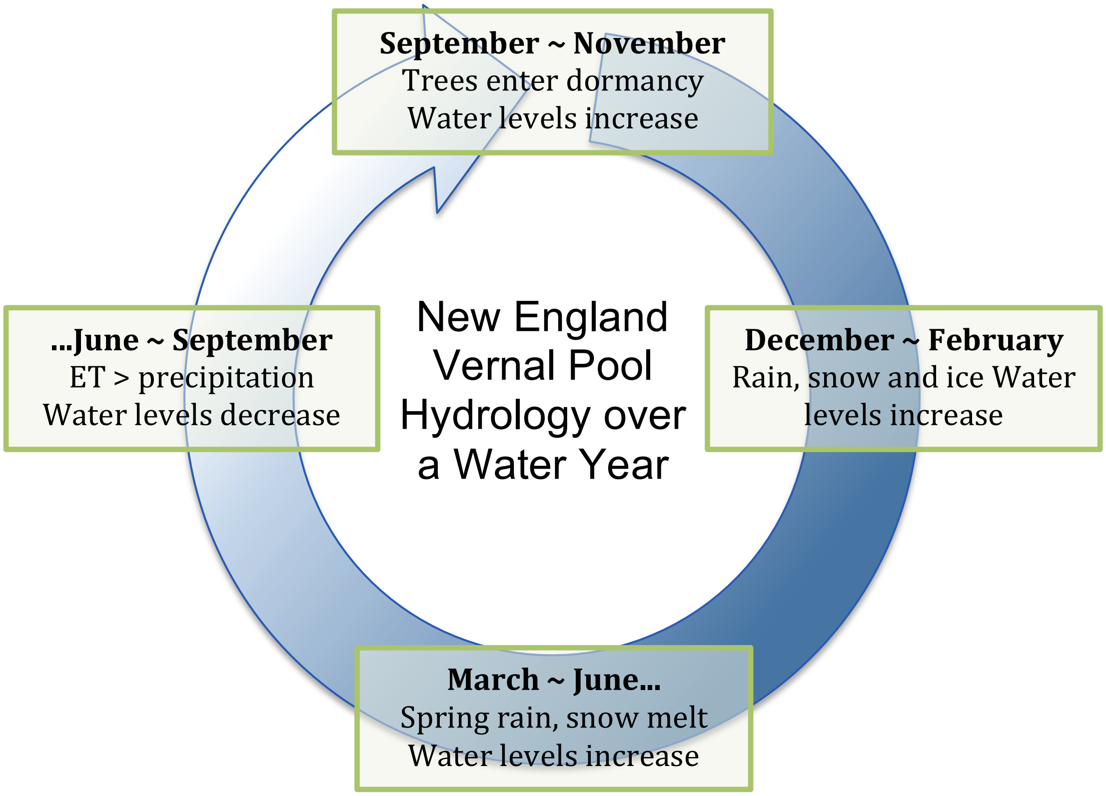

Figure 1: New England vernal pool hydrology over the duration of a typical water year. Precise start and ends dates of each phase of the cycle vary based on changes in water balance parameters, specifically precipitation and evapotranspiration.

These patterns are essential to the survival and success of vernal pool breeding amphibians, the main drivers of New England vernal pool protection (Semlitsch and Bodie, 1998; Calhoun et al., 2003; Zedler, 2003; Babbitt, 2005). Although vernal pool hydrology drives all of the characteristics that define these systems, in most parts of the world, it is not well understood (and has not been quantified) beyond general seasonal trends.

Through the use of traditional hydrologic methods (specifically, water balance analysis), the structure and function of these specialized systems can be explored, understood, and characterized in a way that may foster a greater appreciation of their value and place more emphasis on their protection. With the characterization of vernal pool hydrology and its driving factors, features like wildlife, soils, and vegetation (which depend on these specific hydrologic cycles) can also be described in more detail, and better protected.

1.1 Objectives

The objectives of this project were to (1) study and characterize the hydrology of three South Deerfield, MA vernal pools; and (2) create a water balance representation of the water level in these pools over the course of a water year. The guiding hypotheses were:

(1) Vernal pool hydrology will vary in relation to individual site factors, but will largely follow expected trends for New England vernal pools such as standing water during the winter, and summer drawdown and drying from evapotranspiration; and (2) the estimate of storage derived from water balance analyses will reflect the dynamic interaction of precipitation and evapotranspiration, but may not capture the fine-scale fluctuations of these unique systems.

Wildlife biologist Robert Brooks published a series of papers on the relationships between pool hydroperiod and benthic macroinvertebrate community composition, pool morphology, and weather effects in a complex of central Massachusetts vernal pools (Brooks, 2000; Brooks and Hayashi, 2002; Brooks, 2004). These papers are the basis (and essentially the full extent, to date) of the general understanding of vernal pool hydrology in southern New England. The Brooks (2004) study on weather effects discovered a positive correlation between water level change and precipitation events, and a negative correlation with potential evapotranspiration. This study found that, in 3 of the 4 pools studied, weather effects explained water level changes more than half the time (Brooks, 2004). We also predicted there would be an inverse relationship between air temperature and the water level in the South Deerfield pools. Air temperature controls both evaporation and transpiration rates on the site, since it is also correlated with plant dormancy. Monthly precipitation totals, on the other hand, are relatively consistent throughout the year in New England. We predicted a causal relationship between precipitation and rising pool water levels, and, through the dual effects of the relative presence or absence of evapotranspiration, a strong association between air temperature (as a surrogate for ET, daylength, and available energy) and corresponding changes in pool water level.

The Brooks (2004) study used a simplified weekly water balance equation: ΔPool surface water depth = Precipitation – Potential Evapotranspiration ± Groundwater contribution (Brooks, 2004). A later study refines this water budget to include channelized runoff (Brooks 2005). This series of papers provided the foundation for a more detailed hydrometeorological study of the South Deerfield vernal pools.

CHAPTER 2

LITERATURE REVIEW

As noted above, vernal pools in New England are important habitat for many specialist species. Wildlife use and habitat suitability is one of the most heavily studied subsets of the field of research, as vernal pools are some of the only systems that can be used as habitat for many invertebrates and amphibians (Karraker and Gibbs, 2009). The unique habitat value of vernal pools is due largely to their systematic exclusion of certain types of predators as a result of the aforementioned seasonal hydroperiodicity and isolation (Babbitt, 2005; Baldwin et al., 2006). The lack of inlet or outlet prevents fish species from becoming part of the vernal pool food web. Fish are unable to persist in systems that are reliably dry on an annual basis, allowing mole salamanders (*Ambystoma* spp.) and wood frogs (*Lithobates sylvaticus*) to reproduce without this threat of predation (although wood ducks, raccoons, and other predators may reduce their populations). This facet of vernal pool functioning is fairly well understood. However, the extent of non-wildlife centric knowledge beyond this is relatively limited.

One of the factors contributing to this issue of insufficient knowledge is the very diverse geography of these systems. Vernal pools are found in a wide variety of different biomes, but the term actually first emerged as a descriptor for ephemeral wetlands found in California before it was applied to similar systems in other areas (Keeley and Zedler, 1998). Because the term originated in this specific region, most of the published research did as well. However, the character of pools on the west coast can be markedly different from pools found elsewhere, making California-based research results difficult to extrapolate.

As a result, vernal pool studies based in New England make up a considerably smaller proportion of the research than the total number of articles would suggest. A 2003 review of the existing vernal pool literature discovered that only 6 (of 66) abstracts with an identifiable location were based in the northeastern United States (Zedler, 2003). This same article emphasizes the difference even among pools in the same region, contrasting pools with primarily herbaceous vegetation in Massachusetts with pools with mature forest vegetation in Maine (Zedler, 2003). These distinctions further shrink the number of articles pertinent to this study, and illustrate the limitations of the existing body of knowledge.

Studies based in the Northeast focus mainly on inventorying sites and evaluating habitat, while the niche of studies on hydrology remains largely unfilled. The collection of studies by Brooks discussed above lays the groundwork for a more complete understanding of Massachusetts vernal pool hydrology. To date, these studies have mainly facilitated further study of vernal pool fauna, without delving into study of their hydrology. As mentioned above, the study on hydrologic modeling concluded that the pools were affected most significantly by precipitation and evapotranspiration (Brooks, 2004). In contrast, a previous paper on the South Deerfield pools in this study suggested that evapotranspiration alone had the most significant impact (Collins, 2013). This site-specific difference demonstrates that one set of results is not necessarily transferable to every other vernal pool system in Massachusetts, and emphasizes the importance of a more mechanistic understanding of the individual differences in New England vernal pool hydrology.

The study by Collins (2013), which also focused on the South Deerfield pools, characterized the patterns of soil and vegetation along transects. The objective of this study was to determine if soil and vegetation were similar at comparable positions along a hydrologic gradient, and to quantify the effect of soil organic matter on vegetation community development (Collins, 2013). This study identified relationships between redox potential data and water table fluctuation, and determined that each of the South Deerfield pools produced similar hydrologic gradients (Collins, 2013). Collins used on-site piezometers to confirm that the pools were being filled by shallow subsurface flow from the upland contributing areas (as opposed to direct precipitation inputs or overland flow). The project also determined that water is removed primarily through evapotranspiration. These conclusions are informative, but because the primary objective of the study was not to thoroughly characterize vernal pool hydrology it is difficult to transfer the approach to other sites that lack detailed in situ measurements. We used a complementary approach and commonly available hydrometeorological data to minimize this constraint. Of course, more salient on-site data would help to calibrate and verify water balance calculations, but in many cases the resources for more intensive monitoring are simply not available.

Although some New England vernal pool studies discuss the effects of climatological factors on hydroperiods and contingent vernal pool functions, these studies do not thoroughly address the changes that may occur in relation to climate change. As climate change continues and accelerates, it will only become more essential to better understand the hydrology, which drives or controls a multitude of unique vernal pool functions.

Global Circulation Models (GCMs) predict that, given the trajectory of air temperature and precipitation regimes over the past century, the climate will, in general, continue to become warmer and wetter, particularly if greenhouse gas emissions are not drastically reduced (Karl and Trenberth, 2003; Trombulak and Wolfson, 2004; Oreskes, 2005). In New England, climate change related temperature increases are predicted to have a large effect on vernal pool hydroperiod. As the climate warms, evapotranspiration will increase (Brooks, 2004; Trombulak and Wolfson, 2004). At the same time, precipitation could change in a number of ways: amount of precipitation is expected to increase, but more importantly, the frequency and intensity of storms may change (Trenberth et al., 2003). The combination of increased ET and more frequent, intense storms could result in shorter, or at least more erratic, vernal pool hydroperiods; this could have adverse effects on ecosystem services provided to breeding amphibians (Brooks, 2004; Snodgrass et al., 2000). However, the specifics of the climate change-driven alterations to vernal pool hydrology are uncertain because baseline hydrologic conditions have not been defined across a wide range of sites and hydrometeorological conditions.

CHAPTER 3

STUDY AREA

Three vernal pools in South Deerfield, MA were selected for this study (Figure 2).

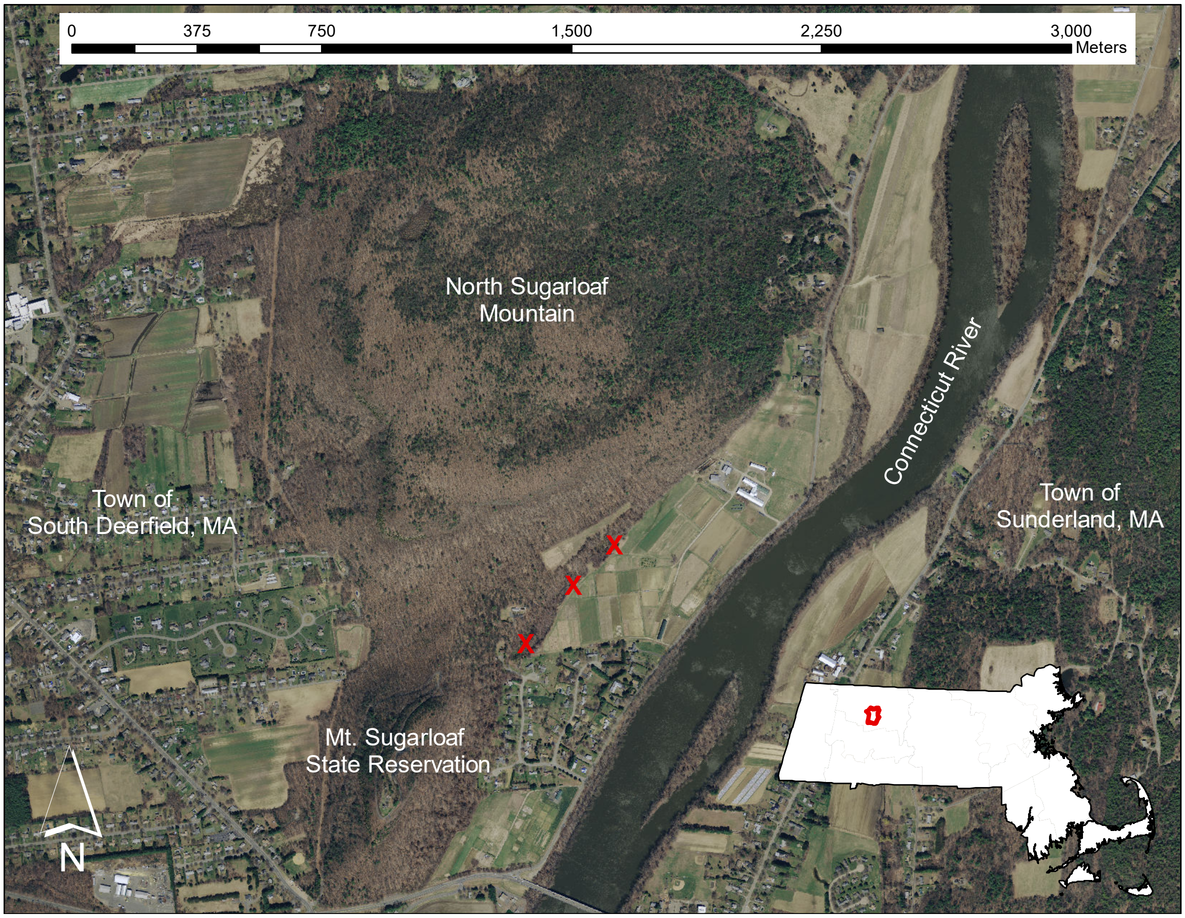

Figure 2. Location of the pools at the base of North Sugarloaf Mountain, adjacent to the Connecticut River, in South Deerfield, MA.

The vernal pools selected for this study are broadly representative of others in temperate regions. Water storage occurs as shallow subsurface flow (Q_{SS}), and groundwater upwelling via deeper flowpaths enters the pool. Direct precipitation (rain and snow) is also stored for varying periods of time. Evapotranspiration is the primary driver and pathway of water loss, and leakage is another, secondary pathway (Brooks, 2004; Collins, 2013). As noted earlier, pools in New England typically exhibit a hydrologic regime of summer drying, followed by fall, winter and early spring recharge

(Figure 1; Brooks, 2004; Colburn, 2004; Collins, 2013). The pools in this study generally follow this pattern, although during particularly wet years they may not dry completely.

The pools are situated at the base of the eastern slope of North Sugarloaf Mountain on the University of Massachusetts Agronomy Research Farm. The pools were chosen for a number of reasons, chiefly their proximity to each other, as well as their consistency in soil series and landscape position. The soil series at the pools is Winooski, which is a coarse-silty, mixed, superactive, mesic Fluvaquentic Dystrudept (Collins, 2013). The primary cover type of the adjacent upland forest is mixed deciduous, though vegetation shifts to primarily shrub and herbaceous wetland species near the pools. Although the species in and around the pools are distinct from the upland community because of their adaptations to anaerobic conditions, the vegetation of the pools is not useful in distinguishing them from other wetland systems, as is the case in California vernal pools (Ciccotelli et al., 2011; Schlising and Sanders, 1982). The study sites are located at a general elevation of 43 m, downslope from a glacially-formed kame terrace, at the edge of the Connecticut River floodplain (Figures 2, 3 and 4; Collins, 2013). Above the South Pool is a house lot with an approximately 150 m long driveway (Figure 4). This noteworthy change in land cover, relative to the forested watersheds of the Middle and North Pools, may influence volume and rate of water movement to the South Pool, and consequently, water level fluctuation. Because of the location of the pools at the toe slope of North Sugarloaf Mountain, watershed slopes are variable, but generally average 20 to 30 degrees (Figure 5).

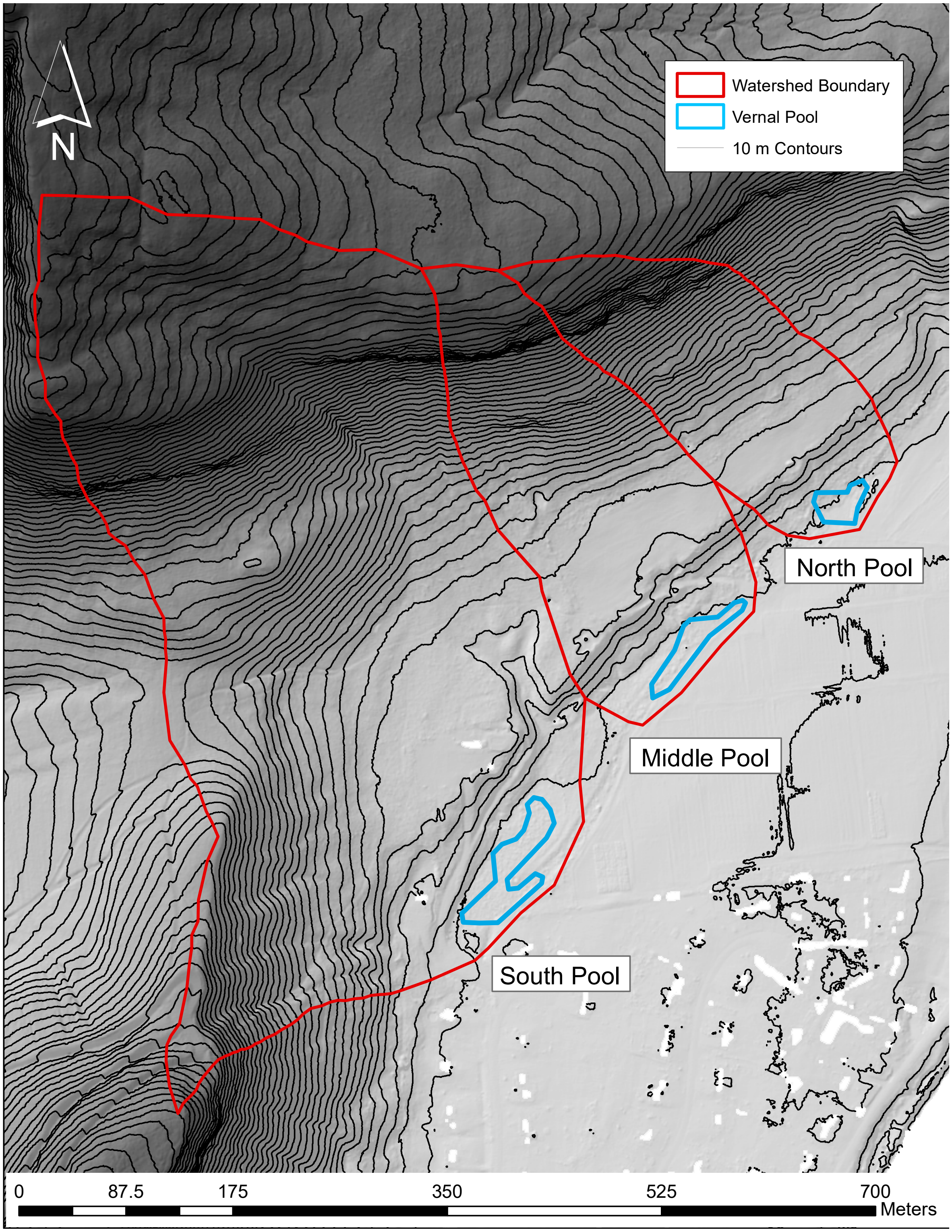

Figure 3: South Deerfield vernal pools. The break in slope located approximately 30 m upslope of the pools is a glacially formed kame terrace. Contours were developed using 2015 NOAA LiDAR terrain data.

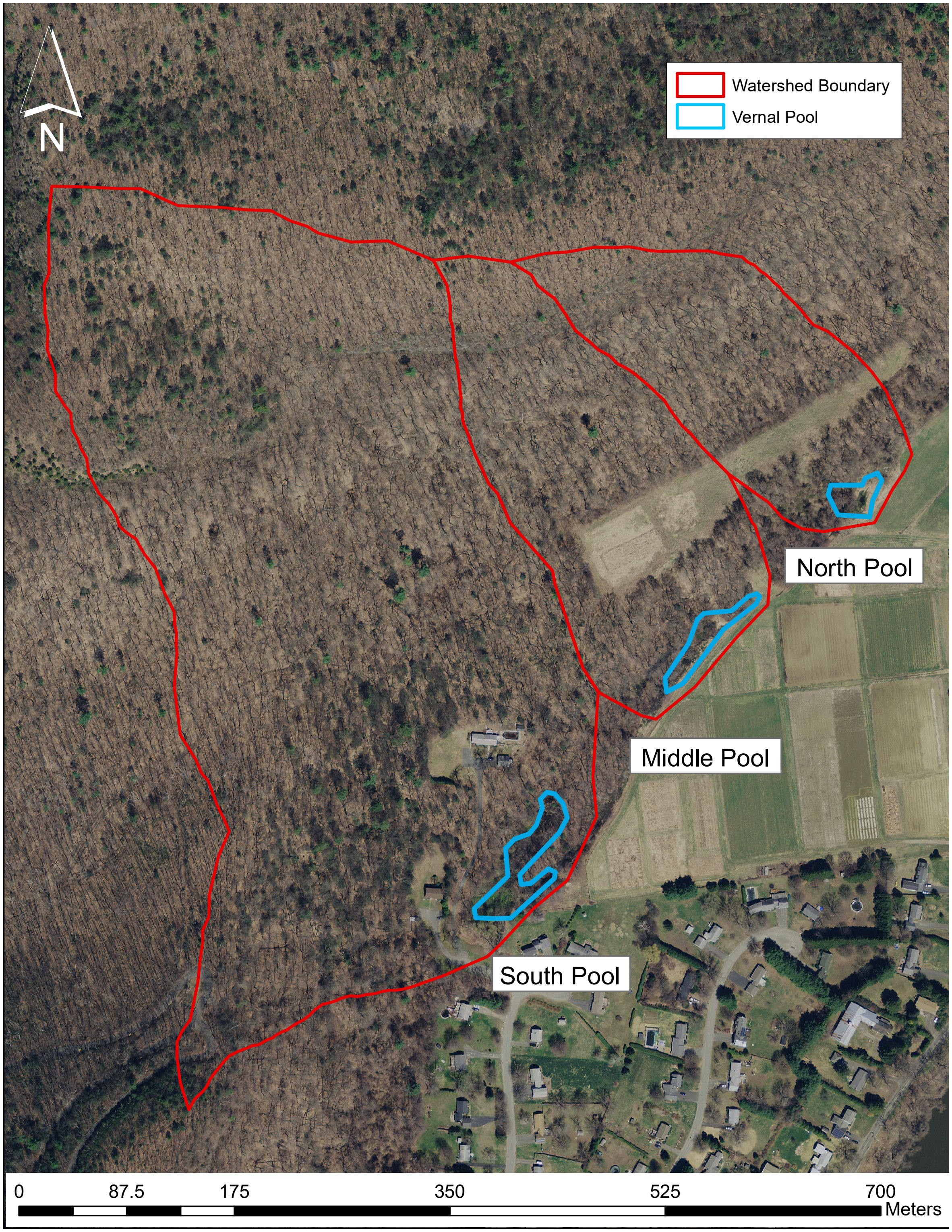

Figure 4. South Deerfield vernal pools and watersheds. The house lot above the South Pool and associated impervious surfaces is visible, as well as the kame terrace above the North and Middle Pools.

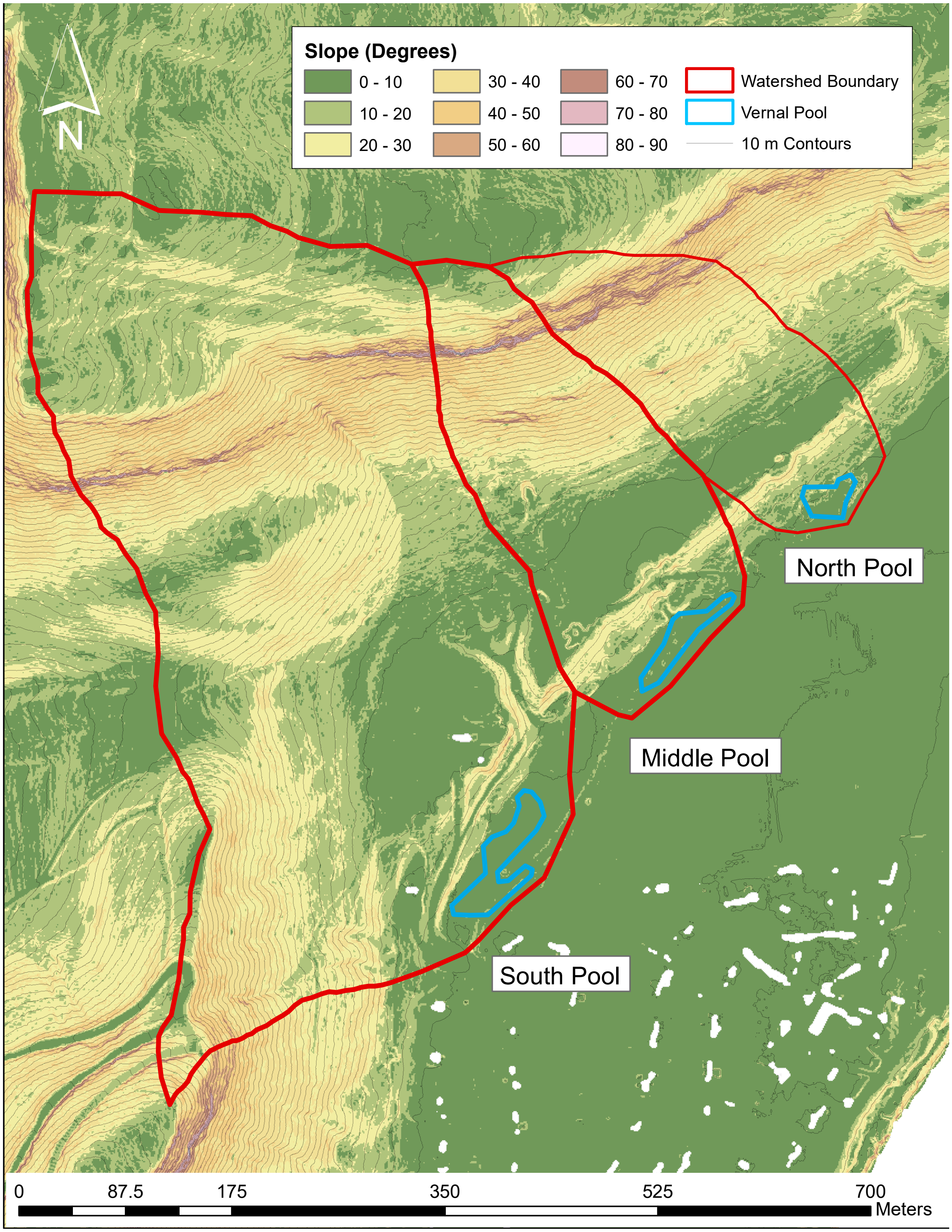

Figure 5. Slope map for the study area. The broad flat area at the base of the slope is the UMass Agronomy Farm, and the flat area above the pools is the kame terrace. Above the South Pool, the house lots are visible as white (flat) polygons.

Although the pools occupy equivalent landscape positions at a very similar elevation, the pool area and watershed sizes differ substantially (Table 1). The differences in the ratio of pool area to watershed area are also likely to influence their hydrologic regimes. The series of papers by Robert Brooks included the identification and mapping of 430 central Massachusetts vernal pools (Brooks, 1998). The majority of these pools (67%) were less than 0.5 ha in surface area. None of the South Deerfield pools are this small, but the North and Middle Pools are in the same size class as 10% of the pools identified, while only 3% of the pools mapped by Brooks are in the same size class as the South Pool (Brooks, 1998). The Middle Pool also has the longest continuous record of water level data. As a result, the full data set for this paper focuses on the Middle Pool, as it is (of the South Deerfield pools) most broadly representative of vernal pools in the region.

Table 1. South Deerfield pool centroid coordinates, pool area, watershed area, and pool to watershed size ratio.

Pool	Coordinates	Watershed Area (ha)	Pool Area (ha)	Watershed to Pool Ratio
North Pool	42.47736° N, 72.58380° W	3.8	0.1	38:1
Middle Pool	42.47641° N, 72.58522° W	5.3	0.15	35:1
South Pool	42.47474° N, 72.58701° W	20.1	0.27	74:1

The pools in the study area are not Certified Vernal Pools with MassWildlife's Natural Heritage and Endangered Species Program (NHESP) (MassGIS, 2019). However, in previous years, researchers have observed the necessary criteria for certification in all three of the pools. Each of the pools is a closed system with no surface inlet or outlet, and each pool is known to be fishless due to periodic annual drying.

Numerous wood frog (*Lithobates sylvaticus*), spotted salamander (*Ambystoma maculatum*) and blue-spotted salamander (*Ambystoma laterale*) egg masses have been identified in each of the pools. In recent years however, egg masses of obligate vernal pool species have not been found in the South Pool, and the mud did not desiccate to a point where the pool could be considered dry. This may be attributed to the larger watershed area, the residential land use noted earlier, or some combination thereof.

CHAPTER 4

METHODS

4.1. Study Design

The South Deerfield vernal pools are part of the USDA Multistate HATCH Project NE1438: Hydropedology of Vernal Pool Systems. This project also included several pools located in South Amherst, MA. They were not included in our study after earlier work demonstrated a lack of reliable correlation between South Deerfield and South Amherst pools (Collins, 2013).

Within each pool are three permanent transects located approximately 6 m apart. Each transect includes three 1 m^2 plots arranged 2 m apart moving from the "summit" (i.e., the driest perimeter position) through the "rim" (the maximum extent of pool during wet periods) to the "basin" (the deepest part of the pool). This study used a variation on a split plot model to test depth effects on redox potential. Redox probes are nested in triplicate at 15, 30, and 45 cm depths, grouped around a salt bridge constructed in accordance with the methods described in Veneman and Pickering (1983). Redox probe and salt bridge construction was performed by previous researchers (Collins, 2013). Redox potential (Eh) readings were taken from the redox probes using a calomel electrode and a Multimeter. These measurements provide information about the potential of a solution to donate electrons to a reducible substance or accept electrons from an oxidizable substance. The redox potential measured at different depths can be used to draw conclusions about how long the soil has sustained anaerobic conditions at the depth of the redox probe, although redox potential can vary based on site specific factors including soil microbial activity, available organic matter, and relative abundance and availability of different electron acceptors (Pezeshki and DeLaune, 2012). At each summit, rim, and basin position, a well constructed out of PVC pipe was installed to approximately 40 cm to monitor the depth to free water. Additionally, two piezometers per pool were installed at 50 and 100 cm to monitor the piezometric head of the water table at each depth. The pools were monitored biweekly during the winter, and weekly during the rest of the year.

4.2. Site Data

We used pool boundaries originally delineated by UMass Amherst staff using 1:12,000 scale, stereo color-infrared (CIR) photography, and verified by the Department of Environmental Protection (DEP) Wetlands Conservancy Program (WCP) for the MassDEP wetlands GIS layer (MassGIS, 2009). Site specific pool information, including ground surface elevations and relative well elevations, was acquired with a differential level survey using a TopCon automatic level and stadia rod. One well was designated at a benchmark elevation of 100.00 feet. These benchmarks were used to bring earlier surveys to a common datum. Initial attempts to delineate the contributing area for each vernal pool on the east face of Mt. Sugarloaf used LiDAR data and flow accumulation and direction algorithms in ArcGIS. Ironically, the very high resolution of the LiDAR data and random variation in microtopography generated unrealistic sub-watershed maps. Consequently, traditional terrain analysis and delineation methods were used with USGS topographic maps, then refined with LiDAR contours generated at 3 and 10 m. The sub-watershed boundaries were imported to ArcGIS for geometry and area calculation (Figure 3).

4.3. Water Balance

4.3.1. Weather Station Data

To create a complete water balance analysis for the study area, air temperature and precipitation data from a relevant weather station are necessary. These data are used to determine the inputs (*P*), outputs (*ET* and *Q*), and change in storage (*S*) in the generalized water balance equation:

$$P - Q - ET \pm \Delta S = 0, \qquad (4.1)$$

where:
P = precipitation;
ET = evapotranspiration;
Q = water yield (streamflow + groundwater flow);
ΔS = change in storage (in soils, vegetation, wetlands, lakes, and/or streams).

In order to estimate or derive these parameters, and to develop an accurate understanding of the relationship between system inputs and outputs, reliable and accurate weather station data are necessary. The weather station at the UMass Crop Animal Research and Education Center, located at 89 River Road, South Deerfield, MA, was originally identified as an ideal prospective data source. This weather station is managed by the Network for Environment and Weather Applications (NEWA) through Cornell University. Since it is co-located with the pools at the base of Mt. Sugarloaf, we expected it would be the optimal source of precipitation and air temperature measurements. Although this was the case during the growing season, large gaps in the dataset (e.g., January – April 2009) were found. Documentation for the dataset also indicated that many intervals contain days where data are missing within the 24 hour period, as well as entire months where the data were estimated with one of three methods: (1) averaging data from the preceding and succeeding hours, (2) retrieving data from a “sister” station located in Worcester, or (3) using predictions from the NWS National Digital Forecast Database archive. Additional review showed instances (e.g., 56.1 inches of precipitation on 4/24/09 [~median annual precipitation in southern New England]) where basic quality control and quality assurance checks for meteorological data were not applied. Finally, there are long periods of zero (0) precipitation during the winter months when, without appropriate instrumentation (e.g., a heated gage, snow pillow, snow board and staff, etc.), snow cannot be measured. All of these discrepancies rendered this station unusable for annual and inter-annual water balance analyses.

The first alternative considered was the weather station at The Joseph Troll Turf Research Center located at 23 River Road, South Deerfield, MA. This station is maintained by the UMass Amherst Extension Turf Program, and is used in various turf and agricultural research projects. However, after making contact with one of the weather station managers, and the manufacturer of the weather station, Campbell Scientific Inc., it was determined that this weather station also did not include a heating mechanism on the precipitation gage, and thus could not accurately measure snow. As a result, we began a systematic search to identify weather stations that could serve as suitable replacements, considering proximity to the study area, elevation, and the length and completeness of the record.

Using the National Oceanic and Atmospheric Administration (NOAA) National Weather Service Database, several stations were identified as possible replacements: the Greenfield 3 weather station, the Leverett 2 weather station and the Orange Municipal Airport weather station. The Sunderland weather station was originally considered for proximity, but was removed from consideration because only air temperature data are recorded at this station. Each selected station had records that were more than 95% complete for both air temperature and precipitation. The elevations for these stations vary (South Deerfield: 40 m; Orange Municipal Airport: 164 m; Leverett 2: 130 m; Greenfield 3: 12 m) but are relatively comparable to the study site. Although an elevation difference of 100 m is not unimportant, this variance is unlikely to cause significant temperature or precipitation differences from the weather station to the pools. For each station, air temperature data for the entire study period (or as long as there was a relevant record) were compiled with the usable concurrent record from the South Deerfield weather station, and the two data series were cross-referenced to ensure that the data arrays were correctly aligned by date. This was also completed for the precipitation data series. An extra step was taken with the precipitation data: because the South Deerfield weather station recorded a number of false zeros during periods of time when the precipitation was frozen, an IF/ELSE statement was written to identify and remove precipitation records when the air temperature was recorded at or below 0 °C (thus removing any periods when precipitation might have occurred but not been recorded).

Once the South Deerfield weather station dates were properly aligned with the candidate NOAA station, the precipitation or air temperature data from both stations were plotted on opposite scatterplot axes and fitted with a linear regression trend line to derive a coefficient of determination. The R^2 values for the air temperature comparisons were similarly high: 0.91 for Greenfield, 0.92 for Leverett, and 0.98 for Orange. In contrast, the precipitation R^2 were not viable (e.g., <0.2) for the concurrent records with the NOAA stations in Leverett and Greenfield. The correlation between Cornell University's South Deerfield station and the NOAA station in Orange was 0.65. The lower precipitation correlation between the stations reflects the spatial variability of rainfall (e.g., summer convective storms) in southern New England, but the Orange Municipal Airport had the only continuous record available to complete annual water balance calculations and inter-annual comparisons. Because the NOAA Orange Municipal Airport weather station has a 98% complete record, brief periods of missing data were supplemented with values calculated using the regression equations developed for the NOAA Orange Municipal Airport in relation to the Cornell University South Deerfield station (when accurate).

4.3.2. Discharge Data

Discharge (*Q*) is also a necessary component of a water balance analysis. However, vernal pools, by functional definition, lack an outlet. Hence, stream gage data were obtained from an off-site station to represent the discharge component of water balance outputs; it is the surrogate for Q_{SS}, shallow subsurface flow from the uplands into the vernal pool. USGS 01174500 is located on the East Branch of the Swift River near Hardwick, MA. Discharge at this station has been measured continuously and consistently for nearly 80 years, and the data are subject to the highest standards of recording and vetting (USGS, 2019). This river reach is unregulated (unlike most Massachusetts rivers), so these data are representative of natural flow conditions (i.e., the dynamic balance of rain, snow accumulation and melt, evapotranspiration, and changes in storage). Nevertheless, in several water years, preliminary analysis of water balance data revealed through the evapotranspiration ratio (ETR) that total annual actual evapotranspiration ($AET \cong P - Q$ for the water year) exceeded potential evapotranspiration (PET, the estimated rate of water movement to the atmosphere when supply is not limited). PET is, by definition, the upper boundary condition of evapotranspiration, and as a result, AET is constrained by PET. This indicated that one of these values was incorrect, and since the method of calculating the index to PET (Hamon's equation) was reliable and unbiased in nine of eleven years, the data contributing to AET values were evaluated for potential inaccuracy.

Two periods of discharge data (all of the 2011 calendar year and May through July of 2014) were identified as questionable (long periods of zero discharge under non-drought conditions). For these periods, weather station and stream gage data from the Fisher Meteorological Station and Prospect Hill Hydrological Stations at Harvard Forest in Petersham, Massachusetts (part of the East Branch Swift River watershed)[1] were used, as a final step to produce a fully vetted water balance database. The precipitation data from Harvard Forest were used to ensure the cause-effect relationship between P and Q was fully represented in the replacement data. Although the distance between the pools and the Harvard Forest monitoring stations is slightly greater than the distance to the Orange Municipal Airport, these stations are still a part of the same regional weather system, making the substitution justifiable. In all cases, the database development process focused on compiling and vetting the best possible input for subsequent analyses.

4.3.3. Water Balance Calculations

Once a complete, fully vetted record of precipitation, temperature, and discharge was compiled, the data were used to calculate additional water balance metrics. Precipitation values were classified as rain and snow based on the rain-freeze threshold air temperature (mean daily air temperature of 0 °C). This threshold was also used to

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[1] https://harvardforest.fas.harvard.edu/harvard-forest-data-archive

define the change in snow accumulation, as well as the daily potential and estimated snowmelt. Evapotranspiration values were determined in two forms: (1) Potential Evapotranspiration (PET)—the amount of water that available energy could move to the atmosphere if the supply of water was not limited, and (2) Actual Evapotranspiration (AET)—a pro-rated estimate based upon the ratio of AET to PET for the water year (typically 0.8 to 0.9). Hence, AET estimates reflect the periodic limitations of water supply (e.g., extended periods with warm air temperatures and little or no precipitation) on this pathway of flow. PET was calculated using the Hamon method (mean daily air temperature, day length at the study site using the US Naval Observatory solar ephemeris, and saturation vapor pressure; Hamon, 1961). The final component of the water balance is change in storage with respect to time. Since ΔS is a composite term it is calculated as a water balance residual, using the equation:

$$S_{i+1} = S_i + P - ET - Q, \tag{4.2}$$

where:
S_i = storage at the beginning of the day;
S_{i+1} = storage at the end of the day;
P = precipitation;
ET = evapotranspiration;
Q = water yield (streamflow).

The initial estimated storage value for iterative calculations is adjusted to account for the minimum potential available water based on soil type (i.e., a non-negative, relatively small positive number representing residual water content). The dominant soil type for the pools in the study area is Winooski series; the soil profiles were dominantly silt loam-textured, which has a water content at -15 bar (wilting point) of 0.06 cm/cm (Collins, 2013; Soil Survey Staff, 2019a). The thickness of the soil profiles taken on the site was between 70 and 95 cm (average: ~80 cm). As a result, the amount of water at wilting point in the soils at the pools is between 4 and 6 cm. As a conservative estimate, we set 6 cm, or 60 mm, as the lower mathematical boundary condition for the storage calculations in Excel (Collins, 2013).

4.4. Water Level Data

Several sources of water level data were used to assess water level changes in response to precipitation: (1) manually collected weekly or bi-weekly water table depths using on-site wells; (2) pressure transducer data collected in 4-hour intervals from HOBO data loggers installed in several wells; and (3) water level data collected in 15-minute intervals by the Harvard Forest Prospect Hill Hydrological Station at the Black Gum Swamp. The 4-hour interval pressure transducer data and the 15-minute interval Harvard Forest data were aggregated to a daily time step (for direct comparison to the other daily hydrometeorological data).

Water level measurements from the lowest well in the Middle Pool (located in the middle transect) were used for comparison with Black Gum Swamp. We chose the well at the center of the pools for study because it most consistently had standing water. The middle transect of the Middle Pool also has the longest continuous data record, and the pressure transducers were installed in all of the wells in this transect. Field measurements of vernal pool water level were taken in relation to the total height of the well, then subtracted from the aboveground height of the standpipe. This standardized the data with respect to a relative ground surface elevation of 0 cm. The data were then adjusted to a reference point near the bottom of the well pipe (to yield an array of positive values). This allowed us to normalize the data on a unitless scale of 0 to 1 based on the maximum measured water level. The data from the pressure transducer data logger were normalized in the same manner. The Black Gum Swamp data were normalized, but because of the differences in location, wetland type, and size, these data were normalized based on the maximum water level for the swamp (with no reference to the South Deerfield survey datum).

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Water Balance Analysis

The development of a water balance for South Deerfield was foundational to understanding the water level fluctuations of the vernal pools in the study area. As discussed above, this analysis incorporated several data sources from the region to quantify the relationship between meteorological parameters (air temperature and precipitation), streamflow, evapotranspiration, and changes in total storage. The 2018 water year is the only period of record with a complete data series for vernal pool water level.

Massachusetts generally averages between 1,000 and 1,200 mm of precipitation a year (U.S. Climate Atlas, 2019). In 2018, 1,440 mm was recorded, which made this year higher than average in both precipitation and discharge. Air temperature followed typical patterns for the area, and minimum and maximum air temperatures were consistent with most other years (Table 2). The inter-annual variability characteristic of New England can be expected to influence vernal pool hydroperiod in a similar manner to the annual streamflow hydrograph, as well as the pattern of water level fluctuation of instrumented forested wetlands such as Black Gum Swamp at Harvard Forest.

Table 2: Summary table of annual totals for water balance components and air temperature data for the water years where pool data has been collected (1 October to 30 September Water Year). The water year is labeled based on the calendar year when most of the months take place. For instance, the 2009 water year begins on 1 October 2008, because the majority of the months between 1 October and 30 September fall in the 2009 calendar year).

	Precipitation (mm)	Q (mm)	Minimum Air Temperature (°C)	Maximum Air Temperature (°C)
2009	1191	780	-19.6	26.7
2010	955	510	-12.7	29.8
2011	1512	660	-21.6	28.9
2012	1069	557	-13.8	27.5
2013	1024	567	-15.8	28.7
2014	1069	672	-19.4	25.2
2015	1130	770	-18.8	25.8
2016	831	521	-19.4	27.5
2017	1012	471	-15.8	25.3
2018	1439	884	-15.3	29.2

Precipitation was consistent (on a monthly basis) throughout the 2018 water year, with several large events occurring in late fall and summer. As expected, discharge was a subdued reflection of rainfall and snowmelt patterns. The amount of water that passed the stream gage was about half of the annual precipitation total. Once again, this is typical in the southern New England region. The climatograph demonstrates the dynamic relationship and compensatory changes in Q and ET in response to rain and snowmelt events (Figure 6). Normalized change in storage (ΔS) is superimposed on the climatograph to show the temporal patterns of water availability.

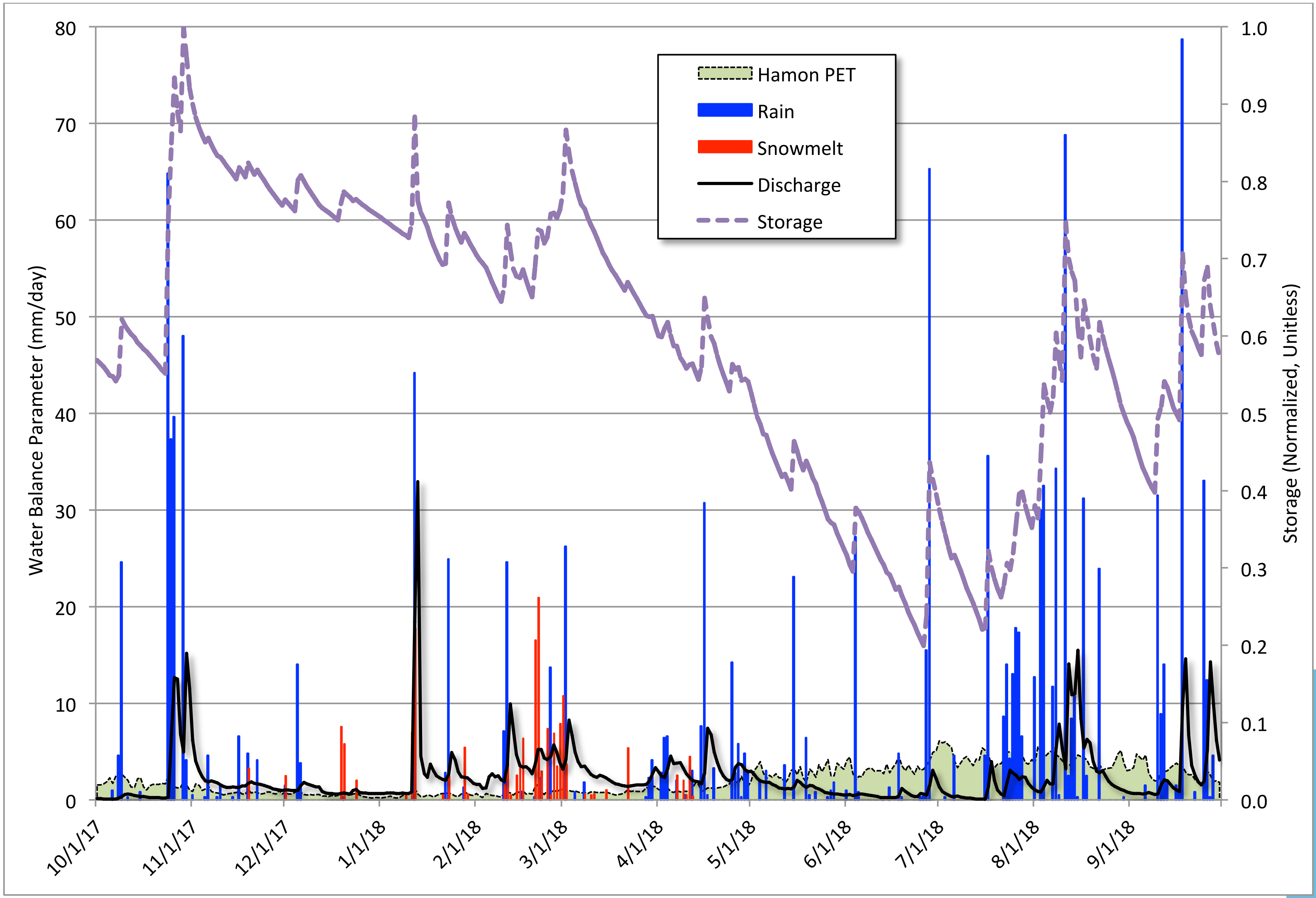

Figure 6. Daily climatograph (Rain, Snowmelt, Evapotranspiration, and Discharge [from the uplands to the vernal pools]) and normalized change in storage representative of conditions in South Deerfield, MA (Data sources: Orange Municipal Airport Weather Station, and USGS 01174500 stream gage).

As described in the Methods section (4.3.3), total storage is calculated as a water balance residual (Equation 4.2) with a lower boundary condition based upon the wilting point water content of the dominant soil type. The absolute range of the estimated storage term was 61 mm (6/26/18) to 308 mm (10/29/17) across the water year. As expected, the strongest seasonal influence on storage is related to the amount of water leaving the system via evapotranspiration. The water year can be divided into several major stages depending on the magnitude of different water balance components (particularly evapotranspiration) on storage at the time. These hydrologic seasons are described below.

5.1.1 Fall Recharge

The beginning of the water year is the transition from the growing season to the dormant season, also known as Fall recharge. Early in the water year, storage was high, reaching a peak as a 65 mm late-October storm completed Fall recharge. Most of the water from this precipitation event entered the soil mantle, becoming temporary storage. Because evapotranspiration is low at this time of year due to decreasing air temperatures and daylength, and dormant vegetation, very little water was taken up by vegetation or lost to evaporation.

5.1.2. Snow Accumulation and Melt

Precipitation in the form of rain has an immediate effect on wetland water level and storage. Snow has an equivalent effect, but is linked directly to temporal patterns of accumulation and melt. During early and mid-winter, as a result of the temperate climate of Massachusetts, cycles of thawing and re-freezing are evident in the snowpack (Figure 10). Colder temperatures yield more consistent patterns of snow accumulation. Soil water content (the dominant component of total storage) declines during this period as drainage proceeds without new inputs.

Snowmelt begins during late-winter and early-spring, whenever air and snowpack temperatures rise above 0 °C. Evapotranspiration at this time was still low and trees were dormant. An early-March snowmelt event caused an abrupt rise in the amount of water moving into storage.

5.1.3. Spring Transition

During the transition between the dormant season and the growing season, evapotranspiration began to have a more substantial effect on the fate of water in storage. While precipitation remained consistent, plant activity and increasing air temperatures caused a larger proportion of inputs to be used by plants or evaporated to the atmosphere, rather than remaining in storage for longer periods of time. At this point in the water year, storage decreased, but also was dynamic—reflecting the interplay and countervailing effects of precipitation inputs and evapotranspiration outputs. While spring in southern New England begins in late-March, most plants do not begin to leaf out until late-April or early-May. Changes in the amount of water in storage became more pronounced during the growing season, when foliage matured and plant growth, nutrient uptake and water use reached their annual maximum.

5.1.4. Growing Season

Estimated storage generally decreased as the year progressed, reaching the lowest point in July. At this point in the growing season, vegetation was in full leaf and air temperatures (total energy available for ET) were highest. The cumulative effect of high ET on soil water content (and vernal pool water level) was, as expected, inversely related.

The effect of evapotranspiration on the amount of water in storage was the most evident at this time of year. A large rainstorm (65 mm) in June 2018 caused the amount of water in storage to rise sharply. There was an immediate discharge response to the storm, yet the hydrograph returned to antecedent baseflow conditions soon after the storm ended. This discharge response was notably smaller than the response to a rain event of (coincidentally) the same size in late-October 2017 (65 mm), as well as a smaller event in January 2018 (44 mm). This indicates that, as precipitation entered the soil it was quickly lost to evapotranspiration, rather than remaining in detention storage or becoming discharge (shallow subsurface flow and/or streamflow). Predictably, as evapotranspiration decreased—entering the dormant season at the end of the water year—the amount of water in storage increased. This was the prelude to Fall recharge at the beginning of the 2019 water year.

5.1.5. Fall Transition

At the end of the water year, though storage is still highly variable due to the countervailing precipitation inputs and evapotranspiration outputs, the senescence of plants decreases the amount of water lost via transpiration. Fall storms, such as the large event in September 2018 (79 mm) increase the amount of water in storage again, resulting in the typical Fall recharge increase in storage.

These general trends are observed in the fluctuation of vernal pool water level as well as in our estimate in storage (Figure 7). For this reason, storage is sometimes used as a proxy measurement for water level change in wetlands. However, due to the unique hydrology of vernal pools, storage is not necessarily an appropriate approximation of water level in these systems. This point will be addressed directly below.

Fall Recharge in the North Pool (South Deerfield, MA), 19 October and 11 November 2018.

Snow Accumulation in the North Pool (South Deerfield, MA), 26 January and 16 February 2019.


Snowmelt in the North Pool (South Deerfield, MA), 14 March and 21 March 2019.


Spring Transition in the North Pool (South Deerfield, MA),10 May and 24 May 2019.

Growing season in the North Pool (South Deerfield, MA), 28 June and 5 July 2019.

Figure 7. The hydrologic seasons in a Massachusetts vernal pool (South Deerfield, MA) during the 2019 water year. The change in water level in these systems varies throughout the year depending on the relative seasonal influences of precipitation, shallow subsurface flow from the adjacent uplands, leakage from the bottom of the pool and evapotranspiration. These photos of the North Pool water level reflect general New England hydrologic trends, but are not representative of the specific data analyzed in this study, which was collected from the Middle Pool.

5.2. Comparison of Vernal Pools and a Forested Wetland

Because of the dearth of research on vernal pool hydrology, baseline hydrologic conditions are not as well understood as in other types of wetlands. As a result, unusual water table fluctuation can be difficult to identify in a vernal pool hydrograph, particularly due to the naturally erratic nature of small, closed systems. As a reference, we utilized data from Black Gum Swamp in Petersham, MA, a long-term research station monitored by Harvard Forest. The precipitation and evapotranspiration effects on vernal pool water level discussed below similarly affect water level in other wetlands, such as Black Gum Swamp, though the effects are more pronounced in smaller systems. The similarities between Black Gum Swamp and the South Deerfield pool can be observed in Figures 8 and 9. The hydrographs differ due to certain site factors, including differences in watershed size and characteristics. Both the Black Gum Swamp (11 ha) and its watershed (33 ha) are considerably larger than any of the pools or their watersheds, respectively, with associated increases in water volumes. The larger Harvard Forest watershed also has longer flow paths, which increase the travel time for shallow subsurface flow to the swamp. The hummock and hollow microtopography and dense herbaceous vegetation, woody shrubs, and trees in Black Gum Swamp generate a high hydraulic roughness and long, circuitous flow paths. This, in turn, reduces flow velocity and increases the length of time water is available for growing season evapotranspiration. Additionally, the slope of the Black Gum Swamp watershed is gentle (average: ~0-5 degrees) compared to the steep (average: 20 to 30 degrees) slopes of the vernal pool watersheds. All of these site characteristics combine to limit the temporal variation in the Black Gum Swamp water level hydrograph in comparison to the vernal pools. Black

Gum Swamp water level is also bounded on the lower and upper ends because: (1) it is a perennial water feature not a temporary pool, and as a result it does not dry out seasonally, and (2) there is discharge from two outlets through rock outcrops (both are instrumented with V-notch weirs on the Nelson Brook tributaries). In summary, the wetland water level in Black Gum Swamp has a hydrologic regime analogous to a simple, unregulated reservoir while the vernal pools are, in plain language, a leaky bucket.

5.3. Exploring the Drivers of Water Level Change

In many cases the direct relationship between rain events and wetland water level rise can be represented by the estimated storage term depicted in Figure 6. This effect and response time is rapid and readily observed in small, closed vernal pool systems (Figure 8). However, the weekly and daily water level measurements for the South Deerfield vernal pools and Black Gum Swamp clearly diverge from watershed storage estimated as a water balance residual (Figures 8, 9, and 10). Before this is explained, the drivers of water level change in these unique systems need to be identified and explored. Figures 8 and 9 document the influence of rain and snowmelt, and evapotranspiration, respectively, on vernal pool water level during the 2018 water year.

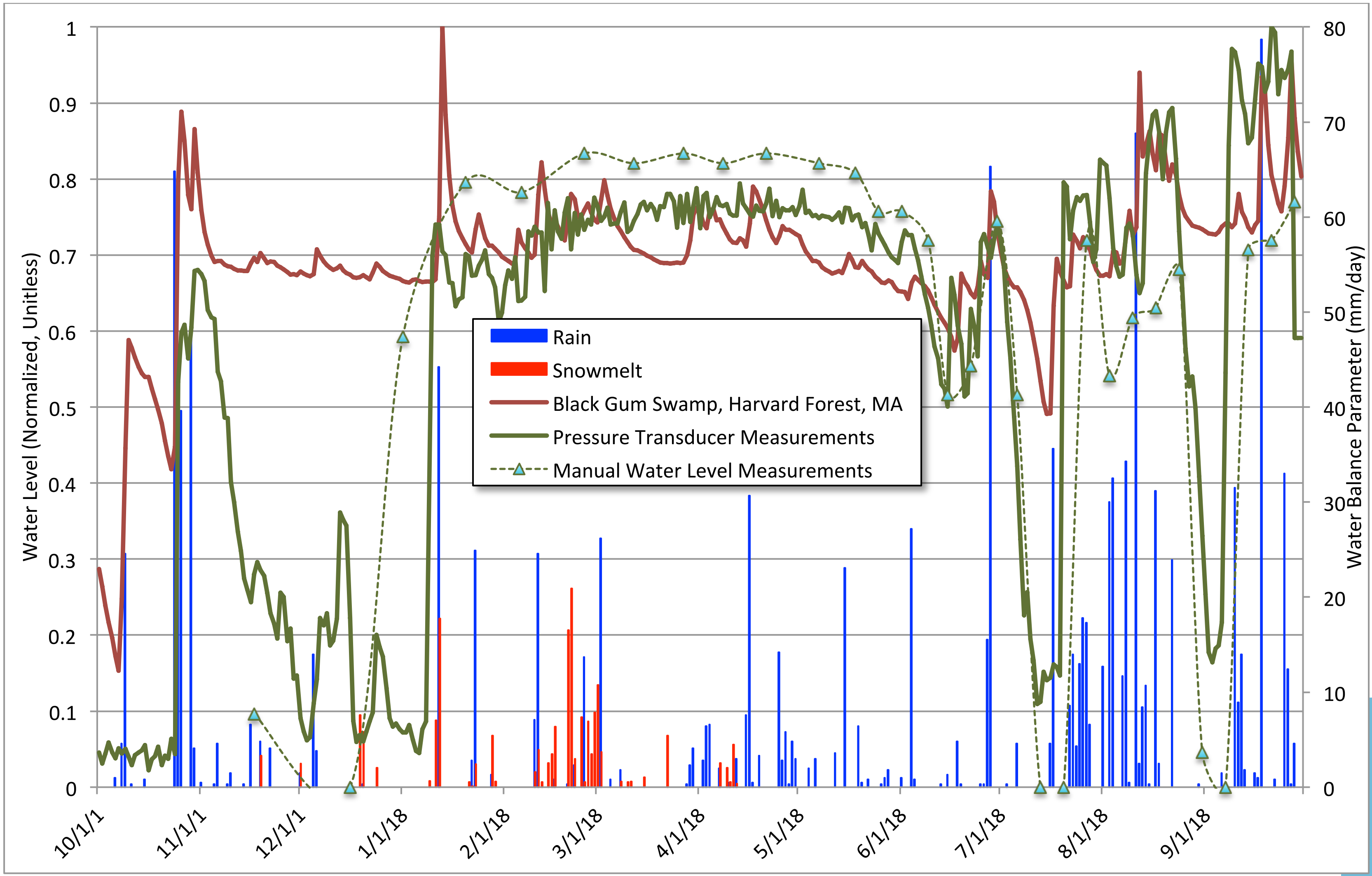

Figure 8. Relationship of middle vernal pool water level (South Deerfield, MA), Black Gum Swamp (Harvard Forest, Petersham, MA) water level, and rain and snowmelt (Orange Municipal Airport, Orange, MA) for the 2018 water year. Water level measurements are adjusted to a common datum, then normalized based on the maximum water level measured during the 2018 water year. Pressure transducer and manual measurements vary slightly because the pressure transducer data are averaged from 4-hour time step data, while the latter are measurements from a single point in time.

5.3.1. Precipitation Effects

The water level observed in the pools is clearly dependent on rain and snowmelt inputs, but the persistence of these effects varies seasonally. Fall recharge has a distinct effect on both the water level in the Black Gum Swamp and the vernal pool water level, as recorded by the pressure transducer. The short-term effect of precipitation events specifically can be seen when Tropical Storm Philippe (65 mm, 10/24/17) caused the water level in both Black Gum Swamp and the South Deerfield Middle Pool to rise sharply, but recede to a more consistent level by mid-November. During the dormant season, when snow is accumulating, the water level in both systems decreases due to lack of inputs—consistent with the trends observed in estimated total watershed storage. However, during snowmelt and spring transition, storage and water level diverge, with vernal pools reaching their maximum water levels as total watershed storage drops rapidly. During this period, snowmelt that occurs in the upland (where the storage term is estimated in the water balance analysis) travels down to the pools through the soil mantle of the watershed as shallow subsurface flow (Q_{SS}), filling them to their maximum extent. This is also evident in the discharge hydrograph in Figure 6, which rises as estimated storage decreases—effect and cause, respectively. During the spring transition period and the growing season, pool and Black Gum Swamp water levels further deviate from total watershed storage. Graphing evapotranspiration with the water level data helps to understand and describe water level changes during this period (Figure 9).

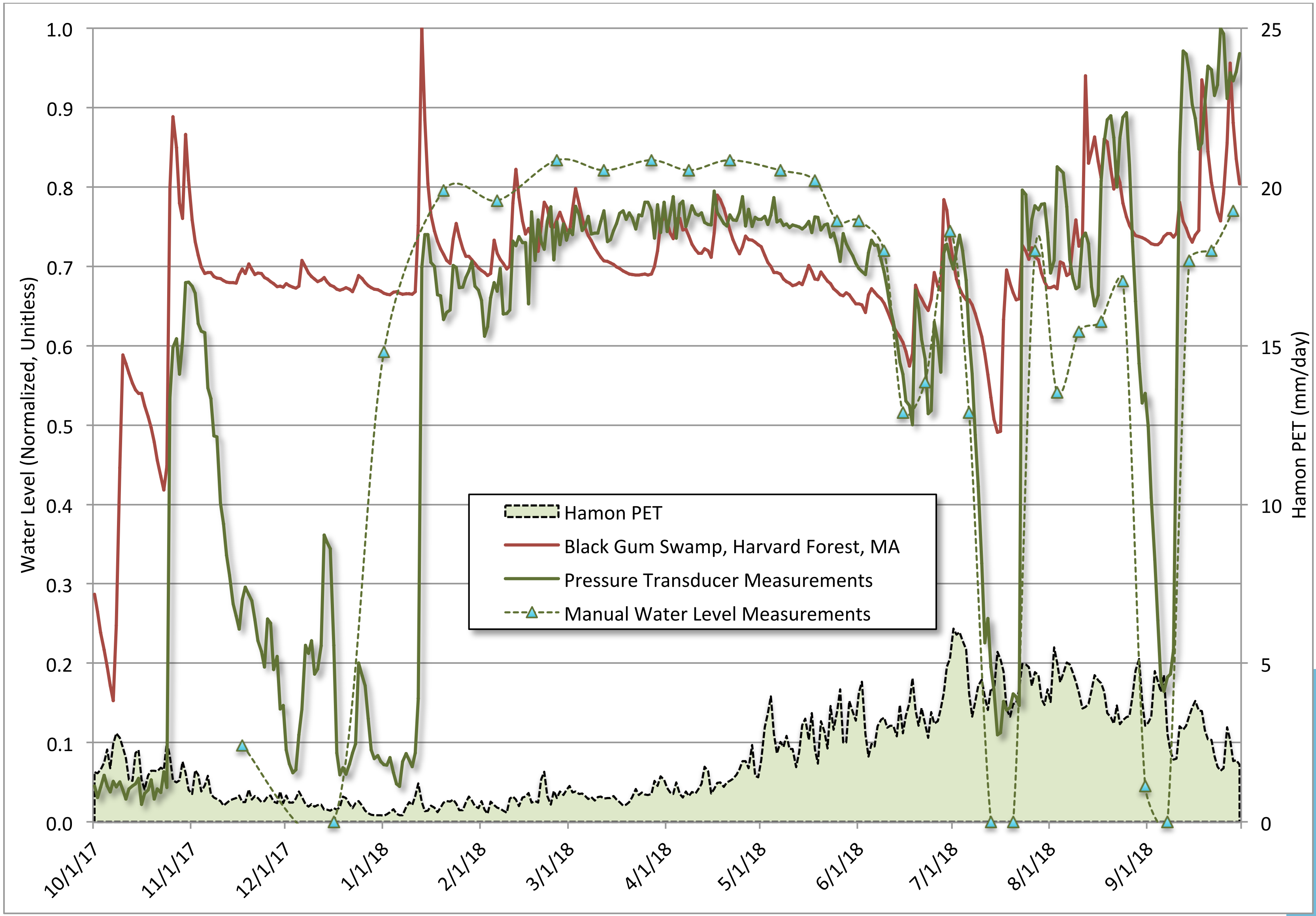

Figure 9. Relationship of middle vernal pool water level (South Deerfield, MA), Black Gum Swamp (Harvard Forest, Petersham, MA) water level, and Hamon PET for the 2018 water year.

5.3.2. Evapotranspiration Effects

As expected, evapotranspiration has a strong and persistent influence on water level trends in both Black Gum Swamp and the South Deerfield vernal pools. The primary period of interest in regard to the effects of evapotranspiration is the time when spring transition becomes the growing season. The previously stable water level of the vernal pool becomes more erratic due to the countervailing effects of evapotranspiration and precipitation. The cumulative influence of evapotranspiration begins to overpower precipitation inputs in vernal pool storage, increasing inversely with vernal pool water level. While evapotranspiration occurs on the scale of millimeters a day, without consistent precipitation inputs the amount of water lost this way can substantially affect water level. The rise or fall of the water level in any given week is reliant on whether precipitation or evapotranspiration exceeds the other (Table 3).

Table 3. Weekly precipitation and evapotranspiration totals for South Deerfield, MA during the late growing season into the Fall transition period.

Date	Weekly Precipitation (mm)	Weekly Evapotranspiration (mm)
8/24/18	0.3	23
8/31/18	1.5	23
9/7/18	56	16
9/14/18	81	20

On 8/24/18, in concert with evapotranspiration far exceeding recorded precipitation, the water level in the middle pool began to drop. This trend continued during the week of 8/31/18, when evapotranspiration remained at a similar level, and precipitation was limited to trace amounts. However, during the weeks of 9/7/18 and 9/14/18, several sizable storms occurred as evapotranspiration was decreasing for the season. This produced a considerable increase in water level, bringing the pools to their almost full level, as was anticipated for the Fall transition period (Table 3; Figure 9).

The snow accumulation and snowmelt periods also effectively demonstrate the relationship between precipitation and evapotranspiration (Figure 10). As noted earlier, precipitation from Tropical Storm Philippe caused a substantial increase in water level. This storm occurred early in the water year, when temperatures remained above 0 °C, but the forest had already entered dormancy. As a result, available energy influenced the melting and refreezing of the snowpack, but transpiration did not increase. This caused water levels to decrease slowly to what may be a typical elevation for this time of year. Over the next several months, air temperatures remained below 0 °C and inputs were generally retained in the snowpack, not contributing to pool water levels. When the main snowmelt event occurred in early-March, the pools responded with rapid water level rise (Figure 10).

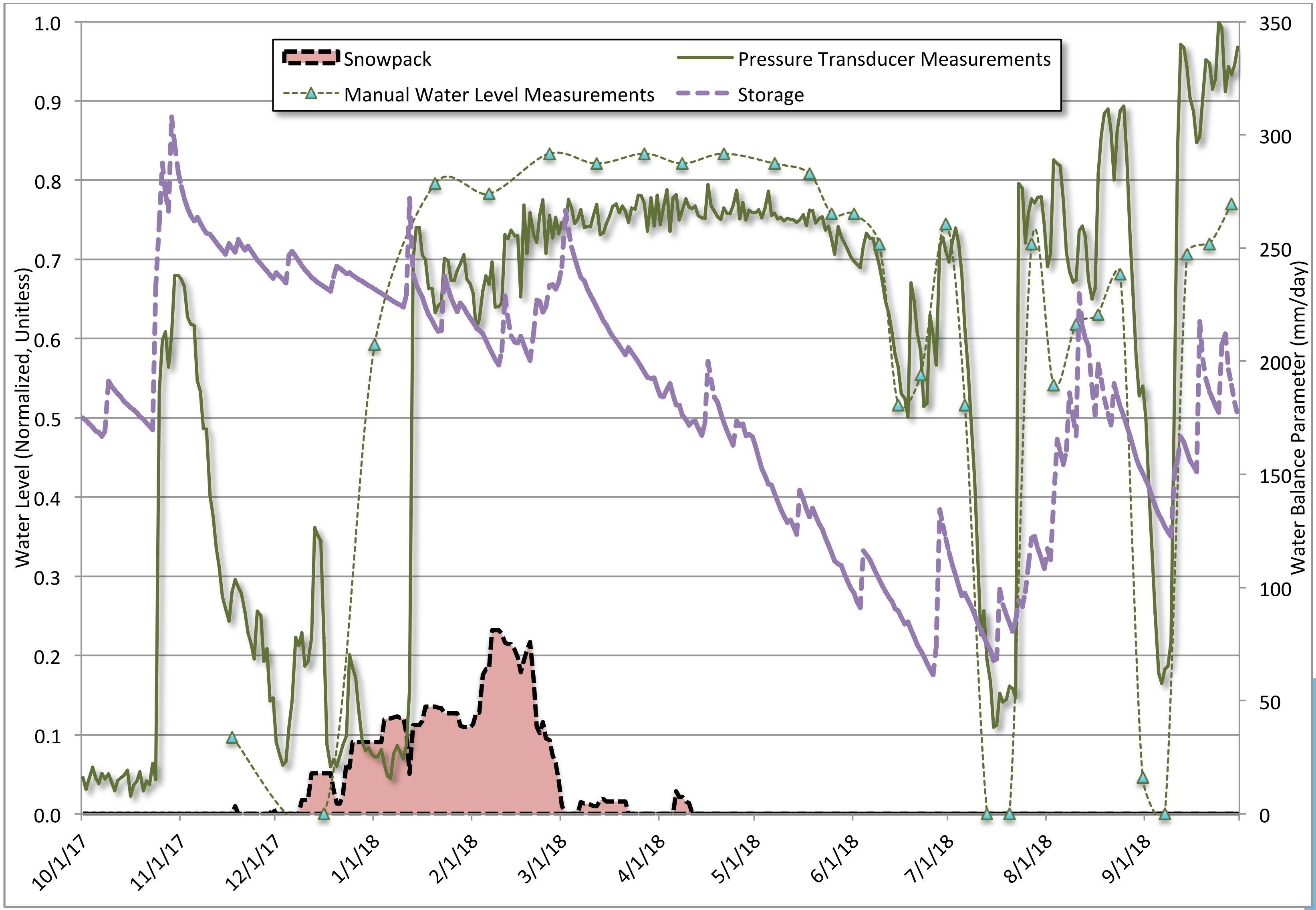

Figure 10. South Deerfield vernal pool water level, calculated upland storage, and accumulated snowpack. Increased water in storage and vernal pool water level rise in February 2018 can be attributed to melting snowpack.

5.3.3. Water Level and Storage

In late-February or early-March, the pools reach the highest annual level as a result of the snowpack melting and releasing the stored water. At this point, our estimate of storage as a water balance residual is also at a near-high point. However, after this point, our estimate of storage began to diverge from the recorded water level data. We determined that this, as referenced in passing above, was a result of storage being calculated for the site’s upland area. Storage declines steadily as a result of the upland contributing area draining (Q_{SS}), and plant uptake rising, while vernal pools remain at their “brim full” condition for another ~75 days before the combined effects of evapotranspiration and precipitation become more evident in vernal pool water level fluctuations. Vernal pools have a distinct, characteristic water conservation effect, which is not represented by the calculated change in storage for the upland contributing area. While it is observable, this conclusion was also confirmed by attempting to correlate both Black Gum Swamp and the South Deerfield water levels with the change in storage water balance residual. Both the comparison of the Black Gum Swamp and storage, and the vernal pools and storage resulted in disappointingly weak correlations. As a result, we concluded that the storage as a calculated water balance residual did not realistically describe the patterns of water level fluctuation in either Black Gum Swamp or the South Deerfield vernal pools.

5.3.4. Vernal Pool Storage

While the components of upland and wetland storage are similar in some ways, the terms vary enough for the resulting daily storage estimates to vary considerably. Using a conceptual model of the factors driving the hydrology of upland contributing areas and vernal pool systems, the terms specific to each system can be defined (Figure 11).

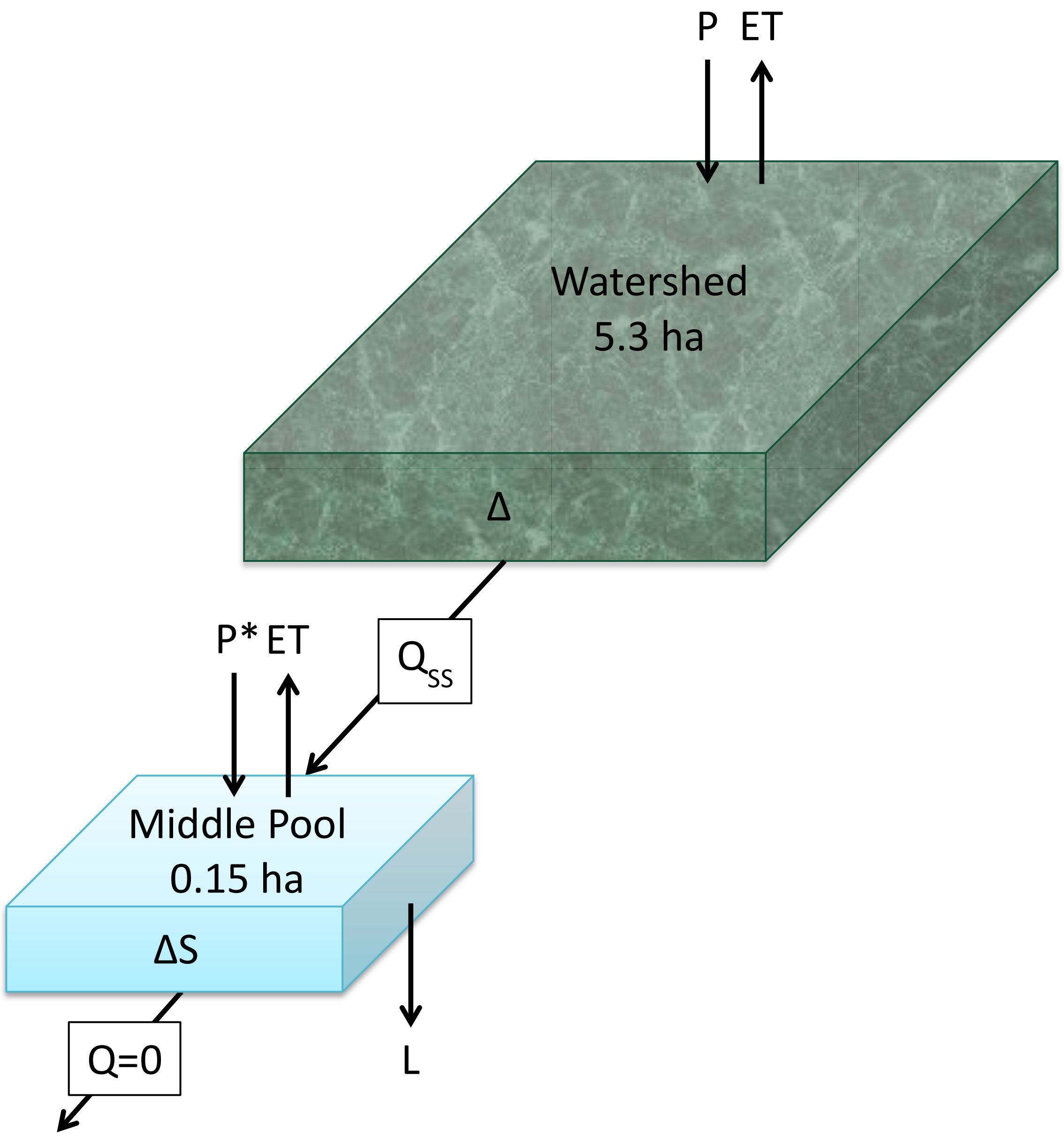

Figure 11. Watershed and vernal pool inputs and outputs. Discharge from the watershed travels as shallow subsurface flow to the vernal pool, where it is detained. Water is not lost from the vernal pool as discharge since it has no outlet. Water losses from leakage (~2 mm/day) or deep seepage, contribute to cumulative changes in vernal pool water level.

There is no standardized equation for determining storage in wetlands, or vernal pools specifically. However, with the understanding of the basic hydrologic structure of these systems, depicted in Figure 11, the water balance calculation for vernal pool storage can be written as follows.

$$S_{i+1} = S_i + Q_{SS} - ET - L + P^*, \qquad (5.1)$$

where:
S_i = storage at the beginning of the day;
S_{i+1} = storage at the end of the day;
Q_{SS} = shallow subsurface flow;
ET = evapotranspiration;
L = leakage;
P^* = direct precipitation input adjusted to pool size.

Vernal pool storage required a 1 October initial value that would not result in a negative value at any point during the year. We set the initial storage at 400 mm by iteration. The corresponding calculated annual minimum was 7 mm (a non-negative, reasonable lower limit condition).

Leakage was an additional term considered in the calculation of vernal pool storage. An in situ estimate for average daily leakage was determined by reviewing the Middle Pool's water level time series to find physical and mathematically useful conditions. Between 12/26/17 and 1/6/18, temperatures remained below freezing, and as a result, any precipitation inputs occurred as snow. These inputs became part of the snowpack and did not enter vernal pool water storage under the ice cover. However, the pressure transducer recorded small but steady decreases in water level. This rate of change of the approximately 2 mm/day water loss was used to estimate the magnitude of daily leakage through the bottom sediments of the pool.

The final adjustment to the vernal pool storage calculation was the modification of the precipitation term. Very little precipitation was likely to fall directly on the Middle Pool, given that it makes up only 3% of the watershed area. However, during large events, the volume of precipitation that lands in the pool should be represented in the calculations. To account for this addition to storage, daily precipitation (measured at the Orange Municipal Airport weather station) was multiplied by 0.03 and added to Equation 5.1.

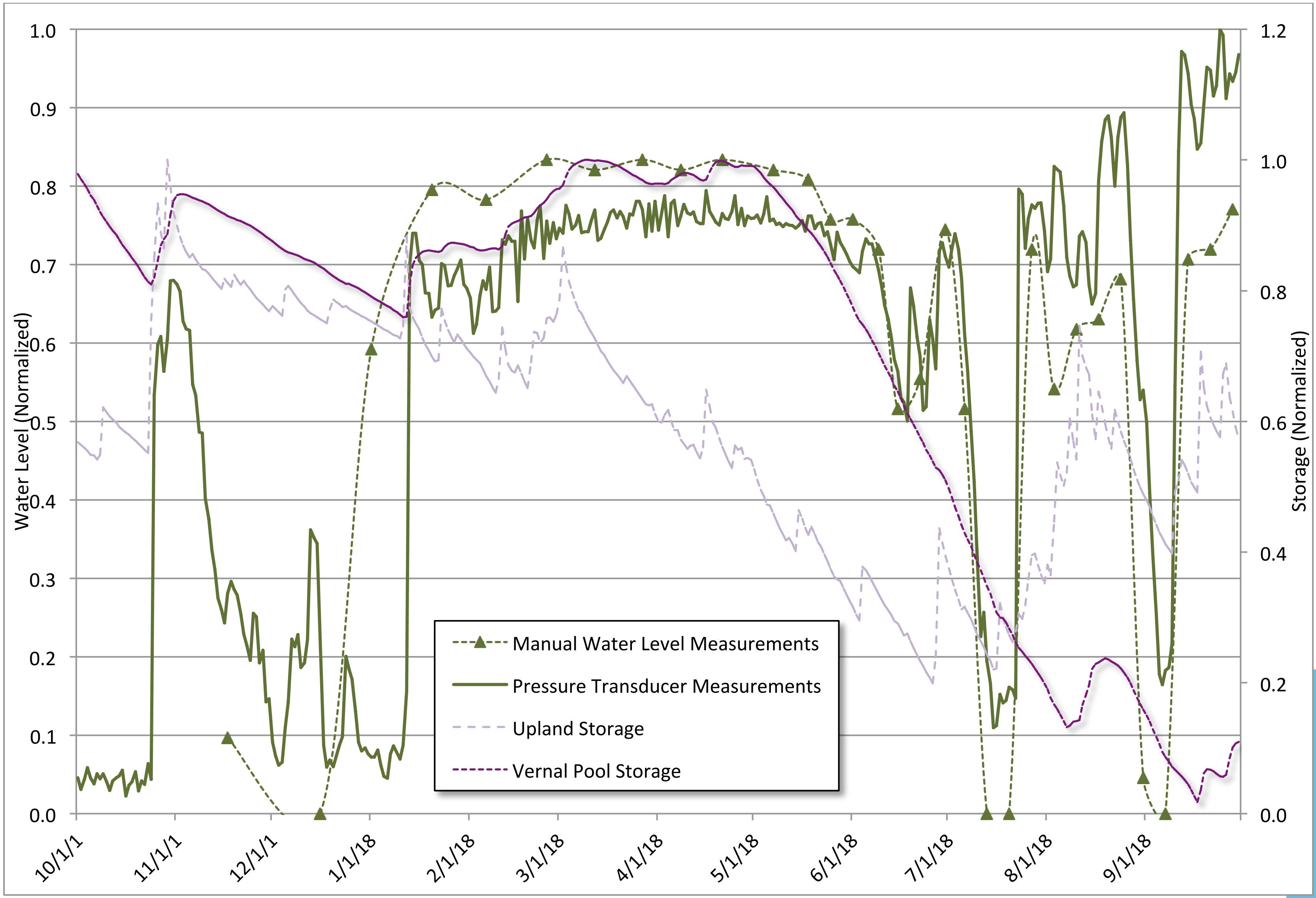

Figure 12. Middle Pool water level, with both vernal pool storage (Equation 5.1) and watershed storage (Equation 4.2) calculated as water balance residuals.

The calculation of vernal pool storage using these adjusted terms resulted in a storage estimate that more closely followed the field data measurements of water level, including accounting for the prolonged period of standing water during snowmelt and spring transition, which the watershed storage estimate did not (Figure 12). As reported in section 5.2.3 (Water Level and Storage), our comparison of pressure transducer measurements and estimated upland storage yielded an unimpressive correlation. A comparison of these pressure transducer data to the recalculated vernal pool storage estimate yielded a slightly better, but still unimpressive correlation. However, we were primarily interested in modeling the time period that is most important to amphibians, when water in the pool is highest during snowmelt and spring transition. From 1/12/18, when pool water level rose due to snowmelt, to 7/21/18, when the countervailing effects of precipitation and evapotranspiration caused more pronounced fluctuations in pool water level, the correlation between pressure transducer measurements and estimated vernal pool storage was 0.84. Unsurprisingly, our storage model did not capture the riotous water level changes that occurred during the growing season. However, the same can be said for any hydrologic model, and the ability to model water level rise during snowmelt and spring transition alone is unprecedented. Because this time period is important for obligate vernal pool breeding organisms, the development of an accurately timed estimate is useful in both a research and regulatory sense, and holds promise for further refinement of vernal pool hydroperiod models.

The storage estimate derived from equation 5.1 does have limitations. The leakage term was derived from in situ measurements of water loss during the snow accumulation period, and is not designed to vary throughout the water year. However, leakage is likely to increase or decrease during different hydrologic seasons based on the pressure head of the fluctuating water level. An estimated leakage rate of 2 mm/day is a reasonable average over the course of the year, but the inclusion of a variable leakage rate could increase the specificity of the vernal pool storage estimate on a daily basis.

5.4. Vegetation Effects on Evapotranspiration

As discussed above, evapotranspiration is the dominant influence on growing season water level fluctuation. In smaller pools, there is a smaller volume of water available for evapotranspiration, and as a result, the pool dries faster. In addition, the physiological characteristics and biomass of vegetative communities surrounding the pools may also affect the variability among sites. Although air and water temperature are likely to be consistent, the transpiration component of ET may vary substantially. A previous study of this site determined that there were notable differences between the vegetation communities at each of the South Deerfield pools (Collins, 2013). The North Pool is dominated by herbaceous vegetation, in particular, spotted jewelweed (*Impatiens capensis*) and sensitive fern (*Onoclea sensibilis*), with a canopy of mature hardwoods, primarily red maple (*Acer rubrum*). These emergent plants begin growing early in the season, and form dense, ground covering thickets, extending into the pool more readily than woody vegetation as the water level recedes.

In the Middle Pool, the species composition is dominantly woody, with large stands of silky dogwood (*Cornus amomum*), willow (*Salix sericea* and *discolor*), buttonbush (*Cephalanthus occidentalis*), and white meadowsweet (*Spiraea alba*) colonizing areas of year-round standing water. A variety of ferns, particularly royal fern

(*Osmunda regalis*) border the pool, and above the high water line, the vegetation abruptly transitions to a primarily upland forest community.

The vegetative community in and around the South Pool is substantially different from the other pools. The dominant herbaceous species is skunk cabbage (*Symplocarpus foetidus*), and the canopy is mostly comprised of red maple. There are also shrub thickets within the pool comprised of mainly high bush blueberry (*Vaccinium corymbosum*) and winterberry (*Ilex verticillata*). While the total volume of water transpired by each community is not known, it is well established that large, deep-rooted, vascular plants substantially exceed the capacity of shallow rooted herbaceous and non-vascular plants to move water via evapotranspiration. Measuring and modeling differences in the soil-plant-atmosphere continuum between the three pools (e.g., plant biomass, phenology and effective growing season length, maximum transpiration rate, leaf area index, etc.) would be a potential focus for future study.

CHAPTER 6

CONCLUSION

Broadly, the objective of this study was to gain a better understanding of the hydrological regime of the South Deerfield vernal pools and general linkages to the soil, plants, and amphibian communities. Earlier vernal pool hydrology studies in Massachusetts found a correlation between water level and precipitation and evapotranspiration effects, but used a simplified version of a water balance analysis. We hoped to create a more detailed, mechanistic understanding of the seasonal climatic influences on water level fluctuations.

The development of a water balance for the site helped to clearly identify the main hydrologic seasons, which drive the movement and storage of water in upland (and wetland) environments. From the upland water balance, we were able to develop an estimate of storage as a water balance residual that corresponded with these hydrologic seasons. While it was not representative of storage in vernal pools, this helped to confirm the estimate of shallow subsurface flow into the vernal pool. These methods can be applied to other pools in southern New England, and the results used to assess pools of similar size in comparable landscape positions and parent materials.

Winooski series soils are found in every New England state (except Rhode Island), and are particularly common in the Connecticut River Valley (Soil Survey Staff, 2019b). Soils formed in silty alluvium (including, but not limited to the Winooski series) are even more widely distributed across the region (U.S. Geological Survey, 2018). Thus, the results derived from the study of the effect of the hydrologic seasons on the water level in the pools on this site are likely to be representative to pools in other areas, particularly given that these floodplain soils are likely also in similar landscape positions.

Using the water balance information, we also developed a quantitative estimate of storage (both time series and relative amount [i.e., normalized storage]) in the Middle pool. The ephemeral nature of these systems makes their hydroperiod difficult to define, and as a result, difficult to model with high accuracy and precision. Although the general trends of water level fluctuation are consistent among sites, our preliminary investigation of the relationship between the South Deerfield pools did not definitively describe the factor(s) controlling hydroperiod differences, primarily because of the unusual hydrologic behavior of the South Pool. As a result, it would be difficult or inaccurate to extrapolate our estimate of vernal pool storage to other sites based on variables such as pool or watershed size, and expect to confidently create a representative estimate of storage and water level fluctuation. Installing pressure transducers at the other two pools and collecting more frequent water level data would allow future researchers to use equation 5.1 to create an estimate of storage and site-specific differences.

Overall, we demonstrated that we could bring together a range of data and analytical tools that convincingly represent the dynamic nature of these pools. However, given the challenge of creating a storage term that fully described the nuances of the water level fluctuation and hydroperiod of these pools, we also concluded that there is no substitute for field monitoring. Daily averaged pressure transducer data clearly depicts essential trends in the hydrologic regimes of these sites. While we have successfully produced a storage estimate that convincingly tracks the general seasonal trends of vernal pool hydrology on this site during a noteworthy part of the year (snowmelt, spring transition and early-growing season), more refinement is needed for the other hydrologic seasons. Because of the uniqueness and ecological values of these systems, and the increasing affordability and reliability of monitoring equipment, field measurements and direct empirical analyses are an essential starting point and reference data set for hydrological modeling.

CHAPTER 7

RESEARCH NEEDS

7.1. South Deerfield Vernal Pools

The characterization of the hydrological regime on this site, in conjunction with the previous studies, provides an opportunity for further research. As mentioned in section 5.4 (Vegetation Effects on Evapotranspiration), there is a potential relationship between the vegetation communities at each of the pools, and the amount of water movement via evapotranspiration. A study of the transpiration rates of different plant or community types could provide a more detailed understanding of the variation among pools. In particular, the year round persistence of wetland-adapted vegetation in the South Pool raises questions about whether this site is actually a vernal pool (or at least about its comparability to the Middle and North pools). A detailed study of the vegetation at each pool, including the relative persistence and abundance of plants most often found in permanent wetlands, and the respective magnitude of water use on each site, might help to clarify the drivers of hydroperiod variation among the South Deerfield pools.

Additionally, although the soils and hydrology on the site have been studied, the amphibian communities have yet to be researched beyond general observation and confirmation of salamander breeding. As the number of potential breeding sites for vernal pool obligate and facultative species decreases due to development and climate change, studies of the sites that support these species will become more valuable in informing conservation choices (e.g., special protection in real estate development proposals). Since the hydrologic regime of the South Deerfield sites, which are confirmed to support these species, has been characterized (and could be supplemented with additional water level recorders), amphibian research is a logical next step.

Although our assessment of the relationship between vernal pool watershed size and hydroperiod was inconclusive, it is clear that the Middle Pool held more water for longer periods of time than the North Pool. This would suggest, in accordance with the findings in Semlitsch et al. (1988), the Middle Pool might provide a better chance of survival for amphibians. A study of the amphibian populations at each of the pools could be used to test this observation and, potentially, to assess the effects of inter-annual hydrological variation on amphibian breeding and population dynamics.

7.2. Massachusetts Vernal Pools

As discussed in Section 2 (Literature Review), the published literature on vernal pool hydrology in New England is limited. Expansion of this research to other sites, and increased monitoring of vernal pool water levels in a variety of pool sizes, landscape positions, and parent materials would increase the volume of data available for analysis. By installing pressure transducers in pools across New England, compiling a standardized database (paired with NOAA and USGS hydrometeorological data), and undertaking comparative analyses, we could gain a better understanding of the variation in vernal pool hydroperiods within the region, and potentially further identify factors that drive these differences.

As was briefly discussed above, our attempts to determine the relationship between vernal pool hydroperiod and contributing area size were unsuccessful. While the North and Middle Pools followed the hypothesized pattern (a larger watershed area, relative to the size of the vernal pool, extends its hydroperiod), the South Pool did not. A potential area of exploration for a future study could include a survey of a larger number of vernal pools in southern New England. Since this case study of three pools includes one system that is substantially different (namely, a larger watershed area to pool area ratio, and residential development and impervious surfaces) from the other two vernal pools, a larger, more diverse sample is needed.

7.3. Vernal Pool Storage

Although the storage term calculated in this study worked quite well to predict the timing of the high water level period in the Middle pool, there is potential to refine this equation. We used a constant one-dimensional leakage term (mm/day). Using a three-dimensional, volume-based (m^3/day) calculation might improve the accuracy of the vernal pool storage estimate. Additionally, while the storage estimate identified the start and duration of the high water period of the Middle Pool reasonably well, cyclical wetting and drying is common in vernal pools. Hence, future attempts might explore the efficacy of volume-based estimates of the effects of precipitation and evapotranspiration on water level during the growing season that was observed in weekly measurements of all three of the pools.

Although all of the pools evinced the same general water level fluctuation pattern, as discussed above, there were distinct volumetric differences among the pools. Equation 5.1 includes an adjusted precipitation term intended to capture the variation in the amount of precipitation falling directly on the pool. However, beyond this, the equation is not designed to vary based on pool size. If this equation for vernal pool storage could be adjusted to vary based on pool or watershed size, it could likely be used to make inter-pool comparisons, rather than to simply estimate the storage for an individual location during a specific time of year.

7.4. Climate Change Scenarios

As the climate changes and alters precipitation and temperature patterns and trends, it is expected that wetlands will reflect these changes. Small, ephemeral systems like vernal pools may be the most dynamic and vulnerable, as is demonstrated in the differences between the pools and Black Gum Swamp (Figures 8 and 9). Scenario analysis of these sites – undertaken by systematically and incrementally varying one parameter (e.g., air temperature) could allow future researchers to estimate changes to vernal pool hydroperiods, and in turn, the range of potential effects on vernal pool-dependent organisms. Brooks (2004) identified correlations between water level and both precipitation and potential evapotranspiration. We also identified this relationship in the South Deerfield vernal pools. Testing a common air temperature scenario (2 °C increase across the water year) could provide information about the potential effects on vernal pool hydroperiod. This air temperature increase would increase potential evapotranspiration throughout the year, and change the proportion of rain versus snow and subsequent patterns of snow accumulation and melt. Additional scenarios based upon long-term variability in climatological records (e.g., the 1960s regional drought) could also provide helpful information for long-term conservation and management of these unique ecosystems.

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