Annual water balance analysis for a vernal pool in southern New England.

Charlotte Axthelm (charlotte.macrae2@gmail.com)
University of Massachusetts Amherst https://orcid.org/0000-0002-4770-7906
Paul Barten
University of Massachusetts Amherst

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Abstract

Vernal pools are ephemeral wetlands lacking an inlet or outlet. Generally, these wetlands are found in a range of biomes, but specific characteristics such as size, vegetation, and wildlife inhabitants vary based on location. While the vegetation of western U.S. pools and amphibians of eastern U.S. pools have been extensively studied, other aspects remain relatively unexplored. Although the general seasonal wetting and drying cycle is understood qualitatively, few studies have attempted to quantify the hydrological regime. As water level variation drives most of the defining characteristics of these systems, more research on this is needed. Our primary objective was to better understand vernal pool hydrology through the study of a typical pool in South Deerfield, Massachusetts. Using a water balance analysis, we found that the countervailing effects of precipitation and evapotranspiration were the primary drivers of water level change. An estimate of storage derived specifically for the pool, through estimated inflow, and outflow via deep seepage, was also successful at estimating water level changes during spring transition, the period most important to amphibian breeding.

1. Introduction

Vernal pools are small wetlands with complex and dynamic seasonal wetting and drying cycles, and no surficial hydrologic connections to stream networks. These two major characteristics make vernal pools unique and essential components of a landscape and have a dominant effect on the faunal communities they support (Semlitsch and Bodie 1998; Brooks and Hayashi 2002).

In New England, the essential pattern of wetting and drying aligns with the growing season. During the summer when evapotranspiration (ET) is strongest, the water level recedes and pools dry because water demands are higher than 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 (Brooks 2004).

These patterns are essential to the survival and success of vernal pool breeding amphibians, the main foci of New England vernal pool protection (Semlitsch and Bodie 1998; Calhoun et al. 2003; Zedler 2003; Babbitt 2005). For many invertebrates and amphibians, these are some of the only systems that can be used as habitat, due to their systematic exclusion of certain types of predators. The aforementioned seasonal hydroperiodicity and isolation prevents aquatic predators from becoming part of the vernal pool food web, and allows mole salamanders (*Ambystoma* spp.) and wood frogs (*Lithobates sylvaticus*) to reproduce without threat of predation from fish (Babbitt 2005; Baldwin et al. 2006; Karraker and Gibbs 2009).

Although the hydrologic regime defines the unique characteristics of these pools, in most parts of the world it has not been quantified or understood beyond general seasonal trends, in part because of the diverse geography of these systems. While the term “vernal pool” (and much of the published research) originated in California, the character of pools on the west coast is markedly different from pools elsewhere, making California-based results difficult to extrapolate (Keeley and Zedler 1998). New England vernal pool studies make up a considerably smaller proportion of the research, and even within the region, characteristics vary (Zedler 2003).

Studies based in the Northeast focus mainly on inventorying sites and evaluating habitat, while the niche of studies on hydrology remains largely unfilled. Schrank et al (2015) discusses hydrologic characteristics of vernal pools in the upper Midwest, but only so far as the surface water area, hydroperiod index, and precipitation, without discussion of evapotranspiration, storage, or leakage (terms which are integral to water balance calculations). Montrone (2013) explores the water balance of a vernal pool in greater detail, but is a study of the Sierra Nevada, a region distinctly climatically different from New England. Other prior studies including Pyke (2004) and Hanes and Stromberg (1998) face similar constraints. Boone et al (2006) contains the most in depth water balance analysis on vernal pools, but is Minnesota based, and not representative of the region discussed in our study.

A collection of studies by wildlife biologist Robert T. Brooks begins to examine pool hydroperiod in a complex of central Massachusetts vernal pools (Brooks 2000; Brooks and Hayashi 2002; Brooks 2004). These papers are essentially the full extent to date of the understanding of vernal pool hydrology in southern New England. The Brooks (2004) study found that, in 75% of pools studied, weather effects explained water level changes more than half the time, with water level positively correlated with precipitation, and negatively correlated with potential evapotranspiration (PET).

Unlike the Brooks (2004) study, a 2013 paper on the pool in our (subsequent) study suggested that evapotranspiration alone had the most significant impact on water level (Collins 2013). This emphasizes the importance of a more mechanistic understanding of individual differences in New England pools. However, the primary objective of the study by Collins (2013) was not to thoroughly characterize vernal pool hydrology. As a result, it is difficult to transfer the approach used to other sites that lack detailed *in situ* measurements.

Through the use of traditional hydrologic methods, the structure and function of these specialized systems can be explored, understood, and characterized in a way that can foster a greater appreciation of their value and place more emphasis on their protection.

Objectives

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

(1) Hydrology on this site 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 fine-scale temporal fluctuations.

2. Study Area

A vernal pool in South Deerfield, MA was selected for this study. This pool is located within a complex of pools, but was selected for more specific analysis as it is the most broadly representative of other pools in temperate regions. The selected pool is in the same size class as 10% of the central Massachusetts pools identified in a 1998 study, and has the longest continuous water level data record (Brooks 1998). The area of the pool is 0.15 ha with a corresponding watershed area of 5.3 ha.

The pool is situated at the toe of the eastern slope of North Sugarloaf Mountain on the University of Massachusetts Agronomy Research Farm. The soil series at the pools is Winooski (Collins 2013). The primary cover type of the adjacent upland forest is mixed deciduous, though vegetation shifts to shrub and herbaceous wetland species near the pool. The pool is located at an elevation of 43 m, downslope from a glacially-formed kame terrace, at the edge of the Connecticut River floodplain (Fig. 1).

Figure 1 South Deerfield vernal pools. The break in slope approximately 30 m upslope of the pools is a glacially formed kame terrace. Contours were developed using 2015 NOAA LiDAR terrain data. The middle pool was the focus of this study.

3. Methods

3.1. Study Design

The South Deerfield pool is part of the USDA Multistate HATCH Project NE1438. Within the pool are three permanent monitoring transects located approximately 6 m apart. At each “summit” (i.e., the driest perimeter position), “rim” (the maximum extent of pool during wet periods), and “basin” (the deepest part of the pool) position, a monitoring well of PVC pipe was installed to 40 cm to measure the depth to free water surface. The pools were monitored biweekly in winter, and weekly during the rest of the year. Water level data from the middle transect “basin” well was used.

3.2. Site Data

We used pool boundaries 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. To determine the watershed boundaries, traditional terrain analysis and delineation methods were used with US Geological Survey topographic maps, then refined with 3m LiDAR contours.

3.3. Water Balance

3.3.1. Weather Station Data

To create a 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:

$P - Q - ET \pm \Delta S = 0$, (3.1)

where:

P = precipitation;

ET = evapotranspiration;

Q = water yield (streamflow + groundwater flow);

ΔS = change in storage.

A weather station at 89 River Road, South Deerfield, MA, was originally identified as a prospective data source, since it is co-located with the pools. Unfortunately, this station is only maintained during the growing season for associated turfgrass and agronomic research. Linear regression analysis of data from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service station at Orange Municipal Airport and concurrent usable data from the South Deerfield station resulted in an r^2 of 0.98 for temperature, and 0.65 for precipitation, reflecting the spatial variability of rainfall in southern New England. Brief periods of missing data were estimated with values calculated using the regression equations developed in relation to the South Deerfield station (when accurate).

3.3.2. Discharge Data

Discharge (*Q*) is also a necessary component of a water balance analysis. 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—namely, 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 (USGS 2019). This river reach is unregulated (unlike most Massachusetts rivers), so these data are representative of natural flow conditions.

3.3.3. Water Balance Calculations

Once a complete, fully vetted record of precipitation, air temperature, and discharge was compiled, the data were used to calculate additional 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 model 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. Hence, AET estimates reflect the periodic limitations of water supply (e.g., extended periods with warm temperatures and limited precipitation) on this pathway of flow. PET was calculated using the Hamon method (Hamon 1961). The final component of the water balance is change in storage over time, which is often used to represent water level change in wetlands. The ΔS term is calculated as a water balance residual, using the equation:

$S_{i+1} = S_i + P - ET - Q$, (3.2)

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 was calibrated to account for the minimum available water based on soil type (i.e. residual water content). 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 average thickness of the soil profiles described on the site was approximately 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. The fixed minimum does not affect the overall trend of calculated storage, but sets a non-negative lower boundary for water content in the soil profile.

3.4. Water Level Data

Several sources of water level data were used to assess water level 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; and (3) water level data collected in 15-minute intervals at 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 daily hydrometeorological data.

Measurements from the lowest well were used for comparison with Black Gum Swamp. Field measurements of water level were taken in relation to the total height of the well, then subtracted from the aboveground height of the pipe, to standardize the data to a relative ground surface elevation of 0 cm. The data were then adjusted to a reference point near the bottom of the pipe (to yield an array of positive values), which 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 based on the maximum water level for the swamp (with no reference to the South Deerfield survey datum) because of differences in location, wetland type, and size.

4. Results And Discussion

4.1. Water Balance Analysis

The 2018 water year was selected for focus because it was the most recent year with a complete record of water level data. 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. Effects of the inter-annual variability typical of the New England region can be expected to have a similar influence on vernal pool hydroperiod, the annual streamflow hydrograph, and water level fluctuation in Black Gum Swamp.

Precipitation was consistent (on a monthly basis) throughout the water year, with several large events occurring in summer and late fall. 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, which, again, is typical in the southern New England region. The climatograph illustrates the dynamic relationship and compensatory changes in Q and ET in response to rain and snowmelt events (Fig. 2). Normalized change in storage (ΔS) is superimposed on the climatograph to show the temporal patterns of water availability.

Figure 2 Daily climatograph (Rain, Snowmelt, Evapotranspiration, and Discharge [from the upland watershed to the vernal pool]) 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 (3.3.3), total storage is calculated as a water balance residual (Eq. 3.2) 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 evapotranspiration. The water year (1 October to 30 September) can be divided into a temporal sequence of events and seasonal patterns.

4.1.1 Fall Recharge

The beginning of the water year is the transition from growing season to dormant season, also known as Fall recharge. Early in the water year at the South Deerfield pool, storage was high, reaching a peak as a 65 mm late-October storm completed recharge. Most of the water from this precipitation event entered the soil, becoming temporary storage. Because evapotranspiration is low at this time of year in relation to dormant vegetation, and decreasing air temperatures and daylength, comparatively little water leaves the system via this pathway.

4.1.2. 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 also linked to temporal patterns of accumulation and melt. During early and mid-winter, cycles of thawing and re-freezing were evident in the snowpack (Fig. 6). Colder temperatures yielded more consistent patterns of snow accumulation. Soil water content (the dominant component of total storage) declined during this period as drainage proceeded without new inputs (i.e., temporary storage in the snowpack).

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

4.1.3. Spring Transition

During the transition between dormant season and growing season, evapotranspiration begins to have a more substantial effect on the fate of water in storage. While precipitation at the pool remained consistent with earlier periods, plant activity and increasing air temperatures caused a larger proportion of inputs to be taken up or evaporated. At this point in the water year, storage generally decreased, but was dynamic—reflecting the interplay 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 all reached their annual maximum.

4.1.4. 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 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 estimated subsurface flow 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 the same size in October 2017 (65 mm), as well as a smaller event in January 2018 (44 mm). This indicates that precipitation entering the soil was quickly redirected to evapotranspiration, rather than remaining in detention storage or becoming discharge (Q_{SS} and/or streamflow). Predictably, as evapotranspiration decreased (entering the dormant season) the amount of water in storage increased.

4.1.5. 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 September 2018 event (79 mm), led to the typical fall recharge increase in storage.

These trends are observed in the fluctuation of vernal pool water level as well as in our storage estimate (Fig. 3). For this reason, storage is sometimes used as a proxy 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 is addressed below.

Figure 3 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 adjacent uplands, leakage from the bottom of the pool, and evapotranspiration. These photos depict a pool on the same site, landscape position, and parent material as the pool analyzed for this study, which simply has vegetation more conducive to the visual demonstration of seasonal water level changes. The photos reflect general New England hydrologic trends, and are comparable to the study pool, but do not represent the specific data analyzed in this study

4.2. Comparison of a Vernal Pool and a Forested Wetland

Because of the lack of in depth research on baseline hydrologic conditions of vernal pools, as well as the inherently dynamic nature of small, closed systems, unusual water table fluctuation can be difficult to identify in a vernal pool hydrograph. As a reference, we used data from Black Gum Swamp in Petersham, MA, an NSF LTER site at the Harvard Forest. Precipitation and evapotranspiration affect vernal pool and other wetland water levels similarly across the region, though the effects are more pronounced in the smaller systems. Similarities between Black Gum Swamp and the South Deerfield pool can be observed in Figs. 4 and 5. The hydrographs differ in relation to site characteristics, principally differences in size. Black Gum Swamp (11 ha) and its watershed (33 ha) are considerably larger than the pool or its watershed, with associated increases in water volumes. The larger Harvard Forest watershed also has longer flow paths, which increase the travel time of shallow subsurface flow to the swamp. The hummock and hollow microtopography and dense herbaceous and woody vegetation in Black Gum Swamp generate a high hydraulic roughness and long, circuitous flow paths that, in turn, reduce flow velocity. Additionally, the slope of the Harvard Forest watershed is gentle (average: ~0−5 degrees) compared to the steep (average: 20 to 30 degrees) slopes of the vernal pool watershed. Black Gum Swamp water level is also bounded on the lower and upper ends because: (1) it is perennial, and does not dry out seasonally, and (2) there is discharge from two outlets. All of these site characteristics combine to dampen the temporal variation in the Black Gum Swamp hydrograph.

4.3. Exploring the Drivers of Water Level Change

In many cases, the direct relationship between rain events and wetland water level can be represented by the estimated storage term depicted in Fig. 3. This effect and response time is rapid and readily observed in small, closed vernal pool systems (Fig. 4). However, the weekly and daily water level measurements for the South Deerfield pool and Black Gum Swamp clearly diverge from watershed storage estimated as a water balance residual (Figs. 4, 5, and 6). Before this is discussed in more detail, the drivers of water level change in these unique systems need to be identified and explored. Figures 4 and 5 document the influence of rain, snowmelt, and evapotranspiration on vernal pool water level during the 2018 water year.

Figure 4 Relationship of 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) during the 2018 water year. Water level measurements were 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

4.3.1. 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 the water level in both the pool, as recorded by the pressure transducer, and Black Gum Swamp. The clear, short-term effect of precipitation events can be seen when Tropical Storm Philippe (65 mm, 10/24/17) caused the water level in both systems to rise sharply, then recede to a more consistent level by mid-November. During the dormant season, as snow accumulated, water levels decreased in relation to little or no input to the soil, consistent with estimated total storage. However, during snowmelt and spring transition, storage and water level diverged, with vernal pool water level reaching its maximum as estimated storage dropped rapidly. During this period, snowmelt in the upland travels down to the pool through the soil mantle of the watershed as shallow subsurface flow (Q_{SS}), filling it to the maximum extent. This is also evident in the discharge hydrograph in Fig. 3, which rises as estimated storage decreases. During the spring transition period and the growing season, vernal pool and Black Gum Swamp water levels further deviate from total storage (Fig. 5).

Figure 5 Relationship of vernal pool water level (South Deerfield, MA), Black Gum Swamp (Harvard Forest, Petersham, MA) water level, and Hamon PET for the 2018 water year

4.3.2. 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 pool. The primary period of interest regarding evapotranspiration is when the spring transition progresses to the growing season. The previously stable water level of the pool becomes more dynamic. The cumulative influence of evapotranspiration begins to overpower precipitation inputs, 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 (Table 1).

Table 1
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 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 notable increase in water level, bringing the pool to its almost full level, as anticipated for the Fall transition period (Table 1; Fig. 5).

The snow accumulation and snowmelt periods also effectively demonstrate the relationship between precipitation and evapotranspiration (Fig. 6). 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, so available energy produced a melting, then re-freezing cycle in the snowpack, causing water level to decrease. Over the next several months, air temperatures remained below 0 °C and inputs were generally retained in the snowpack. When the main snowmelt event occurred in early-March, the pool water level rose rapidly in response (Fig. 6).

Figure 6 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

4.3.3. Water Level and Storage

In late-February, the pool reached the highest annual level as a result of the snowpack melting. At this point, our estimate of storage as a water balance residual was 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 was a result of storage being calculated for the site's upland area. Estimated storage declines steadily as a result of the upland contributing area draining (Q_{SS}), and plant uptake rising, while the vernal pool (lacking an outlet) remains at its "brim full" condition for another ~ 75 days before the combined effects of evapotranspiration and precipitation become more evident in water level fluctuations. This distinct, characteristic water conservation effect of vernal pools is not represented by the estimated 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 vernal pool water levels with the change in storage water balance residual, which resulted in weak correlations. As a result, we concluded that storage calculated as a water balance residual did not realistically describe the patterns of water level fluctuation in either Black Gum Swamp or our vernal pool.

4.3.4. Vernal Pool Storage

While some components of upland and wetland storage are similar, the differences are pronounced enough for the resulting estimates to vary considerably. Using a conceptual model of the factors defining the hydrological regime of upland contributing areas and vernal pool systems, the terms specific to each system can be defined (Fig. 7).

Figure 7 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 Fig. 7, the water balance calculation for vernal pool storage can be written as follows.

$S_{i+1} = S_i + Q_{SS} - ET - L + P^*$, (4.1)

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, as was required for the upland storage equation. We iteratively estimated the initial storage at 400 mm. The corresponding calculated (non-negative) annual minimum was 7 mm.

Leakage was also considered in the calculation of vernal pool storage. We arrived at an *in situ* estimate of approximately 2 mm/day by reviewing the pool’s water level time series data to find physically and mathematically useful conditions (Axthelm 2019).

The final adjustment was the modification of the precipitation term. Although little precipitation is likely to fall directly in the pool, given that it makes up only 3% of the watershed area, during large events the volume of precipitation that lands in the pool is not insignificant, and should be represented. This is a key difference from the pools studied in Montrone (2013). Hence, to account for this addition to storage, daily precipitation was multiplied by 0.03 and added to Eq. 4.1.

Figure 8 Vernal pool water level, with both vernal pool storage (Eq. 4.1) and watershed storage (Eq. 3.2) calculated as water balance residuals

The calculation of vernal pool storage using these adjusted terms resulted in an estimate that more closely followed field measurements of water level, including accounting for the prolonged period of standing water during snowmelt and spring transition (Fig. 8). 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 complex water level changes of the growing season, and has certain limitations (Axthelm 2019). 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 majority of existing research on wetland water balance analysis pertains to systems that differ from New England vernal pools in multiple ways. This includes research on non-vernal pool wetlands with different hydroperiods (permanence) or surface water connectivity, or non-New England vernal pools – such as lakes and wetlands in the Great Lakes Region (Mishra et al. 2010), prairie potholes in the Great Plains Region (Hayashi et al. 2016), and vernal pools in California (Montrone 2013). The water balance equation for wetlands outlets contain an additional mathematical term (Q, streamflow) that is not directly relevant to the movement of water within a vernal pool system. We addressed this by converting Q to Q_{SS}, to represent subsurface movement of water from the contributing area to the pool itself. However, without this adjustment (as in the above studies), comparison of wetlands with surficial connections to vernal pools is challenging. Water balance studies specific to vernal pools, including Montrone (2013), Pyke (2104), Hanes and Stromberg (1998), and Boone et al. (2006), are restricted to regions outside of New England. In Montrone (2013), the main input is direct precipitation, which plays a relatively small role in the water balance of New England pools. The California pools also have relatively small contributing areas, substantially diminishing the influence of our Q_{SS} term (Montrone 2013). This study also takes into account loss of water from overflow (O), which is not a pathway of loss in the eastern United States (Montrone 2013). Pyke (2004) and Hanes and Stromberg (1998) have merit as examples of adjusted water balances, removing the streamflow (Q) component, but are still not comparable to our study area due to location. Boone et al. (2006) comes closer to representing climatically similar conditions to the South Deerfield pool, and was able to successfully model vernal pool hydrology during the high water period, but the water balance analysis used in this study incorporates both surface water inputs and outputs, which are not relevant to our studied pool. Our model is specific to New England vernal pool conditions, and incorporates terms that model the movement of water into ($P*$, Q_{SS}) and out of (L, ET) the pool without discounting the characteristic lack of inlet and outlet in these systems. Additionally, our study successfully models relative water level rise and fall in our vernal pool during the high water period.

We used multiple data sets from credible sources to ensure the reliability of our collected and generated data. Meteorological and streamflow data from federally maintained and monitored NOAA and USGS stations were used. Since our water balance analysis was derived from these data, we can be confident in the reliability of our calculated values (i.e. AET, PET) as well. Comparison with a Long Term Ecological Research site with the National Science Foundation (Black Gum Swamp) was used to further validate the reliability of our data, and detect erroneous values and trends. As an additional measure in ensuring the reliability of our results, we incorporated both automatically and manually collected water level data from the study pool into our analysis. Both datasets communicate the same hydrologic trends, though minor variances exist due to frequency of data collection differing by method (as discussed in section 4.3).

5. Conclusion

The objective of this study was to gain a better understanding of the hydrological regime of the South Deerfield vernal pool. Earlier vernal pool hydrology studies in Massachusetts found a broad correlation between water level and precipitation and evapotranspiration effects, but used a seasonal water balance analysis. We hoped to create a more detailed (daily time step), mechanistic understanding of the seasonal climatic influences on vernal pool water level.

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 developed an estimate of storage as a water balance residual that corresponded with these hydrologic seasons, and helped confirm our estimate of Q_{SS} into the pool. These methods can be applied to other southern New England pools, and the results used to assess pools of similar size in comparable landscape positions and parent materials.

Using the water balance information, we also developed a quantitative estimate of storage (both time series and relative [i.e., normalized] amount) in the vernal pool. The ephemeral nature of these systems makes their hydroperiod difficult to define, and in consequence, challenging to model with high accuracy and precision. Installing pressure transducers at other pools, and collecting more frequent data would allow future researchers to characterize specific differences in hydrologic regime on other sites, and use Eq. 4.1 to create estimates of storage calibrated with *in situ* water level data.

Previous studies on New England vernal pools cover a breadth of topics, from soil to amphibian populations. Ours is the first in this region to do a complete water balance analysis on vernal pools, and incorporate site-specific data to test the success of the model. Through the use of localized hydrometeorological data from NOAA and USGS stations, site-specific soil data, and pool and contributing area size information, future land managers can use Eq. 4.1 to develop representative water balance analyses for other pools in the region, to understand pool hydrology as well as dependent factors such as amphibian breeding.

Our pool was fairly representative of New England vernal pools. Using the system in Schrank et al. (2015), the pool would be classified as “classic”, and according to Brooks (1998), it is in the same size class as 10% of other pools studied. The pool is the average, in terms of size and contributing area, of the three in the immediate area, and is located in a typical landscape position for New England pools. Due to the fairly typical characteristics of our pool, the methodology used to develop the water balance, and the equation itself, can be extrapolated to similarly sized pools in similar landscape positions and soil types. Additionally, due to the nature of Eq. 4.1, none of these factors are prohibitive in identifying other pools for study – differences in pool size can be accounted for in the P^* term, landscape position can be represented with the Q_{SS} term, and soil type can be adjusted to reflect the annual minimum storage. Brooks et al. (2006) also determined that some measurements of pool depth were required to parameterizing the model, which is not a constraint of our model as long as wilting point based on soil type is known.

This is a pilot study [n = 1] to develop and test the potential utility of adapting hydrometeorological analyses using commonly available date (i.e., NOAA-NWS, USGS streamflow and topographic data, NRCS upland soils) to better understand temporal variation in storage and water levels in these unique ecosystems. Overall, we demonstrated that we could bring together a range of data and analytical tools that convincingly represent the dynamic nature of a New England vernal pool. However, we also concluded that there is no substitute for field monitoring. While we have successfully produced a storage estimate that tracks seasonal hydrologic trends on this site during the spring breeding season for amphibians, 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 for hydrological modeling.

6. Research Needs

6.1. South Deerfield Vernal Pools

Although the soils and hydrology on the site have been studied, the amphibian communities have yet to be researched beyond general observation. 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. Since the hydrologic regime of this pool has been characterized, amphibian research is a logical next step.

6.2. Massachusetts Vernal Pools

Published literature on vernal pool hydrology in New England is limited. Expansion of this research to other sites, and increased monitoring 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, 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.

6.3. Vernal Pool Storage

Although our vernal pool storage term worked quite well to predict the timing of the high water level period in the pool, there is potential to refine this equation. We used a constant one-dimensional leakage term (mm/day). A three-dimensional, volume-based (m^3/day) calculation might improve the accuracy of the estimate.

The pool selected for this study is relatively large in comparison to the pools characterized by Brooks (1994). There are likely to be volumetric differences among pools of different sizes. Eq. 4.1 includes an adjusted precipitation term, but beyond this, is not designed to vary based on size. If this equation could be adjusted to vary based on pool or watershed size, it could be used to make inter-pool comparisons.

6.4 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 (Figs. 4 and 5). Scenario analysis of these sites 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 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. 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.

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Dr. Leslie Spokas is responsible for initial study conception and design. Specific design of the water balance and hydroperiod analysis was contributed to by both authors. Material preparation, data collection and analysis were performed by Charlotte Axthelm. The first draft of the manuscript was written by Charlotte Axthelm and commented on by Dr. Paul Barten. Both authors read and approved the final manuscript.

Data Availability

The datasets generated and analyzed during this study are available from the corresponding author on reasonable request.

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Figures

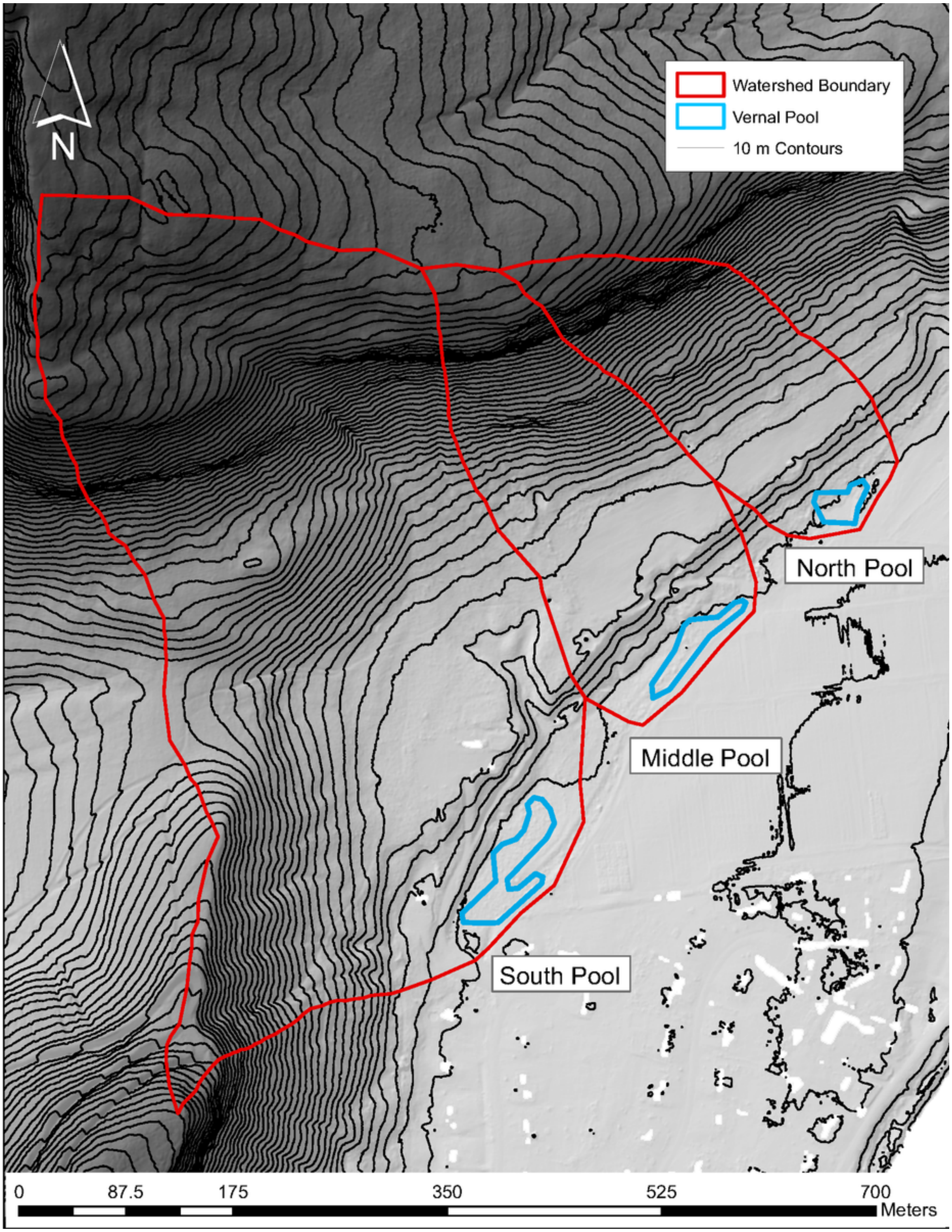

Figure 1

South Deerfield vernal pools. The break in slope approximately 30 m upslope of the pools is a glacially formed kame terrace. Contours were developed using 2015 NOAA LiDAR terrain data. The middle pool was the focus of this study.

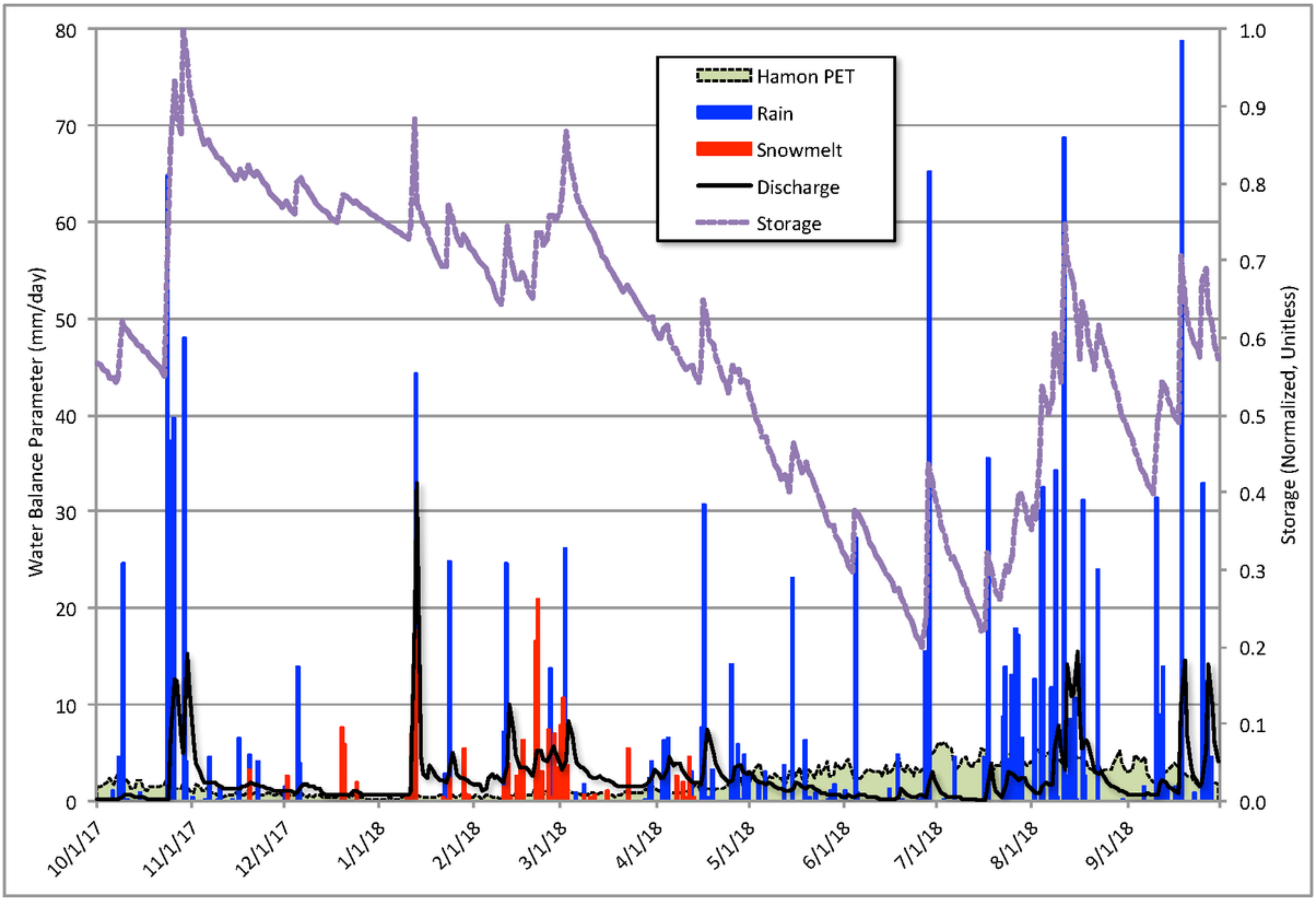

Figure 2

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

Figure 3

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 adjacent uplands, leakage from the bottom of the pool, and evapotranspiration. These photos depict a pool on the same site, landscape position, and parent material as the pool analyzed for this study, which simply has vegetation more conducive to the visual demonstration of seasonal water level changes. The photos reflect general New England hydrologic trends, and are comparable to the study pool, but do not represent the specific data analyzed in this study

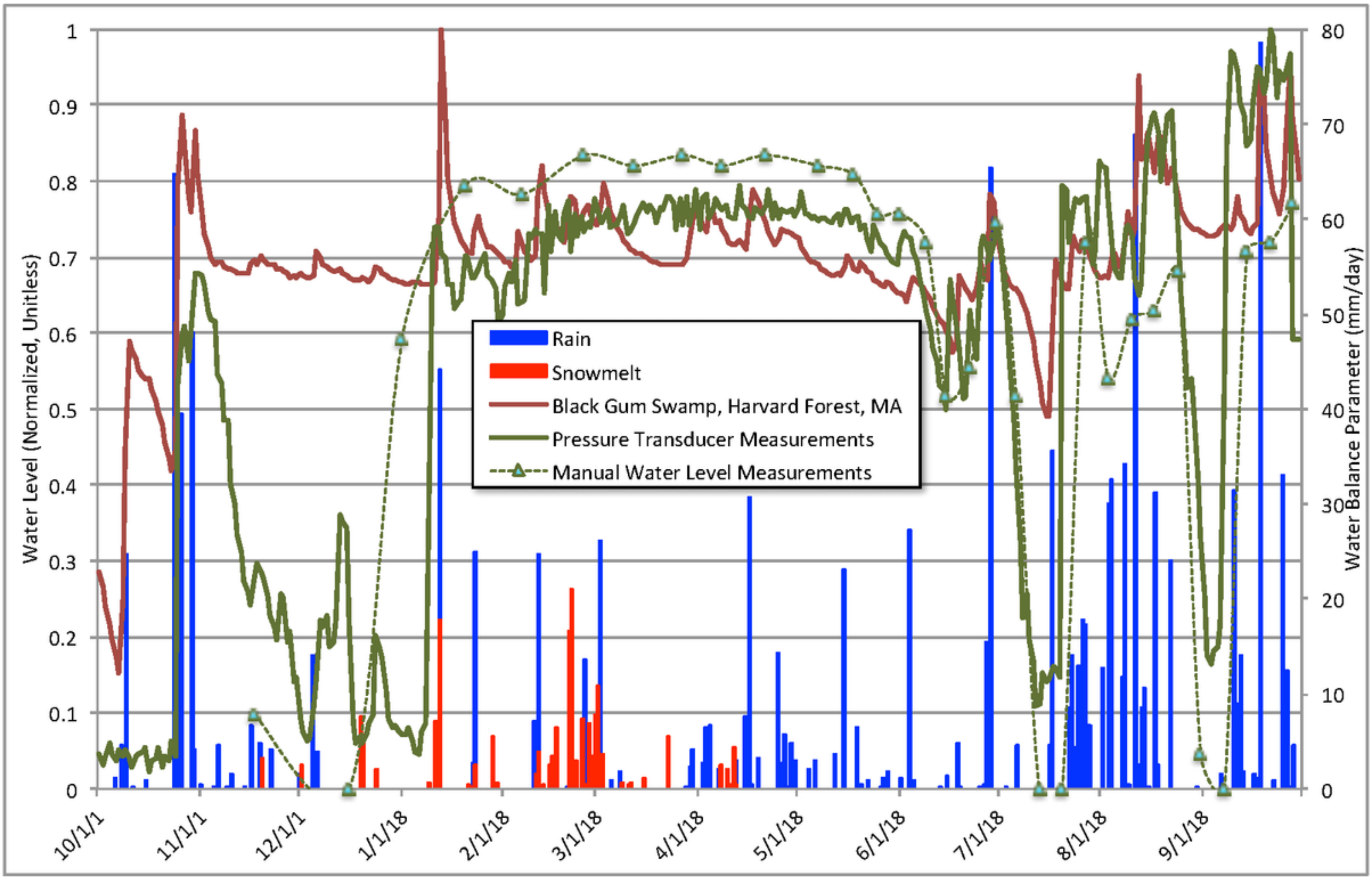

Figure 4

Relationship of 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) during the 2018 water year. Water level measurements were 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

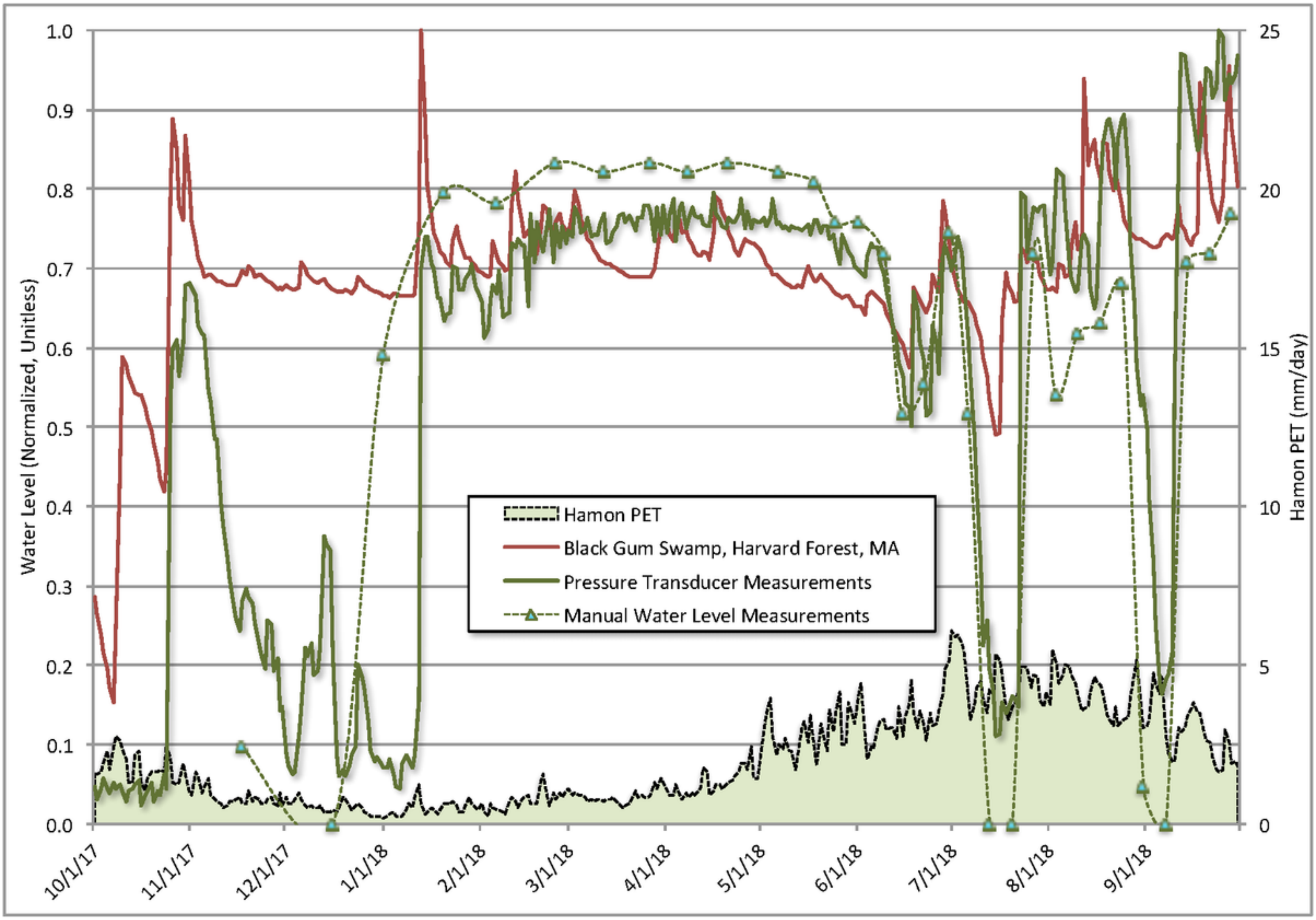

Figure 5

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

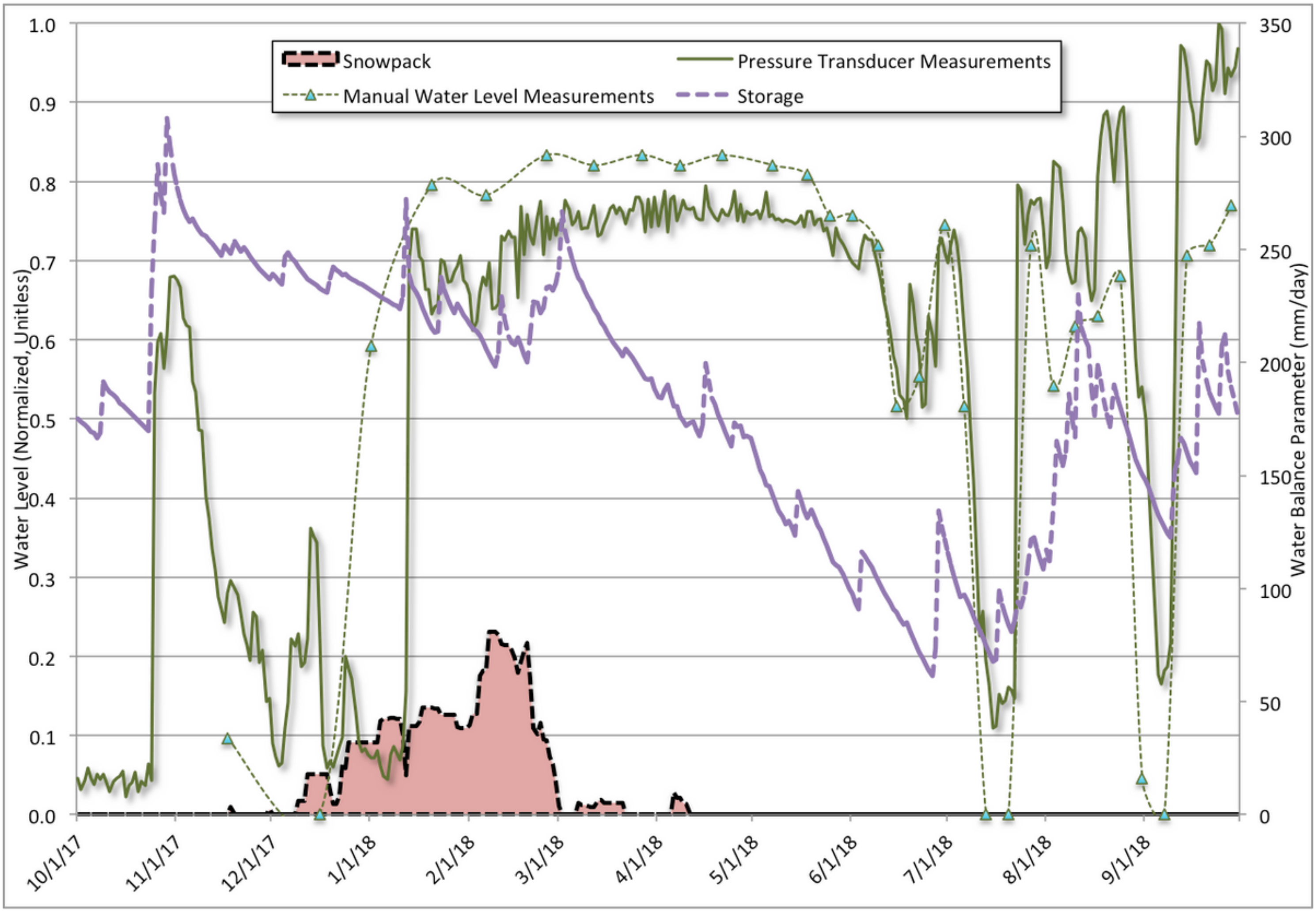

Figure 6

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

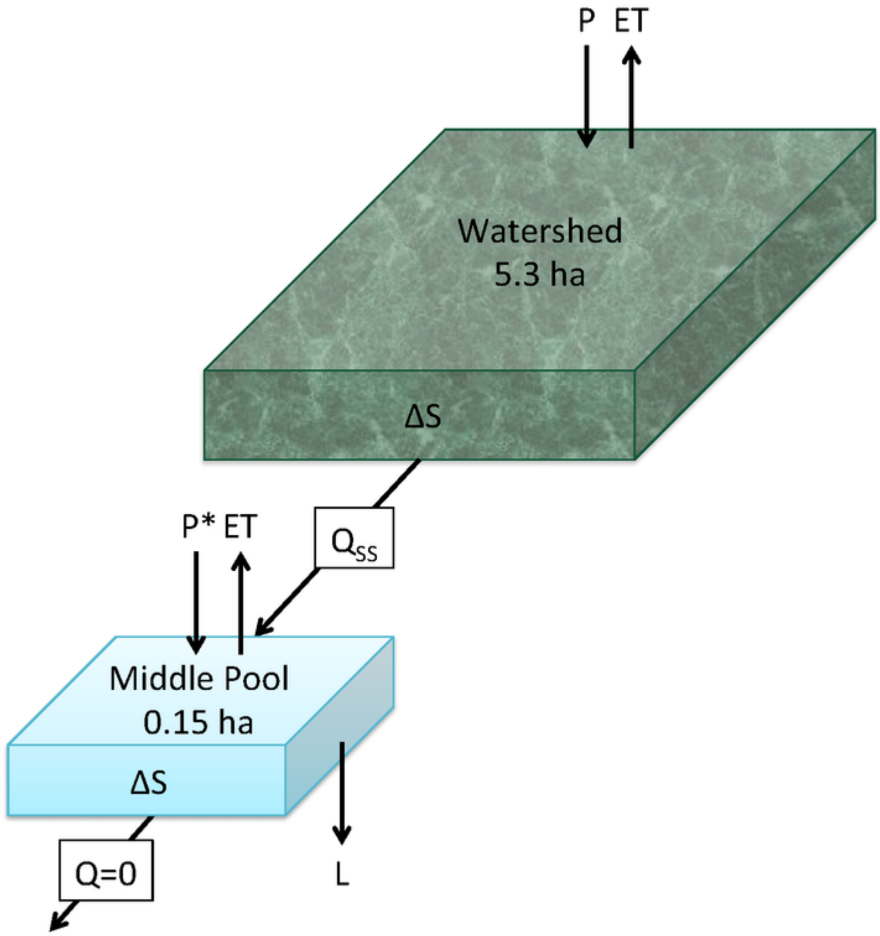

Figure 7

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

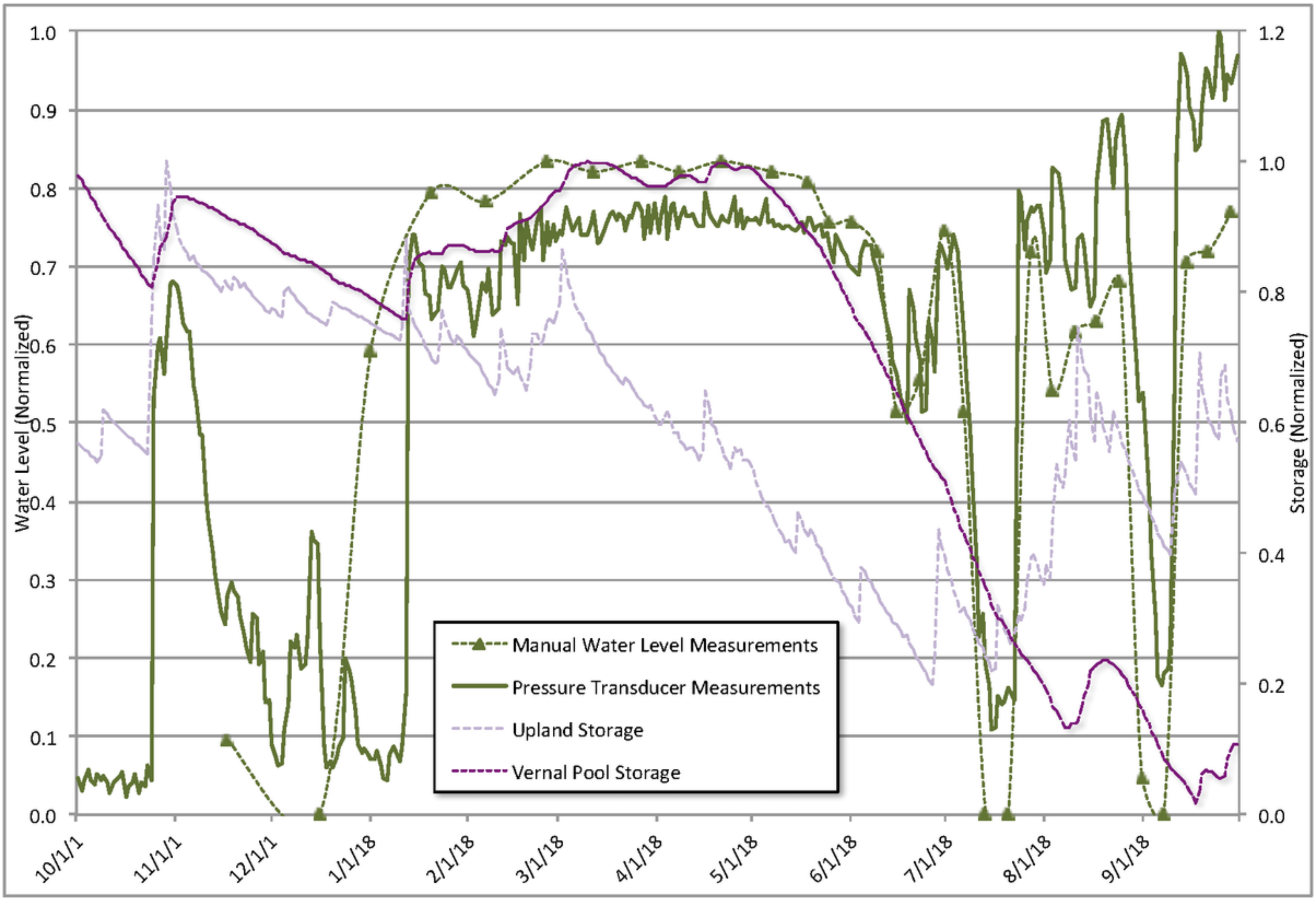

Figure 8

Vernal pool water level, with both vernal pool storage (Equation 4.1) and watershed storage (Equation 3.2) calculated as water balance residuals