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DEPTH-AREA-VOLUME AND HYDROPERIOD RELATIONSHIPS OF EPHEMERAL (VERNAL) FOREST POOLS IN SOUTHERN NEW ENGLAND

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Abstract: Ephemeral or ''vernal'' pools occur commonly throughout the forests of the northeastern United States and adjacent eastern Canada. These pools are critical breeding habitat for a number of amphibian species and support a diverse invertebrate community. The hydroperiod or duration of surface water of vernal pools affects faunal composition and reproduction. We conducted bathymetric surveys of 34 vernal pools located in central Massachusetts in early spring when the pools were at maximum extent after receiving snowmelt runoff. With these data, we estimated maximum pool depths, surface areas, perimeters, volumes, and basin profile coefficients. We calculated relative hydroperiod indices for the pools based on the presence or absence of surface water during periodic pool visits over the three-year study. The ranges of estimated pool morphological parameters were 0.11–0.94 m for maximum depth, 68–2941 m^2 for maximum surface area, 6–506 m^3 for maximum volume, and 30–388 m for maximum perimeter. Basin profile coefficients ranged between 0.60 (convex) and 2.24 (concave), with a median value of 1.02 (straight slope). Maximum pool depth was positively correlated with area and perimeter, but the correlations were only moderately strong, and there were many shallow pools with large surface areas. Correlations between basin profile coefficients and other morphological parameters were weak or non-significant. Maximum pool volume was proportional to the product of area and depth, but the proportionality constant was dependent on the basin profile coefficient. Relative hydroperiod was weakly correlated with pool morphometry; the strongest relationship was found between hydroperiod and maximum pool volume. In general terms, pools with a maximum depth greater than 0.5 m, a maximum surface area larger than 1000 m^2, or a maximum volume greater than 100 m^3 had surface water more than 80% of the times they were visited. In contrast, shallower pools, smaller pools, or pools with lesser volumes had varying hydroperiods. The weak relationships between pool morphometry and hydroperiod indicate that other factors, including temporal patterns of precipitation and evapotranspiration and ground-water exchange may have significant influence on vernal pool hydrology and hydroperiod.

Key Words: ephemeral forest pools, hydroperiod, pool morphometry, vernal pools

INTRODUCTION

Ephemeral pools occur commonly throughout the forests of the northeastern United States, adjacent Canada, and in other areas (Williams 1987, Brooks et al. 1998, Burne 2001). In the northeastern United States, these pools are typically seasonally flooded, pooled, scrub-shrub wetlands (Cowardin et al. 1979) and are commonly called ''vernal'' pools. Vernal pools are considered obligatory breeding habitat for several amphibian species, including wood frogs (*Rana sylvatica* Le Conte), spadefoot toads (*Scaphiopus holbrookii* Harlan), and *Ambystoma* salamanders (Kenney and Burne 2000), some of which are state-listed as species of concern in New England states (DeGraaf and Rudis 1983). Vernal pools also provide habitat for a diverse and unique invertebrate community (Kenk 1949, Wiggins et al. 1980, Brooks 2000). The fitness and composition of the faunal community and other functions of ephemeral pools are strongly affected by the duration of time when a pool holds surface water (pool hydroperiod). Hydroperiod can affect the composition, production, and reproduction of plants (Ebert and Balko 1984), invertebrates (Schneider and Frost 1996, Spencer et al. 1999), and amphibians (Pechman et al. 1989, Rowe and Dunson 1995, Semlitsch 2000, Paton and Crouch 2002) of ephemeral pools, including those of ephemeral forest pools (Brooks 2000).

Despite its importance, the hydrologic regime of small, ephemeral and/or isolated waters is poorly understood (Kirkman et al. 1999). Water bodies such as vernal pools commonly occur in depressions that do not have permanent inflow or outflow streams. Therefore, the water balance of these pools is controlled primarily by direct precipitation, evaporation, and ground-water exchange. For example, the hydrology of Carolina bays—shallow, closed depressions common along the Atlantic coastal plain—is controlled by precipitation and evapotranspiration, with strong linkage to shallow ground water (Rasmussen 1958, Schalles and Shure 1989, Phillips and Shedlock 1993, Lide et al. 1995). A similar hydrologic pattern was observed for cypress ponds (Mansell et al. 2000) and fens (McNamara et al. 1992, Gilvear et al. 1993, Almendinger and Leete 1998). In southern and central California, vernal pools are expressions of shallow, perched ground water in high clay soils, sustained by precipitation coupled with low evaporative losses (Greenwood 1984, Hanes and Stromberg 1998). Water-filled depressions, similar in size to vernal pools, also are common in the drier regions of North America. For example, the northern Great Plains and the Prairies have numerous such depressions—prairie potholes. The water balance of prairie potholes is dependent in large part on the effects of precipitation and evapotranspiration on surface water, as well as infiltration into bottom sediments, which maintains the high evapotranspiration of the surrounding vegetation (van der Kamp and Hayashi 1998, Winter and Rosenberry 1998).

Previous studies suggest that the hydroperiod of eastern vernal pools is affected by pool morphometry (surface area, volume, depth) and by its connectedness to ground water (Biggs et al. 1994, Cole et al. 1997, Gay 1998, Cole and Brooks 2000). Pools that are supplied by surface water alone are more ephemeral than those that also receive ground-water inputs (Gay 1998, Hunt et al. 1999). If a pool has no connection with ground water, the rate of net water gain or loss will be equal to the difference between precipitation and evaporation, regardless of pool surface area or basin shape. However, almost all pools have a certain degree of interaction with ground water, which influences the water balance and hydroperiod. In general, the interaction between surface water and ground water occurs along the shoreline (Shaw and Prepas 1990). Therefore, other factors being equal, the relative importance of ground-water exchange with respect to precipitation and evaporation increases as the ratio of the pool perimeter length to the pool area increases (Millar 1971). The perimeter-to-area ratio is generally greater for smaller pools, and hence, the hydroperiod of smaller pools is more strongly affected by ground-water exchange than larger pools.

Morphometric parameters such as depth, area, basin shape, and volume clearly affect water balance and hydroperiod of ephemeral pools. However, there has been no systematic study to characterize the morphometric parameters of vernal pools and to examine the relationships among these parameters and hydroperiod. The first objective of this paper is to analyze the relationships among depth, area, volume, and wet perimeter of 34 vernal pools in central Massachusetts, USA. We also calculate a coefficient that represents the shape of pool basin profiles and examine how pool volume is related to basin profile. The second objective is to determine if there are any clear correlations between morphometric parameters and the pool hydroperiods. We conclude by suggesting a set of minimum morphometric parameters for pools such that they will have hydroperiods long enough to support a relatively rich and productive pool fauna. Such relationships and standards may be used to classify vernal pools for conservation purposes (Snodgrass et al. 2000). The specific formulae reported in this paper may be geographically restricted in application, but the methods will be useful for studying similar habitats in other environments.

STUDY AREA AND METHODS

The pools of this study are located on the Quabbin Reservation in central Massachusetts (72° 21′ W; 42° 25′ N). The Reservation surrounds the Quabbin Reservoir and comprises approximately 64 percent of the entire Quabbin (Swift River) watershed (O'Connor et al. 1995). The bedrock of the Reservation is composed of Paleozoic intrusive rocks and metamorphosed sedimentary and volcanic rocks, consisting of granite, gneiss, schist, and phyllite (Swensen 1989, Gay 1998). Soils are derived from glacial tills, principally ablation till over lodgment till and are of variable thickness but generally less than 1.5 m (Mott and Fuller 1967, Swensen 1989). The dominant soil associations are described as stony or sandy and generally well-drained; however, wetness occurs in low areas and depressions. Forests cover over 90 percent of the watershed and are dominated by oak (*Quercus* spp.), white pine (*Pinus strobus* L.), or mixed types (O'Connor et al. 1995).

The region has a humid, temperate climate, typical of the northeastern United States. The average annual precipitation between 1961 and 1990 was 1090 mm, evenly distributed throughout the year, with 472 mm falling during the May–September growing season (National Oceanographic and Atmospheric Administration 1999). Evaporation follows a strong seasonal pattern, with large losses (609 mm) occurring during the peak of the growing season and minor to no losses during midwinter (Farnsworth and Thompson 1983).

The vernal pools of the Quabbin watershed in central Massachusetts were inventoried from color infrared aerial photography taken in 1993 (Brooks et al. 1998). From the 430 inventoried pools, 34 had been used for various other vernal pool studies and represented the range of pool surface areas identified in the inventory. Vernal pools are typically dry or have only a small amount of surface water at the beginning of the hydrologic year (1 Oct–30 Sep). The pools begin to fill in the late fall as the soil becomes saturated with fall rains; they then fill to capacity with snowmelt water in the spring. Water depths decrease and the pools are typically dry during the late spring and early summer months. Regular and moderately greater amounts of precipitation can maintain pool surface water later into the summer season, despite water losses to evapotranspiration, allowing time for the successful metamorphosis of larval amphibians. This water regime is typical of southern New England forested wetlands (Golet et al. 1993). Periodic visits to the pools over one or more of three years (1998–2000) confirmed that they were isolated, seasonally-flooded water bodies (i.e., surface water present for extended periods especially early in the growing season but absent by the end of the season in most years (Cowardin et al. 1979) and had no permanent surface hydrologic connection to another water body).

As part of the vernal pool studies, bathymetric surveys were conducted in the 34 pools in the early spring months, when pools were at their maximum area and depth. Water depth was measured on 5 × 1-m grids across the pool surfaces. The expected accuracy of measurements was ≤ 1 m for horizontal distances and ≤ 1 cm for depth. The surveyed depth data were interpolated to estimate the relative basin surface elevation on 0.5 × 0.5-m grids using the computer program SURFER (Golden Software, Golden, Colorado), and the digital elevation model (DEM) of each pool was generated. From the DEM, the surface-water area and the volume of water were calculated for several depth values, and the mathematical relationships between water depth, surface area, and volume were estimated using a model developed by Hayashi and van der Kamp (2000). Their equations did not explicitly contain maximum pool depth, which was presumed to be an important parameter for pool hydroperiod. Therefore, the equations used in this paper are modified from their original forms and expressed as follows:

$$A = \frac{A_{max}}{(d/d_{max})^{2/p}} \qquad [1]$$

$$V = \frac{A_{max} \times d_{max}}{1 + 2/p}(d/d_{max})^{1+2/p} \qquad [2]$$

where d is the depth of water measured at the deepest point in the pool, A is the area of water surface, V is the volume of water corresponding to a depth d, and A_{max} is the area of water surface corresponding to the maximum depth (d_{max}). The maximum depth and surface area occur in the spring when the pools hold water up to the overflow depth. The dimensionless coefficient p represents the average basin shape or profile. For $p = 1$, the basin shape would be an inverted cone with a straight slope profile from the margin to the deepest point; a value less than 1.0 indicates a basin with a generally convex profile, and a value greater than 1.0 indicates a generally concave profile. Substituting $d = d_{max}$ into [2] gives

$$V_{max} = \frac{A_{max} \times d_{max}}{1 + 2/p} \qquad [3]$$

where V_{max} is the volume of water corresponding to maximum depth. The maximum perimeter (L_{max}) of each pool was estimated using SURFER by tracing the contour line corresponding to the maximum extent of the pools (A_{max}) and calculating the total length of the line.

For three years, some or all of the 34 pools were visited periodically for various purposes related to other vernal pool studies. In 1998, 24 pools were visited seven times between 30 March and 29 June. In 1999, 12–15 visits were performed for the same 24 pools between 26 March and 26 August. For 2000, the 24 pools plus an additional 10 pools were visited 14–18 times from 2 March through 29 August. The time frame of each year's pool visits includes the critical egg and larval development period of pool-breeding amphibians. The presence or absence of surface water in the pools was recorded on each visit. An index to hydroperiod was calculated as the ratio of the number of pool visits when the pool held standing water to the total number of visits to the pool (Snodgrass et al. 2000). A ratio of 1.0 indicates that the pool held water on every visit. Hydroperiod indices were calculated over three field seasons for the 24 pools that were visited in 1998–2000 and over one field season for the 10 pools visited only in 2000. The hydroperiod index does not indicate the full length of hydroperiod, as the pools were only visited for portions of each year. However, as all pools were visited for the same length

Table 1. Morphometric parameters and annual pool hydroperiod indices by pool, Quabbin reservation, Massachusetts.

Pool	Estimated Maximum Pool Depth (d_{max}) (m)	Area (A_{max}) (m^2)	Volume (V_{max}) (m^3)	Perimeter (L_{max}) (m)	Basin Profile Coefficient (p)	Hydroperiod Indices[1] 1998	1999	2000	3-Year
HA303	0.67	1530	328	191	0.94	na[2]	na	1.0	na
NS232	0.45	1602	294	204	1.39	0.86	0.60	1.0	0.82
NS257	0.48	1489	371	153	2.19	0.86	0.73	1.0	0.87
NS266	0.21	707	50	113	1.02	0.57	0.07	0.59	0.40
NS445	0.30	284	24	73	0.81	0.86	0.93	1.0	0.95
NS446	0.48	229	36	67	1.00	0.86	0.67	1.0	0.85
NS448	0.45	580	110	122	1.43	0.86	0.73	1.0	0.87
NS472	0.49	243	55	59	1.79	0.86	0.53	1.0	0.80
ON481	0.29	412	45	91	1.20	1.0	0.57	0.94	0.82
PL388	0.60	781	131	142	0.77	1.0	0.87	1.0	0.95
PL391	0.68	843	193	124	1.01	na	na	1.0	na
PL392	0.41	576	90	114	1.26	na	na	1.0	na
PL394	0.34	68	9	30	1.45	1.0	0.60	1.0	0.85
PL397	0.47	696	118	129	1.15	na	na	1.0	na
PL398	0.39	152	17	63	0.75	0.71	0.20	0.81	0.55
PL400	0.58	1073	201	176	0.94	na	na	0.94	na
PL401	0.31	146	19	55	1.41	0.57	0.25	0.56	0.46
PL406	0.94	1482	506	161	1.13	1.0	0.93	1.0	0.97
PL407	0.35	1292	112	316	0.68	1.0	1.0	1.0	1.0
PL421	0.35	370	46	81	1.15	na	na	0.87	na
PL422	0.90	1173	308	160	0.82	na	na	1.0	na
PR236	0.53	1262	223	164	nd[3]	na	na	1.0	na
PR239	0.48	682	111	106	1.02	na	na	0.81	na
PR241	0.30	1380	156	169	1.22	0.86	0.53	0.94	0.76
PR243	0.51	318	70	77	1.56	0.86	0.53	0.94	0.78
PR246	0.38	2941	331	388	0.87	0.86	0.93	1.0	0.95
PR428	0.48	701	175	115	2.24	0.86	0.67	1.0	0.85
PR488	0.35	573	61	107	0.87	0.86	0.60	1.0	0.82
PR489	0.31	283	25	83	0.75	0.57	0.07	0.50	0.33
PR490	0.79	319	83	87	0.99	0.86	0.60	0.94	0.80
PR493	0.43	965	124	165	0.85	na	na	0.81	na
PR505	0.29	140	20	45	1.96	0.57	0.25	0.80	0.56
PR507	0.85	1581	312	210	0.60	1.0	1.0	1.0	1.0
PR508	0.11	129	6	46	1.33	1.0	0.53	0.67	0.67

[1] See text for definition and calculation.
[2] Pool hydroperiod not monitored in the year.
[3] Unable to calculate value.

of time each year, the index does provide a rough but unbiased indication of the variation in hydroperiod among the pools, especially those with shorter hydroperiods. The relationships among pool morphometric parameters and between pool hydroperiod indices and pool morphometric parameters were explored using Spearman's rank correlation coefficient (r_s).

RESULTS AND DISCUSSION

Pool Morphometry

The morphometric parameters of the surveyed pools represent a wide range of size of vernal pools in central Massachusetts. The estimated maximum depth (d_{max}) of pools varied between 0.11 m (PR508) and 0.90 m (PL422) (Table 1), except for pool PL406. The real maximum depth of pool PL406 was almost certainly greater than 1 m, but the center of the pool could not be surveyed safely. There is no obvious reason why most vernal pools are shallower than 1 m, however, it is possible that deeper pools tend to be permanent or semi-permanent water bodies that were not included in this study, which focused on more ephemeral pools. The maximum depth was less than 0.50 m for the majority of pools and was between 0.3 and 0.5 m for more than half (59%) of the pools. The maxi-

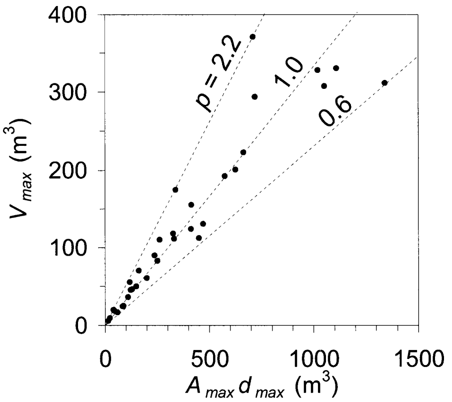

Figure 1. The relationship between maximum volume and the product of maximum surface are and depth for 34 vernal pools, Quabbin Reservation, Massachusetts. The dashed lines indicate Eq. [3] for three values of basin profiles coefficients.

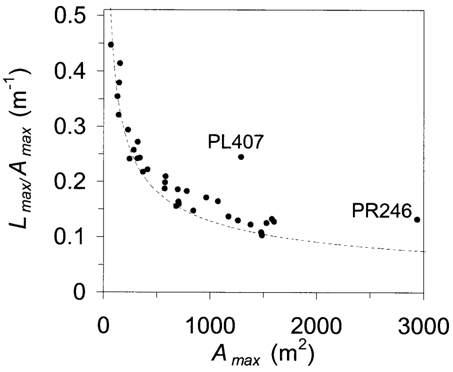

Figure 2. The relationship between maximum surface area and maximum perimeter-to-area ratio for 34 vernal pools, Quabbin Reservation, Massachusetts.

mum surface area (A_{max}) of the largest pools was less than 2000 m^2, with the exception of PR246, with a maximum surface area of 2941 m^2 (Table 1). The smallest pool was PL394, with a maximum surface area of 68 m^2. The abundance of pools decreased with increasing maximum surface area, consistent with Brooks et al. (1998) who examined the distribution of all vernal pools by surface area on the study area. They found that two-thirds were less than 500 m^2 in maximum surface area and that only 14% were larger than 1000 m^2. The maximum surface area of pools in this study was positively and moderately correlated with maximum depth ($r_s = 0.455$, $P = 0.008$). Larger pools were generally deeper but not reliably so.

Estimated maximum pool volumes (V_{max}) were mostly less than 400 m^3, and half were less than 100 m^3 (Table 1). The pools with the largest maximum surface area were not always the pools with the greatest maximum volume because maximum volume is a function of maximum surface area, maximum depth, and basin profile (see Eq. 3). The maximum volume increases with the product of maximum surface area and depth ($A_{max} \times d_{max}$) (Figure 1). The relationship between maximum volume and the area-depth product varies with the basin profile coefficient. The dashed lines in Figure 1 show this theoretical relationship for the minimum, maximum, and median basin profile coefficient of the 34 pools (Table 1). When pool depth and area are known, the approximate pool volume can be estimated using equation 3 with $p = 1.0$. This procedure would be useful because it is reasonably easy to measure maximum pool depth and surface area, but is it much more difficult to measure maximum pool volume or basin profile coefficient.

Perimeter lengths (L_{max}) of pools at maximum surface area (A_{max}) ranged between 30 m for PL394 and 388 m for PR246 (Table 1). Perimeter length was strongly correlated with maximum surface area (r_s = 0.965, $P < 0.001$) as expected and moderately correlated with maximum depth ($r_s = 0.422$, $P = 0.014$). The perimeter-to-area ratio (L_{max}/A_{max}), an important parameter for pool water balance (Millar 1971), decreased as maximum surface area increased (Figure 2). To model the relationship between perimeter-to-area ratio and area, it is convenient to use the relationship of a regular-shaped object as a reference. Millar (1971) used an ellipse because naturally formed depressions tend to have an elongated shape with varying aspect ratio (long axis divided by short axis). The average aspect ratio of the 34 vernal pools in this study was 2.4. The relationship between perimeter-to-area ratio and surface area of the vernal pools was distributed similarly to the theoretical relationship for an ellipse (Figure 2). The exceptions to this distribution are PL407, which is ''fork''-shaped with two lobes, and PR246, which is extremely long in one direction and exceptionally narrow in the other. The observed perimeter-to-area ratio of vernal pools is greater than that of ellipses having the same aspect ratio and area because true pool perimeters are more complicated than the smooth perimeters of ellipses.

Pool basin profiles coefficients (p) occurred in a relatively narrow range of between 0.60 and 2.24, with a median of 1.02 (Table 1). Due to a very irregular basin shape, with two holes in an otherwise large flat basin, a basin profile coefficient could not be calculated for PR236. The basin shape of the pools with profile coefficients greater than 1.0 generally would be concave when averaged over the entire pool—a classic ''bowl-shaped'' basin. However, the actual shape of vernal pools is complex, consisting of both concave and convex slopes. Topographic maps of the basins of the two pools having the smallest and largest basin profile indices illustrate this point (Figure 3). The cross-sectional slope profiles of PR428 ($p = 2.24$) are

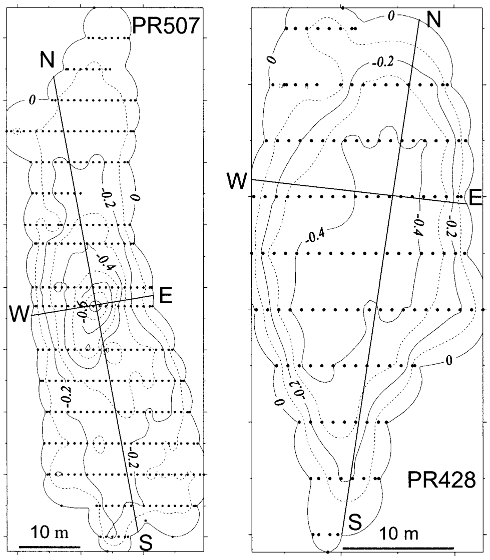

Figure 3. Topographic basin maps of representative pools PR507 and PR428, Quabbin Reservation, Massachusetts. The elevation is relative to the pool edge; principal contours are 0.2 m. The large dots (●) indicate bathymetric survey points. The locations of the south-north and west-east basin profile transects are also shown.

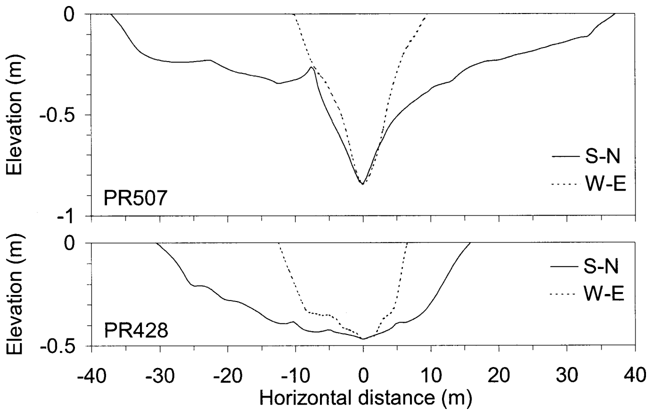

Figure 4. Basin slope profiles of representative pools PR507 (p = 0.60) and PR428 (p = 2.24), Quabbin Reservation, Massachusetts, along the transects shown in Figure 1. Elevation is relative to the edge of the pool, and horizontal distance is measured from the deepest point in the pools.

generally more concave than those of PR507 (p = 0.60), but both pools have irregular slope profiles (Figure 4). Basin profile coefficient was weakly and negatively correlated with maximum depth ($r_s = -0.159$, $P = 0.394$), maximum surface area ($r_s = -0.266$, $P = 0.140$), and with perimeter length ($r_s = -0.370$, $P = 0.038$). This indicates that shallow, deep, small, and large pools all have pool basins of varied profiles.

Pool Hydroperiod

One-year hydroperiod indices ranged between 0.5 (PR489) and 1.0; three-year indices ranged between 0.33 (PR489) and 1.0 (PL407 and PR507) (Table 1). Vernal pools with the greater maximum depths are expected to have longer hydroperiods. One-year and three-year hydroperiod indices were moderately and positively correlated with maximum depth (1-year index $r_s = 0.527$, $P = 0.002$; 3-year index $r_s = 0.508$, $P = 0.013$; Figure 5A). The hydroperiod indices of deep pools ($d_{max} > 0.5$ m) were consistently greater than 0.8, indicating the presence of standing water on 80% or more of pool visits, with the exception of the three-year index for PR243, which has a maximum depth of 0.51 m. The hydroperiod indices of shallow pools ($d_{max} < 0.5$ m) varied considerably among pools, indicating that factors other than maximum pool depth influenced the hydroperiod of these pools.

The relationship between hydroperiod and maximum surface area (Figure 5B) was less distinct than that for maximum depth. Hydroperiod indices were moderately and positively correlated with maximum surface area (1-year index $r_s = 0.448$, $P = 0.009$; 3-year index $r_s = 0.564$, $P = 0.005$). Bilton et al. (2001) also observed this moderate relationship between area and hydroperiod. Pools greater than 1000 m^2 in surface area tended to have longer hydroperiods, while the hydroperiod indices of those smaller than 1000 m^2 varied considerably. For example, many pools with surface areas less than or equivalent to NS266 had longer hydroperiods; however, these pools were all considerably deeper (Table 1).

Deeper and larger pools have greater maximum volumes (Figure 1), and the relationship between hydroperiod indices and maximum volume reflects the relationships between hydroperiod indices and maximum depth and surface area. Relative hydroperiod was moderately and positively correlated with maximum volume (1-year index $r_s = 0.459$, $P = 0.006$; 3-year index $r_s = 0.579$, $P = 0.004$). The hydroperiod indices of pools with maximum volumes less than about 100 m^3 ranged widely, while pools with maximum volumes greater than 100 m^3 generally held standing water on greater than 80% of the visits (Figure 5C). Hydroperiod was independent of basin profile coefficient (p) (1-year index $r_s = -0.029$, $P < 0.50$; 3-year index $r_s = -0.234$, $P = 0.287$). This was probably due to the relatively narrow range of basin-profile coefficient values observed in the pools and also to the complex basin profiles of vernal pools that deviate from the ideal cone- or bowl-shaped basins.

Ground-water/surface-water exchange generally has a strong influence on the water balance of ephemeral pools with high perimeter-to-area ratio (Millar 1971). Hydroperiod indices were weakly and negatively correlated with maximum perimeter-to-area ratio (1-year

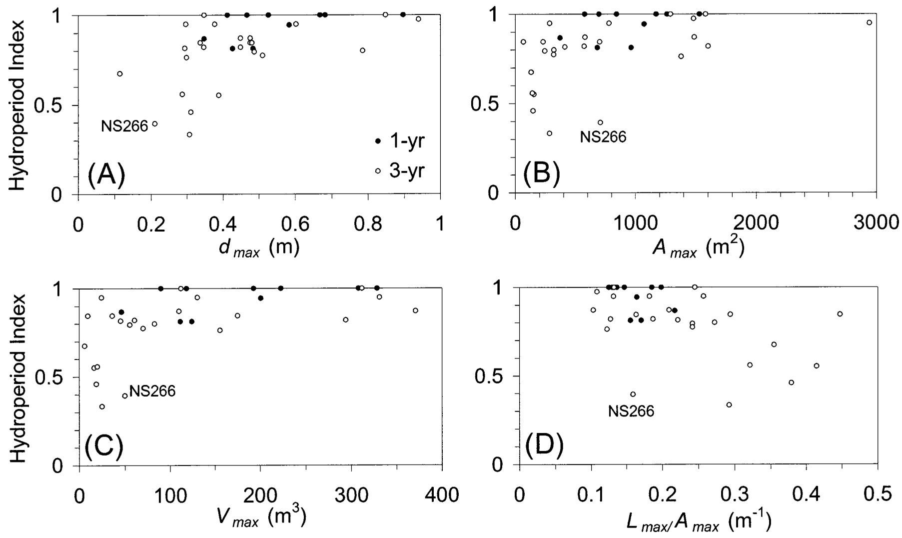

Figure 5. The relationships among 1-year (2000; closed circles) and 3-year (1998–2000; open circles) hydroperiod indices and (A) maximum depth, (B) maximum surface area, (C) maximum volume, and (D) perimeter-to-area ratio for 34 vernal pools, Quabbin Reservation, Massachusetts.

index $r_s = -0.391$, $P = 0.024$; 3-year index $r_s = -0.446$, $P = 0.033$; Figure 5D). Pool NS266, a very shallow but median-sized pool, had considerably smaller hydroperiod indices than other pools with similar perimeter-to-area ratios because of the strong influence of the depth on hydroperiod.

The difference between water input to and water loss from pools determines the water balance of vernal pools. Precipitation provides the principal water input after spring snowmelt, and evapotranspiration accounts for a significant portion of water loss. Depending on the hydrogeologic setting, pools may receive ground-water discharge or provide ground-water recharge (Golet et al. 1993). If pool hydroperiods were determined solely by the balance between precipitation and evaporation, deeper pools would seldom dry during the spring and summer because May–September evaporation (609 mm) evaporation is only slightly greater than precipitation (472 mm) during this time. Since many pools frequently do go dry at this time, this suggests that water loss to shallow ground water by infiltration may play a major role in the hydrology and hydroperiod of vernal pools. Most shallow ground water, temporarily recharged from pools, is likely consumed by transpiration demands from the vegetation adjacent to pool perimeters, and the effects of transpiration are more pronounced for pools with higher perimeter-to-area ratios (Millar 1971).

The critical pool size measures of 0.5 m depth, 1,000 m^2 surface area, and 100 m^3 volume identified in this study may be limited to the combination of weather patterns, physiology of adjacent vegetation, and the hydraulic properties of the pool basin soils typical of the northeastern United States. In a much drier environment, van der Kamp et al. (1999, Figure 2) presented water-level records for ten prairie potholes in Saskatchewan, Canada. In these systems, the critical water depth was in excess of 1 m, in contrast to 0.5 m for the pools in this study in a well-watered temperate forest.

SUMMARY AND CONSERVATION IMPLICATIONS

Ephemeral (‘‘vernal’’) pools are common throughout the northeastern forests of the United States and adjacent Canada. The richness and successful reproduction of the faunal community of vernal pools are strongly affected by pool hydroperiod. The ability to characterize pool hydroperiod from simply measured pool morphometric parameters, such as the size and depth of the pool basin, would be helpful in identifying pools that would more likely serve as source habitats to the larger populations of invertebrates or amphibian species. In this study, the morphometric parameters of 34 vernal pools were estimated from detailed bathymetric survey data. The depth-area-volume relationships of the pools were represented adequately by simple equations with three parameters: maximum depth (d_{max}), maximum surface area (A_{max}), and basin profile coefficient (p). The maximum depth and surface area occurs when a pool is filled to overflow level in spring. All but one of the studied pools had maximum depths smaller than one meter. The maximum surface area generally increased as maximum depth increased, but the relationship was not simple. The basin profile coefficient was confined to a narrow range between 0.60 (convex) and 2.24 (concave) with a median value of

1.02. The maximum pool volume increased as the product of maximum area and depth increased.

Hydroperiod was generally longer for pools that were deeper, of larger area, greater volume, or smaller perimeter-to-area ratios, although the correlations are not very strong. In very general terms, pools having a depth greater than 0.5 m, area larger than 1000 m^2, and/or volume greater than 100 m^3 have longer hydroperiods. These pools had standing water more than 80% of times when the pools were visited. The pools having smaller depth and/or size showed a large variability in hydroperiod, which suggests that factors other than pool morphometry control variation in the hydroperiod of these pools. The study area in the northeastern United States experiences roughly equal amounts of precipitation and evaporation in May–September, a critical period for vernal pool fauna. Therefore, during this period, evaporation alone cannot drive the water-level recession observed in the pools. The likely cause of water recession from vernal pools is infiltration that feeds shallow ground water, likely induced by transpiration demands of shoreline and upland vegetation. This study showed that the pools with higher perimeter-to-area ratios, which enhance the effects of shoreline vegetation, tend to have shorter hydroperiods.

Pool size can serve as a guiding tool to indicate pools with sufficient depth and/or area with a higher probability for successful amphibian reproduction. Maximum pool depth is measured easily and area can be estimated from aerial photography or simple field measurements. The accurate determination of the basin profile coefficient requires a detailed bathymetric survey, but approximate values may be used for the estimation of pool volumes because the coefficient values are confined to a narrow range and can be estimated from observation of the basin profile. It should be emphasized, however, that pool hydroperiod also is dependent on many other factors, particularly groundwater exchange. Therefore, conservation efforts should not be directed solely towards larger vernal pools to the exclusion of smaller pools. Smaller pools, while not as reliably productive as larger pools, nevertheless are important to the persistence of pool-breeding fauna. Further studies are required to investigate the nature of water exchange between vernal pools and shallow ground water.

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