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A review of basin morphology and pool hydrology of isolated ponded wetlands: implications for seasonal forest pools of the northeastern United States

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Abstract

Seasonal forest pools (SFPs) are geographically- and hydrologically-isolated ponded wetlands, in that they are topographically isolated from other surface waters. SFPs occur commonly throughout the temperate forests of the eastern United States and adjacent Canada. SFPs are ephemeral in occurrence, typically drying annually. The regular drying of SFPs excludes fish from these habitats, and as a result, they are the preferred breeding habitat of some amphibians, notably ambystomid ('mole') salamanders and wood frogs (*Rana sylvatica* Le Conte). The pools also support a rich and diverse invertebrate fauna. The duration of the wet phase, or hydroperiod of SFPs, has been repeatedly shown to be the dominant influence on the composition and fitness of the faunal community of the pools. Despite the importance of SFP hydrology, it is a poorly studied subject. This paper reviews the limited state-of-knowledge of seasonal forest pool hydrology and associated basin morphology. The review discusses findings from studies of other isolated ponded wetlands that could be applicable to our understanding of the hydrology of SFPs.

Introduction

Isolated, ponded wetlands occur commonly in the United States (Tiner et al. 2002). Across the eastern temperate forest region, isolated wetlands account for almost 70% of all wetlands, but only 14% of total wetland area (Table 1). Seasonal forest pools (SFPs; also woodland vernal pools Tiner et al. 2002, vernal pools Burne 2001, seasonal ponds Palik et al. 2001) are a type of isolated wetland and are abundant in temperate forests. In an extensive survey of pools, Burne (2001) identified over 29,000 potential vernal pools in the 12,650 km^2 of forest (1 pool/44 ha of forest) in Massachusetts (Alerich 2000). Brooks et al. (1998) identified 430 pools on the 38,880 ha (1 pool/90 ha) Quabbin (Swift River) watershed in central Massachusetts. In northern Minnesota, Palik et al. (2003) identified 2064 pools on two forested study sites of 24,499 ha (1 pool/12 ha).

Seasonal forest pools are small in size, with maximum surface areas typically much less than 1 ha, and are physically and hydrologically isolated, in that they are surrounded by upland forest with no permanent connection to other surface waters (Burne 2001; Tiner et al. 2002). SFPs are ephemeral, typically inundated during wet seasons and drying on a regular, usually annual basis. The

Table 1. Area and number of wetlands and isolated wetlands in the temperate forest area of the United States by U.S. Fish and Wildlife Service Region (Tiner et al. 2002).

Region	Area (acres)		Number	
	All	Isolated	All	Isolated
Northcentral	172,362	29,629 (17.2%)	21,081	15,782 (74.9%)
Southeast	55,418	6041 (10.9%)	22,468	15,947 (71.0%)
Northeast	258,883	30,782 (11.9%)	25,166	15,624 (62.1%)
All regions	486,663	66,452 (13.7%)	68,715	47,353 (69.8%)

period of inundation or hydroperiod of SFPs varies greatly among pools, ranging from temporarily to semi-permanently flooded (*sensu* Cowardin et al. 1979). The most common hydroperiod of SFPs is seasonal in duration (Burne 2001; Brooks and Hayashi 2002; Brooks 2004), with pools partially re-inundating in the fall, filling to capacity with spring rains and snowmelt, and then drying through the late spring and summer seasons. The recurring dry phase of SFPs precludes the occurrence of predatory fish. The dry phase of SFPs also allows for the aerobic decomposition of plant litter, which enhances the availability and quality of food resources in these detritus-based systems (Barlocher et al. 1978; Wiggins et al. 1980; however, see Svensson 1999). As a consequence of the absence of fish predation and abundant food resources, SFPs are preferred breeding habitat for amphibians (Paton: this issue), support a rich and diverse invertebrate community (Batzer and Sion 1999; Higgins and Merritt 1999; Schneider 1999; Williams: this issue), and provide habitat for numerous other wildlife species at various times (Paton: this issue).

It is widely accepted that the hydrology and hydrologic regime of wetlands is a major if not principal factor affecting the structure and functions of wetlands (Cole et al. 1997). The duration of the wet phase or hydroperiod is the dominant hydrological feature of SFPs and other ephemeral wetlands (Wiggins et al. 1980; Pechmann et al. 1989; Schneider 1999; Brooks 2000). However, the hydrology of wetlands, and of isolated wetlands and SFPs in particular, is possibly the least studied and understood feature of these systems (Sharitz and Gibbons 1982; LaBaugh 1986; Cole et al. 1997). It is critical that we have a better understanding of their hydrology if we are to better protect or manage isolated wetlands (Winter et al. 2001). This review summarizes the limited published research on the basin morphology and hydrology of seasonal forest pools.

As there are few published studies of these topics specifically for SFPs, I have included findings from studies of other isolated, ponded wetlands (e.g., Carolina bays (Sharitz and Gibbons 1982), prairie potholes (Kantrud et al. 1989), and Mediterranean-type (West Coast) vernal pools (Zedler 1987)). Carolina bays are depressional wetlands occurring in the flatwood wetlands and upland forests of the Atlantic Coastal Plain of the United States. They vary greatly in size, are hydrologically isolated, and are nutrient poor. The vegetation of bays is composed predominantly of tree and shrub species. Prairie potholes are shallow, depression wetlands that occur abundantly across the prairies of north central United States and adjacent Canada. Potholes vary considerably in their hydrology, depending on their topographic position. Water input is from snowmelt and precipitation and water loss is to evaporation. The vegetation within potholes varies depending on hydroperiod, with concentric zones of species increasingly tolerant of flooding towards the center of the wetland. West coast vernal pools exhibit distinct wet and dry phases due to the Mediterranean-type climate that occurs along the western states of the United States and into adjacent Baja Mexico. The extremes in soil moisture have resulted in a unique herbaceous flora characteristic of these wetlands. Despite their different settings and climate, general patterns in the hydrology of various types of isolated ponded wetlands can illustrate conditions that are likely to occur for SFPs.

Basin morphology

The geologic location and the morphology of seasonal forest pool basins affects pool hydrology, and at the same time, pool hydrology affects the structure of pool basins. Local geologic conditions can affect surface groundwater exchange in wetlands (Winter 1999). Larger, and especially deeper pools, all other factors being equal, should have longer hydroperiods than smaller or shallower pools: there is simply more water to lose. Hydroperiod is related to detritus processing, decomposition rates are slower and organic matter accumulates in longer hydroperiod pools (Barlocher et al. 1978; Kirkman et al. 2000).

Geologic location and distribution

For a complete understanding of wetland hydrology, it is important to know the position of the water body in relation to groundwater flow, the geologic characteristics of the wetland basin (e.g., permeability), and the wetland's climatic setting (Winter 1999). The exchange of groundwater and surface water are affected by their relative positions. Typically, groundwater is recharged at high elevation sites and discharged at low elevations, but this is valid mostly for regional groundwater systems (Winter 1999). Local groundwater flow is superimposed on regional patterns and can result in complex relationships between ground and surface waters, regardless of their relative positions. Additional hydrological processes, such as climate-driven evaporation and transpiration of shallow groundwater adjacent to wetlands contribute to the complexity of isolated wetland hydrology.

Prairie basin (prairie pothole) wetlands occur due to geologic settings and hydrologic processes that favor the ponding of water (Kantrud et al. 1989). Continental glaciation created edaphic conditions that resulted in large numbers of prairie potholes. Prairie potholes form in glacially derived depressions underlain by glacially derived soils (i.e., tills), with low permeability. The tills of the eastern Dakotas are high in shale-derived material, which are higher in silt and clay and are less permeable than tills derived of other materials or of outwash deposits (Kantrud et al. 1989). These tills are of poorly sorted, largely unstratified material and groundwater flows most readily through surface joints (Sloan 1972). Consequently, groundwater flow is shallow and localized adjacent to the potholes.

In Minnesota, the abundance of seasonal (ponded) wetlands differs among terrestrial ecological units, particularly at the scale of land-type association or glacial landform (Palik et al. 2003). Wetlands were more likely to occur on ground moraine land-type associations, a probable consequence of the higher frequency of small ice blocks stranded on these lands with the retreat of continental glaciation. In central Pennsylvania, a chain of ephemeral ponds, with hydroperiods ranging between 33 and 192 days, occur on karst terrain in topographic depressions between 0.5 and 2 m deep (O'Driscoll and Parizek 2003). The depressions were formed by differential solution of the underlying carbonate rock, with a thick layer of low permeability clay under each pond. Topography is an important determinant of the occurrence of West Coast (U.S.) vernal pools (Zedler 1987). Pools form in closed depressions on level surfaces, underlain by impermeable soils. In California, such conditions are found on coastal terraces and broad alluvial valleys, especially the Central Valley (Zedler 1987). Impermeable clay subsoil, allowing for a perched water table, occurs in both regions.

Large (>0.2 ha) depression wetlands (e.g., Carolina bay) in western South Carolina were disproportionately distributed between the two major landforms of the site, with a greater density of wetlands occurring on the riverine terrace than on the more extensive uplands (Kirkman et al. 1996). However, the wetlands that occurred in the uplands were significantly larger than those on the terrace. No explanation for these patterns was provided, however, the well-studied Thunder Bay, a Carolina bay in western South Carolina, is underlain by a clayey hardpan of relatively low permeability, with estimated hydraulic conductivities ranging between 1.1×10^{-6} and 3.6×10^{-9} m/s (Lide et al. 1995). Depths to the hardpan ranged between 0.9 m at the center of the bay and 0.4 m at the margins of the bay.

Seasonal forest pools in central Massachusetts were not distributed uniformly across the landscape, but significantly aggregated (Brooks et al. 1998). The relationship between the location of pools and surface geology was not investigated, though the aggregation of pools suggests an influence. In a preliminary study of the hydrology of four SFPs located on till-derived soils at two sites in central Massachusetts, Gay (1998) calculated hydraulic conductivities of soils at the sites in order of 1.77×10^{-6} to 7.38×10^{-8} cm/s, with the soils of the southern of the two sites as being very shallow with frequent bedrock outcrops and those of the northern site occurring over a relatively impervious, compact soil layer (i.e., hardpan). The location of these four pools suggests that SFPs occur in areas of impeded drainage due to shallow soils over bedrock or compacted subsurface soil horizons.

Across a wide spectrum of locations, from the grasslands of coastal California and prairies of mid-continental North America to the temperate forests of the eastern United States, isolated, ponded wetlands occur in shallow natural depressions which are shallow to bedrock or underlain by impervious soil horizons. These edaphic conditions allow for the formation of local, perched groundwater and for water to collect in the depressions.

Morphology

Few extensive surveys or inventories of isolated wetland basin morphologies have occurred. In the forested landscapes of northern Minnesota, Palik et al. (2001, 2003) found that seasonal ponds were small (0.01–0.25 ha), with high perimeter-to-area ratios, suggesting they would be sensitive to change in their forested catchments (Millar 1971; Palik et al. 2001). Over 80% of the 299 Carolina bay and bay-like wetlands in western South Carolina were <3 ha in surface area and only 20 of these wetlands were >6 ha (Kirkman et al. 1996). Sloan (1972) described prairie potholes occurring in a large range of sizes; those >40 acres (16.2 ha) are arbitrarily classified as lakes. Potholes are shallow, few are >150 cm deep and most are <60 cm. Pothole shapes are varied, but basins are saucer-shaped (Sloan 1972), and being shallow, have low-grade shorelines that contribute to their dynamic hydrologic regimes (Kantrud et al. 1989).

The pool and basin morphometry of California vernal pools is highly variable, both spatially among pools and temporally for any individual pools over time (Zedler 1987). The volumes of pools surveyed on the Kearny Mesa near San Diego, CA were estimated to range between 5 and 50 m^3, while the volume of another 'large' San Diego pool was estimated at 540 m^3 (Zedler 1987). The slope of the pool bottom was important in these systems as its steepness determines the range in soil moisture conditions from the pool margin to the center as the pool dries. This in turn defined zones of growing conditions that determined the characteristic floral communities of the pools (Bauder 2000).

Seasonal forest pools in central Massachusetts are small, only 33% were >500 m^2 in maximum surface area (Brooks et al. 1998). A study of the morphology of a representative sample ($n = 34$) of these pools identified the pool of median size to have a maximum depth of 0.46 m (range 0.11–0.94 m), surface area of 689 m^2 (68–2941 m^2), volume of 110.5 m^3 (6–506 m^3), and perimeter of 118.5 m (30–388 m) (Brooks and Hayashi 2002). The maximum values for these morphological parameters were estimated from early spring bathymetric surveys of pools when the pools were filled to overflow capacity. A cross-sectional profile of the pool basins was described by an index (p) that would have a value of 1.0 for an inverted cone. Values of p less than 1.0 describe a convex basin profile and values greater than 1.0, a concave basin. The range of basin profile indices for the 34 pools was 0.6–2.24 with a median value of 1.02 (Brooks and Hayashi 2002).

The size and shape parameters of seasonal forest pools were related (Brooks and Hayashi 2002). Maximum surface area was positively correlated with maximum depth; larger pools are generally deeper, but not reliably so. Maximum pool volume was related to surface area and depth, but the relationship varied with basin profile. In general terms, pools with concave basins held more water at any given depth than do convex-shaped pool basins. Since volume is difficult to measure, it can be estimated by the formula:

$$V_{max}(A_{max}d_{max}/(1+2/p),$$

where, V_{max} = maximum volume, A_{max} = maximum area, d_{max} = maximum depth, p = pool basin profile index ~1.0.

The perimeter and area of central Massachusetts' SFPs were distributed as the theoretical relationship for an ellipse (Brooks and Hayashi 2002). From this relationship, one can estimate surface area and perimeter from measures of the long (a) and short (b) axes of a pool and the formulae for the approximate circumference ($2\pi[\{a^2+b^2\}/8]^{0.5}$) and area ($\pi ab/4$) of ellipses (Millar 1971, 1973).

The principal morphological features (maximum depth, area, and volume) of seasonal forest pools were positively, but weakly correlated with pool hydroperiod (Brooks and Hayashi 2002). The study determined that pools with maximum depths ≥0.5 m, areas ≥1000 m^2, or maximum volumes ≥100 m^3 tended to consistently have longer hydroperiods. The hydroperiods of pools of lesser sizes varied considerably. Hydroperiods were negatively correlated with maximum perimeter-to-area ratio (Brooks and Hayashi 2002). This relationship implies a surfacewater–groundwater exchange. Surface–groundwater exchange has been shown to increase with increasing perimeter-to-area ratio (Millar 1971), so it is likely that small SFPs receive little groundwater input when both groundwater and surface water levels are high, but lose water to shallow marginal groundwater when groundwater levels decline due to forest transpiration demands.

Catchments

There is very little published information on the size and characteristics of isolated wetland catchments. In Florida, groundwater levels 81 m from the center of an ephemeral cypress pond were found to be independent of water levels in the pond (Mansell et al. 2000). A catchment, circular in shape and with a radius of less than 81 m, would be 2 ha or less in size. The estimated hydrologic catchment for a cluster of 17 small, ephemeral, ponded karst wetlands in Pennsylvania based on surfacewater budgets or elevational potential for groundwater flow was approximately 1.8 or 8 ha, respectively, much less than the catchment area of 69 ha based on surficial topography (O'Driscoll and Parizek 2003). The catchment of any individual pond would be much less than the size of the catchment for the entire cluster of ponds. The limited amount of information that is available on the catchments of isolated wetlands suggests that those of seasonal forest pools should be quite small in area, similar in scale to their small size.

Hydrology

The hydrology of seasonal forest pools, as with other aquatic systems, can be described by a simple hydrologic budget (see LaBaugh 1986, for a more thorough discussion of wetland water budgets):

$$\Delta SW = P - R - E \pm \Delta GW,$$

where, ΔSW = change in surface water storage (volume) or depth; P = precipitation, including surface runoff from precipitation; R = channelized runoff; E = evaporation (or evapotranspiration); and ΔGW = exchange with groundwater.

The principal components of SFP hydrology, precipitation, evapotranspiration, and groundwater exchange, are discussed below in detail. Channelized runoff has minimal effects on SFP hydrology. The pools are, by definition, geographically isolated from other surface water systems, so channelized surface inflow does not generally occur. Overflow runoff from SFPs is highly ephemeral, occurring only briefly in the spring with snowmelt and spring rains, or at other times when unusually heavy rain events exceed the maximum storage capacity (i.e., maximum volume) of the pools. However, runoff needs to be considered. Since SFPs, as depressional wetlands, have relatively small and finite capacity, water inputs in excess of this capacity need to be accounted for. The water from heavy rainfall events, in excess of maximum capacity are lost from the system through runoff. This situation may be important if rainfall patterns become more episodic under climate change (Karl and Knight 1998; Karl and Trenberth 2003). Runoff can be assumed when projected storage or depth exceeds the maximum for a pool.

Groundwater influences

Groundwater exchange with wetland surface water is difficult to assess. From a survey of the water chemistry of 49 Carolina bays, Newman and Schalles (1990) concluded that there was a clear influence of surficial groundwater on bay waters. However, the relationship was affected by the accumulation of peat in the bays, which appeared to inhibit groundwater exchange and resulted in the dominance of precipitation effects on bay water chemistry. In South Carolina's Thunder Bay, the variation in water level change, not explained by precipitation patterns, was ascribed to groundwater exchange (Schalles and Shure 1989). The comparison of surfacewater and groundwater well hydrographs indicated groundwater exchange during periods of high groundwater. The authors concluded, upon further examination of these data, that the exchange must be primarily lateral, occurring at the margins of the pool basin. More thorough studies of the hydrology of Thunder Bay (Lide et al. 1995) and two other bays (Pickens and Jagoe 1996) determined that the occurrence of and that water level change in these bays were expressions of change in the water table. However, both bay water and shallow groundwater fluctuation were controlled by precipitation and evapotranspiration. The direction of the bay-groundwater flow depended on the relative elevations of the bay and groundwater but a net loss of bay water to groundwater was dominant. A similar seasonal shift in the direction of surfacewater-groundwater exchange was found in a study of the hydrochemistry of a series of bay-like seasonal forest ponds on the Delaware coastal plain (Phillips and Shedlock 1993). During wet winter and spring seasons, transient mounds in shallow groundwater develop adjacent to the ponds and groundwater flowed to the ponds. In the dry summer season, the groundwater mounds disappear and water flowed from the ponds.

Shallow, perched groundwater contributed little to California vernal pools in Sacramento County, California (Hanes and Stromberg 1998); precipitation was more than sufficient to fill the pools. However, surfacewater exchange with groundwater affected the hydroperiod of the pools. When groundwater was below the pool bottom, precipitation input was lost to seepage, delaying re-inundation. In years of average or greater precipitation, a perched groundwater layer formed and sustained the duration of the pool by eliminating lateral seepage. Later, as the groundwater was lost to evapotranspiration, lateral seepage of surfacewater hastened pool drying.

The specific conductance of precipitation and groundwater compared to that of wetland surfacewater is an indicator of the relative contribution of precipitation and groundwater inputs (Sloan 1972; Kantrud et al. 1989). The relative contribution of highly mineralized groundwater to pool surface water can be determined by comparing their conductivities to that of clean precipitation (Winter 1999). The relative contribution of groundwater to prairie potholes was determined by this method by Kantrud et al. (1989). Potholes with low surfacewater conductivity functioned as groundwater recharge areas and had temporary or seasonal hydroperiods; potholes with intermediate surfacewater conductivity were flow-through systems and had longer hydroperiods; and potholes with surfacewater conductivities as high as 700 μs/cm were groundwater discharge areas and had the longest hydroperiods. Amon et al. (2002) confirmed there was a significant deep groundwater input to temperate-zone fens of the glaciated Midwestern United States, as the conductivity of surfacewaters was greatly in excess of 100 μS/cm $\bar{x}$ = 624 μs/cm). Conversely, Palik et al. (2001) and O'Driscoll and Parizek (2003) determined that the source of surfacewaters of seasonal ponds in northern Minnesota forests and karst wetlands in central Pennsylvania was largely from precipitation, surface runoff, or shallow (< 5 m), perched groundwater, as the pool surfacewater conductivity was < 100 μS/cm.

The predominant influence of precipitation on pool hydrology was also identified in a study of the geochemistry of seasonal forest pools (Gay 1998). The chemistry, including specific conductivity and total dissolved solids of the surfacewater, precipitation, throughfall, and groundwater was measured at four pools at two sites on the Quabbin watershed in central Massachusetts. The conductivity of pool surfacewater was significantly less than that of groundwater and not statistically different than that of either precipitation or throughfall at three of the four pools (Figure 1). These results imply a minor input of groundwater to pool surfacewater. Generally, deep groundwater input appears to contribute minimally to ephemeral forest pools.

Weather influences

The influences of precipitation and temperature (energy)-related evapotranspiration on isolated wetland hydrology have been observed in numerous isolated wetland types. Water volumes were highly correlated with seasonal precipitation patterns, and high temperatures influenced evaporation rates and pool drying in temporary forest pools in central Mississippi (Bonner et al. 1997). The hydrologic regime of pocosins (i.e., southeastern U.S. shrub bogs) were influenced by

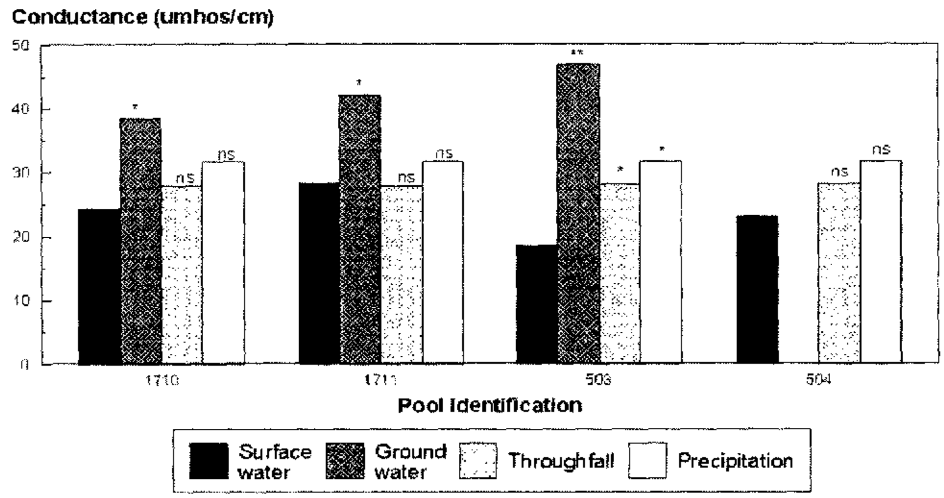

Figure 1. Average specific conductance of pool surfacewater, groundwater, precipitation, and throughfall at four seasonal forest pools, Quabbin Reservation, Massachusetts, USA, 1993–94 (Gay 1998). Significant difference from surface water indicated by * ($p < 0.05$); ** ($p < 0.01$); and ns ($p > 0.05$).

precipitation, as the exclusive source of water, and by evapotranspiration and surfacewater runoff, and groundwater discharge as a minor factor, as the sources of discharge (Sharitz and Gibbons 1982). The hydrology of Carolina bays has been found to be dependent on seasonal and annual precipitation patterns (Sharitz and Gibbons 1982; Schalles and Shure 1989; Lide et al. 1995), with water loss to temperature-related evapotranspiration (Sharitz and Gibbons 1982). The timing and duration of flooding of temporary ponds in southeastern Louisiana were determined by three interrelated factors: (1) the amount of precipitation occurring within limited periods of time, (2) the moisture content of the basin substrate, and (3) the relative humidity and evaporation rate, related to prevailing temperatures (Moore 1970). Precipitation and evapotranspiration were the major components of water gain and loss in prairie basin wetlands (Kantrud et al. 1989), accounting for as much as 90% of input and loss, respectively (Winter et al. 2001). The most striking feature of California's vernal pools was their dynamic hydrologic regime, a consequence of the region's strongly seasonal rainfall and climate (Zedler 1987).

The long-term annual hydrological regime of seasonal forest pools in central Massachusetts, responds to seasonal patterns in precipitation and evapotranspiration (Figure 2) as it does for west coast vernal pools (Zedler 1987: Figures 6 and 7). The pools begin to fill with water in the late fall when precipitation exceeds evapotranspiration (Brooks 2004). Pools not already at capacity, fill to overflow with spring rains and snowmelt. Following the full development of the forest foliage in the late spring, evapotranspiration exceeds precipitation and pool water levels decline. The quantification of these relationships explains a large component of the variation in water level change of SFPs (Brooks 2004).

Precipitation

Precipitation is the principal source of water for isolated wetlands. The hydrology of California vernal pools is driven by precipitation (Zedler 1987; Hanes and Stromberg 1998). Winter-season rain is often episodic, with short periods of intense rainfall followed by long periods of dry weather. Precipitation rates can exceed infiltration during heavy events in these dry grassland ecosystems, which allows for surface runoff into adjacent pools. Infiltration and overland flow into a pool is determined by (1) the topographic characteristics of the pool and catchment, (2) the vegetative cover and surface micro-conditions of the catchment, (3)

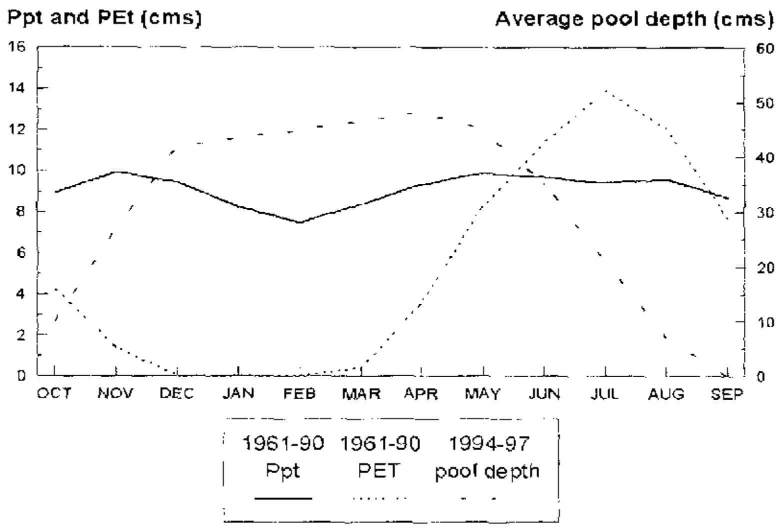

Figure 2. Thirty-year normal (average) precipitation and potential evapotranspiration and average 4-year water levels in a seasonal forest pool by month, Quabbin Reservation, Massachusetts, USA.

antecedent soil moisture conditions, and (4) precipitation rates (Zedler 1987).

Prairie potholes are depressional wetlands with no permanent outlets or inlets and have limited groundwater exchange (Winter et al. 2001), however, Sloan (1972) and others have reported a significant groundwater contribution, especially for longer hydroperiod potholes. A 17-year record comparing pothole water levels and cumulative departures from normal precipitation demonstrated that potholes are dependent on exchange with atmospheric water; inputs from precipitation and losses to evapotranspiration (Winter et al. 2001). Autumn through spring precipitation was highly correlated with water-level change in prairie potholes, but summer precipitation had little effect due to the high evaporation loss from these small, exposed water bodies. Most water input was derived from snow accumulation in wind-protected depressions and from spring precipitation and snowmelt flowing down from frozen uplands (Kantrud et al. 1989).

Surface water levels in Thunder Bay in South Carolina varied largely in response to precipitation patterns (Schalles and Shure 1989). The relationship between pond stage and precipitation was observed at annual, seasonal, daily, and even hourly time steps (Lide et al. 1995). A strong linear relationship was found between precipitation and water level in the Bay, with an estimated 62 cm of precipitation required over a 6-month period to offset water loss and maintain a stable pool water level.

I have monitored surfacewater change in four seasonal forest pools in central Massachusetts on a weekly basis since 1992 (Brooks 2004). The

Table 2. Correlations (*r*) between weekly precipitation amounts and water level change in four seasonal forest pools and weekly precipitation (Ppt) amounts (cms) required to maintain constant pool water depths, by season and annually, Quabbin Reservation, Massachusetts, 1992–2002.

	Fall		Spring		Summer		Annual	
	r	Ppt	*r*	Ppt	*r*	Ppt	*r*	Ppt
Pool 503	0.682	1.1	0.696	3.2	0.857	4.3	0.714	2.9
Pool 504	0.743	2.4	0.51	3.3	0.838	6.7	0.576	3.5
Pool 1710	0.794	1.4	0.683	3.3	0.904	3.9	0.779	2.9
Pool 1711	0.784	1.6	0.517	3.5	0.819	4.2	0.691	3.1

predominant effect of precipitation on water-level change in other isolated, ponded wetlands was also observed in these pools (Table 2). Precipitation alone explained ≥ 50% of water level change in the SFPs during the summer and fall months. Pool water level change was less sensitive to precipitation during the spring months. Excess water from precipitation was lost from the pools as runoff during the early spring, which would account for the lesser sensitivity between precipitation and water change during these months.

Evapotranspiration

Evapotranspiration is the loss of surface and groundwater to the atmosphere and is a major factor in the water balance of aquatic systems. Over long time periods, evapotranspiration can be quantified by using the water balance equation (Church et al. 1995; Lu et al. 2003). Evapotranspiration is highly sensitive to temperature (Huntington 2003) and decreases latitudinally from the southern U.S. to the northeast and from the coast to the interior with increasing elevation along the Appalachians (Lu et al. 2003). Estimated long-term evapotranspiration in the northeast ranges between 40 and 60 cm/year, with greater amounts occurring along the coast and lesser inland (Church et al. 1995).

Evapotranspiration losses from isolated wetlands include both the direct evaporation of surfacewater and the indirect loss of water by the transpiration from vegetation of the pool basin and adjacent catchment. The evaporation and transpiration of shallow groundwater from around the perimeter of surfacewater bodies are important determinants of local flow systems associated with surfacewater bodies (Millar 1971; Winter 1999). Transpiration demands from catchment vegetation creates a drawdown zone and can cause water loss from prairie potholes to adjacent, shallow groundwater (Sloan 1972; Winter et al. 2001; Hayashi et al. 1998). This effect can even be observed on a diurnal basis in prairie potholes, with partial recovery of ground and surfacewater levels at night (Sloan 1972).

Water loss from Thunder Bay during 4-day precipitation-free periods averaged 0.12 cm/day in January and 0.76 cm/day in July 1976 (Schalles and Shure 1989). A strong correlation existed between pool water loss and temperature ($r = 0.93$). Water loss from California vernal pools can be as high as 20+ mm/day (Zedler 1987). A large portion of this is due to direct surfacewater evaporation. However, a larger portion is likely due to infiltration to shallow groundwater through macroscopic channels. Weekly water loss from four seasonal forest pools in central Massachusetts, for weeks with no precipitation, frequently averaged greater than 1 cm/day (Table 3). Water losses during rain-free periods tended to be greater from smaller or shallower pools (503, 504) and less from larger or deeper pools (1710, 1711). Except for one pool, water loss from

Table 3. Weekly mean daily average temperature, number of weeks with no precipitation, average weekly water loss over those weeks from four woodland vernal pools, by season and pool, and Pearson correlation coefficients (and p) between weekly water loss and temperature, Quabbin Reservation, Massachusetts, 1992–2002.

	Spring	Summer	Fall	Correlation
Weekly mean daily average				
Temperature (°C)	16.2	19.5	5.2	
Pool 503				
Number weeks	8	2	4	−0.655
Water loss (cm)	−14.6	−16.0	−4.3	(0.044)
Pool 504				
Number weeks	5	1	2	−0.614
Water loss (cm)	−15.4	−28.0	−10.5	(0.422)
Pool 1710				
Number weeks	9	6	5	−0.523
Water loss (cm)	−7.4	−8.7	−2.4	(0.072)
Pool 1711				
Number weeks	8	5	4	−0.677
Water loss (cm)	−7.0	−18.8	−2.8	(0.008)

the SFPs was correlated with temperature (Table 3). Water loss to evapotranspiration was greatest in the summer months, when a forest canopy would mostly cover the pools and water loss would be indirectly through vegetative transpiration. Water loss in the early spring would be to direct evaporation from the pool surface, and later, after full foliage development, to transpiration. Water loss in the fall, after the leaves have senesced and fallen, would again be to direct evaporation.

Modeling

The development and use of hydrologic models is an important achievement in the study of all aquatic systems. A successful model was developed for the hydrology of an individual ephemeral cypress pond in north-central Florida (Mansell et al. 2000). Model input was limited to rainfall, air temperature, soil characteristics, and pond geometry. Pond water level simulations demonstrated the importance of atmospheric water exchange. Pond water levels rose during periods of increasing cumulative net water input (NWI = rainfall − interception − evapotranspiration) and fell during periods of decreasing cumulative NWI, when surface water flowed radially to shallow groundwater in the surrounding forest.

Su et al. (2000) modified an existing river basin hydrological model to simulate water level variations in a 3-ha prairie pothole wetland (Woo and Rowsell 1993). They estimated daily water balance based on precipitation, snowmelt, evaporation, surface runoff, and subsurface flow. Sensitivity analysis affirmed that wetland water levels were strongly influenced by surface runoff of snowmelt over frozen ground (Woo and Roswell 1993; Hayashi et al. 1998).

Pyke (2002) developed a process-based model of the hydrology of California vernal pools to assess the potential effects of climate and land-use change. This model calculates a daily water balance, using meteorological data, and successfully matched field data from vernal pools on both the coast and inland Central Valley. The structure of the model re-emphasized the importance of precipitation as the dominant input to the pools and water loss to evapotranspiration. However, soil and topographic constraints complicate direct simple weather effects.

Modeling is an important component of the study of seasonal forest pool hydrology. Successful model development will provide a tool for the assessment of land use and land management impacts on pool hydrology. A hydrologic model will also provide a means for analyzing the potential effects of climate change on these important wetland resources.

Climate change

Projected climate change, including changes in temperature, precipitation, atmospheric circulation, and the frequency and severity of storms, will almost certainly result in major changes in temperate freshwater wetland hydrology (Brinson and Malvarez 2002). Regional-scale modeling has projected large declines in annual streamflow and water supply in the northeastern United States as a consequence of projected climate change (Kirshen and Fennessey 1995; Moore et al. 1997; Vogel et al. 1997; Wolock and McCabe 1999; Huntington 2003). Projected declines in streamflow are a consequence of increased evapotranspiration, due to increased temperatures, the lengthening of the growing season, and an increase in the ratio of rain to snow (Moore et al. 1997; Huntington 2003).

Wetlands in differing hydrologic and climatic settings can be expected to have differing sources of water (i.e., ground vs. atmospheric), which in turn would affect their response to climate change (Winter et al. 2001). Hydrologically isolated wetlands, with weather effects being the dominant influence on their hydrology, are especially sensitive to climate change (Winter 2000; Poff et al. 2002). Wetlands that depend primarily on precipitation for water input are most vulnerable to changes in climate and weather patterns (Burkett and Kusler 2000). Decreases in precipitation and/or increases in temperatures can be expected to result in shortened hydroperiods, decreases in wetland area, or conversion of wetlands to uplands.

Climate projections for New England, based on a projected doubling of atmospheric CO_2 concentrations, include temperature increases of 3–5 °C, a decrease in the amount and duration of snow cover, and a decrease in the frequency, but increase in intensity, of summer convective storms (Moore et al. 1997; New England Regional

Assessment Group 2001). These changes portend at least two major impacts on small, isolated seasonal forest pools (McCarthy et al. 2001; Root and Schneider 2002). With increased temperatures, temperature (energy)-related evapotranspiration will increase and the annual water balance would become negative (i.e., precipitation input < evapotranspiration loss) earlier in the year resulting in earlier pool drying. Enhanced evapotranspiration during the summer would place increased demands on groundwater and delay pool re-inundations later into the fall. Shortened hydroperiods in the spring would result in more frequent reproductive failures of spring-breeding amphibians. Later pool re-inundations in the fall would negatively affect the fall-breeding marbled salamander (*Ambystoma opacum* Gravenhorst).

Changes in total precipitation for the northeast under climate change projections are uncertain, but there is consensus that precipitation patterns will become more episodic, with less frequent events of greater intensity and more frequent and longer, inter-event droughts (Karl and Knight 1998; Karl and Trenberth 2003). Such changes in precipitation patterns would result in a pattern of drying and reflooding of pools, especially smaller ones, during the spring and summer months. SFPs have a fixed capacity and excess water from intense rainfall events are lost. Longer intervening drought periods would result in pool drying. The faunal community would be seriously impacted by this changed hydrologic regime. Developing amphibian eggs or larvae would be killed by exposure (Paton et al. 2003) and may not be replaced after a pool has re-inundated.

Conclusions

The dearth of information on the hydrology of isolated wetlands, and on seasonal forest pools specifically, calls for increased focus on this important subject. It is critical that we better understand wetland hydrology if we are to fully understand wetland structure and function (LaBaugh 1986) and if we are to best protect and/or manage isolated wetlands (Winter et al. 2001).

By definition, hydrologically isolated, ponded wetlands are located in depressions on impervious substrates. The distribution of isolated wetlands, including seasonal forest pools, is not random, implying an association with patterns in surficial geology. In regions that experienced continental glaciation, depressional wetlands occur more often on till-derived soils than other glacially derived soils. Topographic depressions are locations of water accumulation, which is blocked from downward seepage by bedrock or impervious soil layers. The basin morphology of these wetlands is highly variable but they are shallow and small, typically < 1 m in depth and 1 ha in area. Basins of greater size occur but they are the exception and are more likely to have longer hydroperiods, allowing for the presence of fish and reducing their value to vernal pool fauna. Basin size is related to hydroperiod, though the relationship is weak. While larger pools have longer hydroperiods and, on average, would have more successful amphibian reproduction, it is, nevertheless, important to retain smaller pools to serve as spatial links between larger pools and allow for the dispersal of juveniles and genetic exchange among metapopulations (Gibbs 1993; Semlitsch and Bodie 1998).

Weather effects determine the hydrology of isolated wetlands. Precipitation is the dominant input and temperature (energy)-related evapotranspiration, either as direct evaporation of surfacewater and/or indirectly through transpiration by basin and adjacent catchment vegetation, is the major water outflow. Precipitation has been shown to have a strong positive effect on water level change in isolated, ponded wetlands. The impact of evapotranspiration is less clearly understood, due, in part, to the difficultly of quantifying this affect. The influence of water exchange with groundwater varies among differing isolated wetland types and among individual wetlands, depending on site and weather effects. When exchange does occur, the prevalent direction appears to be from pond surfacewater to shallow, adjacent groundwater.

The dominant influence of precipitation and temperature-driven evapotranspiration on the hydrology of isolated wetlands implies that climate change will have important effects on these systems. Projected temperature increase will increase evapotranspiration demands on these wetlands that are small to begin with and are isolated from larger ground and surfacewater resources that could replace additional losses. Increased evapotranspiration losses will cause pools to dry earlier in the spring and reflood later in the fall. Changes in precipitation patterns, even without change in total precipitation amounts will also affect the hydroregimes of isolated wetlands. An increase in the occurrence and duration of drought periods between less frequent, but more intense rainfall events will result in the drying and reflooding of smaller wetlands. Shortened hydroperiods or the fragmentation of a continuous hydroperiod into cycle of brief wet–dry periods will have significant impacts on the success of larval amphibian development and the richness of the invertebrate community of seasonal forest pools.

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