

Forecasting the resilience of vernal pool ecosystems to climate-mediated hydrological disruptions

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Report

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Introduction

Identifying climate change refugia

Climate change is altering temperature and precipitation regimes worldwide (IPCC 2013) and consequently causing species extinctions and threatening ecosystem services to humans (Parmesan and Yohe 2003; Moritz et al. 2008; Chen et al. 2011; Urban 2015). The current challenge is to predict these changes accurately so that we can design effective mitigation strategies that protect ecosystems facing rapid climate change. We must make critical decisions about climate mitigation now, and we cannot make these decisions without understanding the underlying resilience of natural ecosystems (Urban et al. 2016).

We seek to understand *ecological resilience* to global climate change, which is defined as the degree to which a system resists transitions among stable states (Holling 1973; Gunderson 2000) even if the structural domain shifts (Walker et al. 2004). This definition applies to the shallow, temporary ponds that we study, where alternative ecological states are common (Scheffer et al. 1993). One effective strategy to enhance ecosystem resilience is to identify those habitats that are especially resilient to climate-induced alterations and thus offer so-called climate change refugia for associated taxa (Ashcroft 2010; Morelli et al. 2016). In seeking climate change refugia, land managers search for habitats that are less sensitive to climate change and thus could allow for the future maintenance of biodiversity, ecosystems, and ecosystem services to humans (Morelli et al. 2016).

A recent review proposed the hypothesis that small, isolated temporary ponds in glaciated landscapes – like those in Connecticut – are the most susceptible water bodies to climate-induced changes because of their dependence on seasonal precipitation (Winter 2000). These temporary ponds, often called vernal pools, usually dry in mid- to late-summer. Despite their temporary nature, they host a disproportionate diversity of organisms (Schneider and Frost 1996; Wellborn et al. 1996), which can provide important ecosystem services such as mosquito control. We propose that certain temporary ponds might act as hydrological refugia (*sensu* McLaughlin et al. 2017) during climate change because groundwater inflow or other local factors buffer climate-induced changes in their hydrology. Yet, we know little about how hydrological factors in temporary ponds and their watersheds either buffer or exacerbate predicted climate change on the biological communities (Brooks 2004; Corn 2005). Our current understanding of future climate change on aquatic systems is largely limited to impacts on permanent lakes and streams (Jeppesen et al. 2010). To fill this gap, we seek to elucidate the mechanisms that underlie hydrological and ecological resilience in temporary ponds in the northeastern US.

Temporary ponds and climate change

Wetlands support some of the densest concentrations of diversity on Earth and provide 40% of its renewable ecosystem services (Costanza et al. 1997, Zedler 2003). Yet, wetlands are among the most degraded ecosystems in the world: 50% of wetlands are already lost (Dahl 2000, Zedler and Kercher 2005), and obligate wetland species face high extinction rates (Millennium Ecosystem Assessment 2005). Moreover, temporary ponds, one type of common wetland, continue to disappear in northeastern US as they are filled during residential development or converted to permanent wetlands (Tiner et al. 2013). Historically, agriculture degraded most

wetlands, but climate change poses a new, but uncertain, risk to these critical habitats (Corn 2005; McMenemy et al. 2008).

Climate change likely affects temporary pond hydrology more strongly than any other aquatic habitat (Winter 2000). The physical, chemical, and biological properties of temporary ponds are tied directly to their period of inundation and drying (Wellborn et al. 1996; Urban 2004; McMenemy et al. 2008). Thus, temporary ponds are more susceptible to altered temperature and precipitation than more permanent bodies of water such as lakes. Their overall water balance depends on inputs of precipitation and groundwater versus loss via evapotranspiration, especially from trees (Brooks 2004). Under climate change, warmer temperatures are expected to increase evaporation and evapotranspiration from surrounding vegetation in the pools and drainage basin and also extend the growing season for vegetation (Xie et al. 2015), thereby indirectly expanding the period of evapotranspiration. Higher evapotranspiration could decrease water levels and cause early drying.

However, predicted increases in precipitation could offset these temperature-related losses. Precipitation in the northeastern US is predicted to increase 10-20% by the end of this century at the same time as the distribution of precipitation across seasons is also expected to shift toward longer drought periods (USGCRP 2017). Longer droughts could cause ponds to dry and kill aquatic organisms even if overall annual precipitation increases. For instance, a long-term drying trend in Yellowstone National Park caused ponds to dry earlier and faster, in turn reducing the number of amphibian species (McMenemy et al. 2008). We currently do not know if increased precipitation will be sufficient to overcome the deficit owing to increased evapotranspiration. The answer will likely depend on critical, local features of pool watersheds, including type of vegetation and groundwater influence.

By understanding changes to the hydrology of temporary ponds, we can also understand and predict climate change impacts on aquatic organisms that live in these habitats. The species composition and diversity of temporary ponds depend critically on hydroperiod. In particular, species diversity increases with hydroperiod length because early drying eliminates species that cannot complete their life cycle rapidly enough and thus provides a hard limit on diversity ((Schneider and Frost 1996; Wellborn et al. 1996; Urban 2004). Permanent pools cannot completely compensate for loss of temporary ones because they often include fish, which eliminate most vernal pool specialists (Wellborn et al. 1996). Recent work in Connecticut demonstrates that even highly temporary pools can provide habitat for unique species that cannot survive elsewhere (Urban and Roehm 2018).

Methods

Site description

We collected hydrological, physical, and ecological data from two locations: a site close to the coast in Northford, Connecticut and a more inland site located near the border with Massachusetts in Union, Connecticut. The two sites are similar in terms of topography, limited human disturbance, and access to a large number of natural temporary ponds. However, the two sites differ in temperature, with the interior site 1.3°C warmer than the coastal site. At each of the two sites, we selected 12 ponds (24 total ponds) that varied along a gradient of permanence at each site and which included ponds suspected to have substantial groundwater influence owing to observed open water in the winter.

Climate variables – We collated daily data on temperature, precipitation, and evaporation from the weather stations at Storrs and Meriden, which are located close to our study sites and thus should reasonably represent regional climate conditions. We used the Northeast Regional Climate Center's (NRCC) evaporation/soil moisture model (DeGaetano et al. 1994) to calculate evapotranspiration for specific vegetation types. The NRCC has modified and calibrated the British Meteorological Office Rainfall and Evaporation Calculation System (MORECS) for the northeastern US to calculate actual evapotranspiration (incorporating vegetation and soil moisture) from grass and deciduous forests (DeGaetano et al. 1994). Vegetation type and density can be included in the evapotranspiration model by changing the flux density of heat into the soil, wind friction, and surface water resistance.

Watershed variables – Next, we used the watershed delineation package in Autodesk Civil 3D to delineate pond watersheds using 2016 1-m Lidar digital elevation maps available from the UConn CLEAR (clear.uconn.edu) website. We then used these delineations to calculate watershed area. On a cloudless day, we recorded photosynthetically active radiation using a ceptometer (AccuPAR PAR/LAI, LP-80, Decagon Devices) at 1 m aboveground along a linear transect through each watershed from its outlet to source at approximately every 1 m along the transect. These estimates were compared to light estimates from nearby sites without forest canopy to estimate leaf area index as an estimate of relative watershed vegetation contributions to evapotranspiration.

Recording hydrological regimes

To track changes in pond depth, we set up remote game cameras (Stealthcam 4K) focused on a standardized stream gauge at the maximum depth in each study pond (Fig. 1). The cameras were set up to take photos 2 or more times per day. We then recorded the depth on the marker from each photo. Preliminary work indicated that camera data was almost perfectly correlated with physical pressure transducers of water depth ($R^2 = 0.99$). Game cameras also have the added advantage of recording the phenology of leaf-on and leaf-fall, which are critically linked to evapotranspiration dynamics.



Fig. 1. The refilling of Quarry pond at the northern site in autumn following a 3-day, 6-cm rain event captured by our remote cameras.

In addition, we also measured groundwater contributions to pond hydrology in a subset of five ponds at each site. At each pond, we dug a shallow 2-m well next to the pond and in the vicinity of suspected groundwater flow. We lined each well with a PVC pipe with a screened end, surrounded the pipe well with sand, and then sealed the top with clay. We lowered a HOBO U-20 water level recorder to estimate groundwater height, and then compared this height to the stream gauge using a laser-light level to evaluate if groundwater levels were higher or lower than pond level as an indication of groundwater discharge or recharge.

Results and progress

Hydrological dataset

We collected depth data from game camera photos twice daily at 24 ponds across two sites for at least one year (May 2019 - June 2020) with a subset of ponds with data back to January 2018, totaling approximately 26,400 data points. All these data have been quality checked and aggregated. We measured groundwater levels twice per day in wells in 10 ponds for one water year (June 2019 - June 2020). We also collected information on leaf-out and leaf-fall from photos to provide an accurate window for evapotranspiration calculations. A side benefit of the photos is that we also gained a high-resolution dataset of ice coverage on ponds, which we have used to build models of small pond ice dynamics (see Modeling: other).

Watershed dataset

We delineated the small watersheds associated with temporary ponds using high-resolution digital elevation maps. From these watersheds, we calculated watershed area and collected PAR measurements across each watershed to calculate an estimate of leaf area index. This watershed index adjusts contributions from evapotranspiration to pond hydrology for each pond. We found that the southern site had lower overall leaf area indices than the northern site, creating a distinctive bimodal distribution (Fig. 3). These differences might also affect the hydrology of the two sites differently.

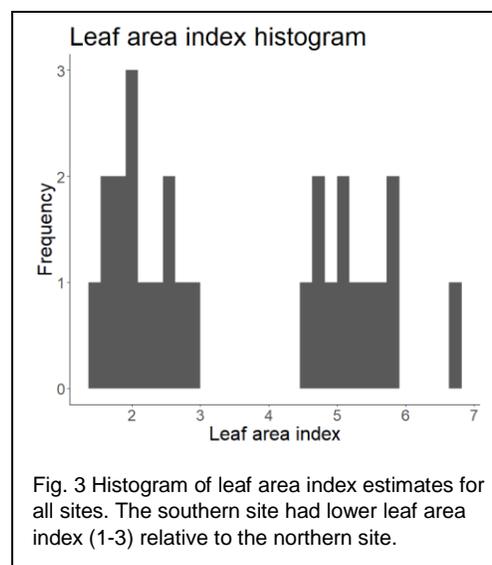


Fig. 3 Histogram of leaf area index estimates for all sites. The southern site had lower leaf area index (1-3) relative to the northern site.

Pond biodiversity dataset

At each pond, we performed surveys of amphibian egg masses in the spring and standardized dip net surveys in early summer at all study ponds for the years 2017 - 2020. From these surveys, we can estimate an average density of each wetland species, as well as the richness and evenness of these communities in relation to drying events.

Hydrological modeling

We have started modeling pond hydrology, beginning with simple models that relate precipitation and evapotranspiration to daily pond depth. We have been applying the model developed for four woodland temporary ponds in central Massachusetts (Brooks 2004). This simple model equated the weekly change in pool surface water depth (ΔD) to regional precipitation (PPT) and potential evapotranspiration (PET) and then fit regression coefficients for each pool: $\Delta D_i = a_i \cdot \text{PPT} - b_i \cdot \text{AET}$. Using this relationship, we can demonstrate that this simple model explains approximately 40% of the variation in the change in pond depth, in line with previous research (Brooks 2004). The sum of the current and previous day's precipitation were found to be especially important (Fig. 2). However, this analysis does a poor job of predicting pond re-fill, suggesting a need to model belowground water tables. The next complications to add are groundwater influences, as indicated by our groundwater wells, and to correct PET values based on variation in vegetation evapotranspiration, as informed by our estimates of watershed leaf area.

These initial models are regression-based approaches, which do not incorporate our mechanistic understanding of the hydrological process. Therefore, we will next develop our own simulation-based approaches to model hydrology. We have developed a sketch of this approach,

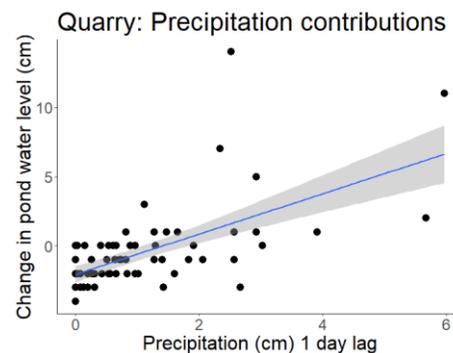


Fig. 2 - Change in pond water levels as a function of recent precipitation.

which takes an iterative approach by incorporating daily inputs (precipitation, groundwater/pond gradient) and outputs (PET modified by canopy cover and phenology) as well as the mediating factor of ice cover, which reduces evaporative losses. Our goal is to build a full-year simulation that can predict actual pond levels (rather than changes) across years and applies to both sites.

For unknown parameters, we have been developing a pipeline that applies Approximate Bayesian Computation, or ABC for short (Sunnåker et al. 2013). This method takes the outputs derived from random parameter values from any simulation and evaluates them against measures of model performance (e.g., correspondence between modeled and observed pond depths). It then performs a Markov chain-like search for an optimum and calculates a distribution that can be used to inform measures of uncertainty.

Lastly, we will use a deterministic simulation model created by the USDA Agricultural Research Service. The Soil and Water Assessment Tool (SWAT) is a deterministic climate-soil-land cover-climate watershed model used to predict water yields (Douglas-Mankin et al. 2010). The available simulation software allows the user to input topography, soils, and land use heterogeneity for sub-watershed-level detail and calculate water yields, including for ponds (Neitsch et al. 2011). The simulation accounts for a wide range of factors not included in models 1-3 and could thus provide the most generalizable and accurate predictions.

Modeling: other

One side benefit of our hydro-cameras is that they record a detailed history of ice cover on ponds. As students quantified water levels, they also recorded when ice appeared and disappeared on ponds. We have used these datasets to test and parameterize models of ice cover for these ponds. We are using these ice cover models to estimate the longest period of ice cover because increasing ice cover is associated with declines in oxygen content in the ponds. These oxygen levels ultimately determine the distribution of a keystone predator, the marbled salamander (*Ambystoma opacum*). By understanding how winter weather affects ice cover, we can also predict if this predator will increase in distribution as winters become warmer.

Eco-hydrological modeling

We will correlate community richness, evenness, and composition with drying times to form a biological submodel that relates aquatic communities to pool drying times. We will then apply climate change scenarios to predict how changes in climate change might affect aquatic species and diversity as mediated by changes in pool hydrology. We have this data ready to be applied to outcomes from the best hydrological models.

Projections

We will use downscaled climate projections from the North American Regional Climate Change Assessment Program (<http://www.narccap.ucar.edu/>), which provides projections at a resolution of 50 km from an ensemble of 8 leading climate models (Laflamme et al. 2016). We will develop climate parameters for the study region under the RCP 2.6, 4.5, 8.5 climate change scenarios representing low, middle, and high expectations for greenhouse gas emissions, respectively. Using a decade of predictions for 2050 and 2100, we will generate a mean and variance for weather variables, which will be used to calculate model inputs for the most accurate model found in Objective 2. Based on projections, we will calculate the change in the distribution of drying times for study pools in the future as well as rank pools as potential climate refugia, i.e., the least change in drying times. We will explore how these ranks change with local factors such as groundwater influence to provide recommendations for choosing wetlands for protection.

Significance

Globally, predictive modeling is needed to understand and predict future climate change impacts on one of the most threatened freshwater habitats in the US (e.g., Gamble et al. 2007, Todd et al. 2011, Hossack et al. 2013). Building accurate models to predict the effects of climate change on vernal pool hydroperiod will be useful for scientists and land managers worldwide. Currently, we do not know the degree to which climate change threatens wetlands around the world. More accurate hydrological-ecological models will allow federal, state, and local land managers to understand and predict how the regional climate change will affect the distribution of drying times for temporary ponds. Such models will also identify refugia pools that should be priorities for land protection as well as inform the hydrological design of state-mandated constructed wetlands. Understanding hydrological refugia in a changing climate will be invaluable for ensuring that vernal pool species and their unique benefits to humans are protected during ongoing climate change.

Locally, the northeastern US is concurrently facing some of the most dramatic changes in temperature and precipitation patterns in the US (USGCRP 2017). However, we lack the predictive framework to make informed forecasts for its effects on aquatic systems and associated organisms. This knowledge gap is especially true for temporary ponds, which support a diverse and threatened biological community. Connecticut wetlands host a disproportionate number of endangered, threatened, and special-concern species, including five amphibians and four reptiles (<https://www.ct.gov/deep/cwp/>). Moreover, these pools differ from other regions of the US in their hydrological regime. Unlike true vernal pools often in grasslands in western US, our study pools (more correctly termed ‘temporary or autumnal ponds’) fill in autumn following leaf-off and begin drying with leaf-on in the spring. Thus, their hydrological regime depends critically on the phenological dynamics of forest evapotranspiration, in addition to temperature and rainfall patterns. We do not currently know enough about these hydrological-ecological dynamics in the northeastern US to make decisions about how to protect temporary ponds and their unique and threatened biota in the face of future climatic change.

Project Findings and Impact

Small temporary ponds provide habitat for a disproportionate number of unique and endangered aquatic species. Understanding the hydrology of these ponds is important because their biological diversity is strongly tied to pond hydroperiod, the length of time that ponds are inundated. Precipitation, evapotranspiration, and groundwater are expected to determine the hydroperiod. As climate change progresses, it is unclear if ponds will dry earlier or later given future projections for both increased rainfall and increased evapotranspiration. To date, few models exist that can accurately predict pond hydroperiod. Here, we collected fine-scaled data on temporary pond hydrology and ecology from 24 ponds at two sites in Connecticut to inform a joint hydro-ecological model. We found strong effects of precipitation events and groundwater flow in determining drying times in preliminary analyses. Evapotranspiration had smaller, but more constant, effects throughout the season. We also detected differences in sites in leaf area index, a measure of vegetation related to potential evapotranspiration. We developed simple statistical models that can predict pond levels with moderate accuracy, but we now need to develop more complicated, iterative simulation models that can better represent seasonal variation in hydrological drivers. These developing models will inform questions about the effects of future climates on temporary pond hydrology and the organisms that inhabit these important habitats. Such projections will be important to conserve temporary ponds, given their ubiquity and disproportionate contributions to biodiversity and ecosystem services.

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