Video Article

Continuous Hydrologic and Water Quality Monitoring of Vernal Ponds

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Abstract

Vernal ponds, also referred to as vernal pools, provide critical ecosystem services and habitat for a variety of threatened and endangered species. However, they are vulnerable parts of the landscapes that are often poorly understood and understudied. Land use and management practices, as well as climate change are thought to be a contribution to the global amphibian decline. However, more research is needed to understand the extent of these impacts. Here, we present methodology for characterizing a vernal pond's morphology and detail a monitoring station that can be used to collect water quantity and quality data over the duration of a vernal pond's hydroperiod. We provide methodology for how to conduct field surveys to characterize the morphology and develop stage-storage curves for a vernal pond. Additionally, we provide methodology for monitoring the water level, temperature, pH, oxidation-reduction potential, dissolved oxygen, and electrical conductivity of water in a vernal pond, as well as monitoring rainfall data. This information can be used to better quantify the ecosystem services that vernal ponds provide and the impacts of anthropogenic activities on their ability to provide these services.

Video Link

The video component of this article can be found at https://www.jove.com/video/56466/

Introduction

Vernal ponds are temporary, shallow wetlands that typically contain water from fall to spring and are often dry during the summer months. The inundation period of vernal ponds, generally referred to as the hydroperiod, is primarily controlled by precipitation and evapotranspiration[1].

Vernal ponds can also be referred to as vernal pools, ephemeral ponds, temporary ponds, seasonal ponds, and geographically isolated wetlands[2]. In the northeastern United States, vernal ponds are most often characterized by the critical habitat they provide for amphibians, serving as the breeding grounds and providing support during early life stages (*i.e.*, tadpoles) and metamorphosis. In California, vernal ponds are characterized by the unique vegetation and endangered plant species that they support[2].

These habitats are increasingly threatened due to land use and climate change, and amphibian populations are experiencing a significant global decline largely due to anthropogenic activities[3,4]. Water quality concerns due to pollution are also thought to be contributing factors in recent amphibian declines globally[5]. Furthermore, recent studies have revealed an increased occurrence of intersex characteristics in frogs inhabiting vernal ponds impacted by human wastewater[6]. There is therefore a need to conduct more intensive monitoring of both natural and impacted vernal ponds to better understand the contributors to the global amphibian decline.

The physical parameters of vernal ponds that need to be measured and monitored include the pond morphology and water level. The morphology is the geometry of the pond, and is developed by conducting a survey to determine changes in elevation across the pond. The survey data are then used to establish a stage-storage curve, which enables the volume of the pond to be estimated based on water level measurements. Because the water level in a vernal pond is heavily influenced by precipitation, measurements should be made at a high temporal resolution to best understand both short (*i.e.*, on the order of minutes to hours) and long-term fluctuations (*i.e.*, on the order of months to years) in water level.

Water quality parameters of interest that are known to affect the function of vernal ponds include temperature, pH, electrical conductivity, dissolved oxygen levels, and oxidation-reduction potential. These parameters can all be measured *in situ* with relatively cheap technologies and sensor networks. Some water quality parameters of interest such as some nutrient species (*i.e.*, total Kjeldahl nitrogen) and other pollutants (*i.e.*, emerging contaminants) require samples to be collected and brought to a laboratory for processing and analysis.

Critical parameters that affect the ability of vernal ponds to function as appropriate habitat for breeding amphibians and the early developmental stages of tadpoles include water level, pH, and dissolved oxygen concentration. Compared to vernal ponds located in relatively pristine landscapes, elevated levels of electrical conductivity, higher pH, reduced dissolved oxygen concentrations, and high nutrient concentrations have been recorded in vernal ponds impacted by anthropogenic activities[2,7]. Reducing or anaerobic conditions may occur in these habitats, particularly ones that are impacted by anthropogenic activities. This can cause a shift in the microbiological community, altering the nutrient cycling within the pond and potentially reducing degradation of endocrine disrupting compounds and other pollutants[8,9].

The goal of this paper is to provide information for how to establish a station for monitoring the water quantity and quality of a vernal pond. This method can be applied to any vernal pond, but requires access to the site (*i.e.*, the site must be on public property or have land-owner permission to install equipment).

Protocol

1. Conducting a Survey of a Vernal Pond Morphology

1. Select a location to designate as the benchmark and mark it with a small survey or marking flag.
   NOTE: The location should be a higher elevation than the pond and have line-of-sight from all locations across the pond.
2. Assign the benchmark a reference elevation; the exact number does not matter, it simply provides a reference to which all other elevations can be compared.
3. Using a tape measure and marking flags, make transects at a 3 m interval over the pond area, resulting in a 3 m x 3 m grid (see example in **Figure 1**).
4. Determine the elevation of the bottom of the pond (*i.e.*, the ground) at 3 m intervals along each transect by measuring the height on a leveling rod using an automatic level. Ensure that the profiles extend to the highest elevations on every side of the pond.
5. At the end of each transect, make a backsight to the benchmark and record the elevation.
6. Determine the survey error as the difference between the benchmark's assigned elevation (*i.e.*, the reference value assigned in step 1.2) and the elevation measured from the most distant location on the profile transect.
7. Calculate the allowable error (AE) of closure for the profile as AE = $K(2{*}M)^{0.5}$, where *K* is a constant between 0.001 and 1 and *M* is the distance (in miles) between the benchmark and the most distant location on the profile.
   NOTE: The value of *K* depends on the required accuracy of the survey, which in this case can be taken as 0.1[10].
8. Compare the survey error calculated in step 1.6 to the AE calculated in step 1.7. If the survey error is greater than the AE, then redo the profile leveling (steps 1.3 and 1.4) for that transect. If the survey error is less than the AE, then the profile leveling for that transect is complete, conduct the profile leveling for the next transect.
9. Repeat steps 1.4 through 1.8 to conduct profile leveling at 3 m intervals across the pond in the other direction to create a grid of known elevations (see an example of profile transects in **Figure 1**).
10. Develop a stage-storage curve for the pond once the elevations (with respect to the benchmark) are known across the 3 m x 3 m grid surveyed across the pond.
    NOTE: Larger intervals can be used, but the error in determining the relationship between water level and pond volume may increase.

2. Determining the Vernal Pond's Stage-Storage Curve

NOTE: Each vernal pond will have a unique relationship between water level and water volume in the pond. This relationship is called the stage-storage curve.

1. Using the elevation data gathered in Section 1, determine the highest and lowest elevations in the pond.
2. Determine the difference between the highest and lowest elevation and select an interval for which to draw contour lines; a contour interval of 0.1 to 0.2 m is recommended[11].
3. Calculate the surface area of each contour (A_i). This can be done either by hand using a planimeter or electronically using geographic information software (GIS).
4. Use the average-end-area method to calculate the volume between each contour interval (V_i):
   $$V_i = (E_{i+1} - E_i)\frac{A_{i+1} + A_i}{2}$$
   where *E* is the contour elevation.
5. Calculate the total volume (V_P) of the vernal pond as the sum of the volume between each contour interval:
   $$V_p = \sum_{i=1}^{H} V_i$$
   NOTE: Here *H* is the maximum depth of the pond. An example is given in **Table 1**.
6. Determine the stage-storage relationship for the pond by graphing the cumulative volume of the pond as a function of depth.
   1. After installing the water level sensor, use the water level as the "stage" and estimate the water volume, or storage, in the pond.
      NOTE: An example of a stage-storage curve is shown in **Figure 2**. If the water level sensor is installed above the lowest point in the vernal pond, an offset will be needed to convert the measured water level into the stage-storage curve (add the offset in step 3.3 to the water level recorded by the water level sensors to determine the stage).

3. Installing a Monitoring Station

NOTE: Sensors for parameters of interest for this study included a pressure transducer (measures both water level and temperature), dissolved oxygen concentration, oxidation-reduction potential, electrical conductivity, pH, and a tipping bucket rain gauge. The pH probe, dissolved oxygen sensor, and oxidation-reduction probe must be calibrated in the lab prior to deployment per the sensor's user manual. Here, a central datalogger (programmed to record data at 15 min intervals) is selected, to which all sensors are connected during deployment. A viable alternative scenario would be that each of the sensors is autonomous and do not need one central datalogger, since each sensor would record its own data.

1. Attach each of the sensors (with the exception of the rain gauge) to a cinder block or a wooden stake (**Figure 3**). Use hose clamps or zip ties to ensure that the sensors remain near the bottom of the vernal pond (or the depth of interest).
    1. Attach the dissolved oxygen sensor such that it is at an angle (per manufacturer instructions), to allow oxygen to diffuse across the membrane. Install the pressure transducer upright, as the pressure that it will measure is the water column above it, and the water level should be recorded in a vertical manner.
2. Install the mounted sensors at a location towards the center of the pond that is unlikely to become dry during the study period.
3. Determine the vertical distance between the sensors and the lowest point in the pond using a ruler or the surveying equipment. Record this distance for use in developing the stage-storage curve as described in step 2.6 (*i.e.*, an offset may be needed when relating the depth measured using the pressure transducers to the total water depth in the pond).
4. While they can be submerged in the water, the sensor wires are vulnerable to mice or other animals that may chew on them when the water level is low in the pond, to prevent this use apolyvinyl chloride pipe to protect the sensor wires (optional, but recommended). Run the sensor wires up to the edge of the vernal pond through a PVC pipe (3 m long, 6.35 cm diameter), as shown in **Figure 4**.
NOTE: For temporary installation *(e.g.*, a few weeks to a few months) the PVC pipe may be deemed unnecessary.
5. Set up a tripod and mount it to the ground by inserting stakes into each of the tripod legs.
NOTE: Some tall tripods may have a lightning rod that requires installation, too.
    1. Position the tripod near the edge of the vernal pond to ensure that it is accessible even when the pond is full of water.
6. Attach the enclosure box for the datalogger and battery (12 V) onto the tripod, leaving room above the tripod for the solar panel to be mounted above the enclosure box (**Figure 4**).
7. Attach a 10 W solar panel to the top of the tripod and angle it towards the sun. A solar angle calculator[12] can be used, if desired, to determine the optimum angle at which to install the panel.
8. Attach the rain gauge to the tripod if there is room. Otherwise, attach it to a wooden stake or metal pole near the edge of the pond and the tripod (**Figure 4**). Ensure (if possible) that the rain gauge has tree cover that approximately represents the tree cover of the pond (if any).
9. Bring all sensor and solar panel wires into the enclosure box through the hole at the bottom of the box.
10. Connect all sensors to the datalogger's wiring panel in accordance with the sensors' instructions or the datalogger's wiring diagram. See example in **Figure 5A**.
11. Connect the solar panel wires to the 12V battery to recharge the battery (**Figure 5B**).
NOTE: Select a battery that also has a voltage regulator (recommended) to ensure that the battery does not receive too much electricity from the solar panel.
12. Connect the battery to the power input panel on the datalogger (**Figure 5B**) to provide power to the datalogger and the sensors.
13. Place a desiccant pack inside the enclosure box to reduce the likelihood of moisture damage to the datalogger.
14. Recommended but optional: connect a field laptop with the datalogger communication software to the datalogger using a serial cable (**Figure 5B**) to ensure that the sensor network is working properly.
15. Close the enclosure box and place clay around the hole at the bottom of the enclosure box where the wires enter to keep insects and water out of the box. If security of the equipment is a concern, secure the enclosure box with a padlock.

Representative Results

Vernal ponds can exhibit a wide range of morphology, with profiles ranging from convex to straight slope to concave. Example morphology for a vernal pond in Central Pennsylvania is shown in **Figure 1**, along with the results of the stage-storage curve for this pond (**Figure 2**, **Table 1**). Maximum pond depth is not a strong indicator of surface area, as hydroperiod has only a weak correlation with pond morphology[12]. Therefore, understanding the contributions of precipitation, evapotranspiration, and groundwater flow (into or out of the pond) are important factors in determining the hydrology of vernal ponds.

Given the importance of vernal ponds to amphibian breeding, the monitoring study described in this protocol was conducted from mid-April to mid-June, during the breeding and metamorphosis period of wood frogs (*Rana sylvatica*) in the northeastern United States. The three vernal ponds selected for analysis are located at the Pennsylvania State University's Living Filter, which is a ~2.4 km^2 site that is spray-irrigated with the University's treated wastewater. The installed monitoring station equipment is shown in **Figure 4**. Therefore, water level changes measured in the pond increase due to both natural rainfall and wastewater irrigation events (**Figure 6**). For most vernal ponds, the water level is expected to fluctuate less, as a function primarily of groundwater flow, evapotranspiration, and rainfall. Therefore, the results shown in **Figure 6** may not be typical of sites less impacted by anthropogenic water inputs.

Data collected for temperature, pH, dissolved oxygen concentration, oxidation-reduction potential, and electrical conductivity for each of the three study sites are shown in **Figure 7.** It is important to note that various sensors require weekly calibration to ensure that the data are accurate. Recommendations in the user manuals for the sensors should be followed, with pH, dissolved oxygen, and ORP typically needing weekly maintenance or calibration. In general, the temperature of the ponds increased over the study period (from mid-April through mid-June), with temperatures generally decreasing in response to effluent irrigation events. The pH was relatively consistent for the majority of the study period, between 6 and 8, which is similar to the pH in both natural and vernal ponds impacted by wastewater irrigation activities[13]. The electrical conductivity of the ponds increased over the course of the study period, likely due to the higher electrical conductivity of wastewater (approximately 1 mS/cm) compared to rainwater[14].

Dissolved oxygen concentrations and oxidation-reduction potential generally followed a similar trend, as expected, with higher values at the beginning of the study period and decreasing to relatively consistent low values from early May through the end of the study period. Dissolved oxygen is known to be inversely related to temperature, and thick mats of duckweed were observed to grow on the surface of the ponds over the course of the study period (spring to early summer), likely limiting the partitioning of oxygen from the atmosphere into the ponds. Additionally, the measurements were made near the bottom of the pond, and therefore the conditions may have been different near the surface of the pond. For this study, the exposure of tadpoles to conditions near the bottom of the pond was of interest. The location of the sensors in the pond may influence the water quality measurements, and therefore the sensors should be installed in the pond in a way that represents the conditions of interest.

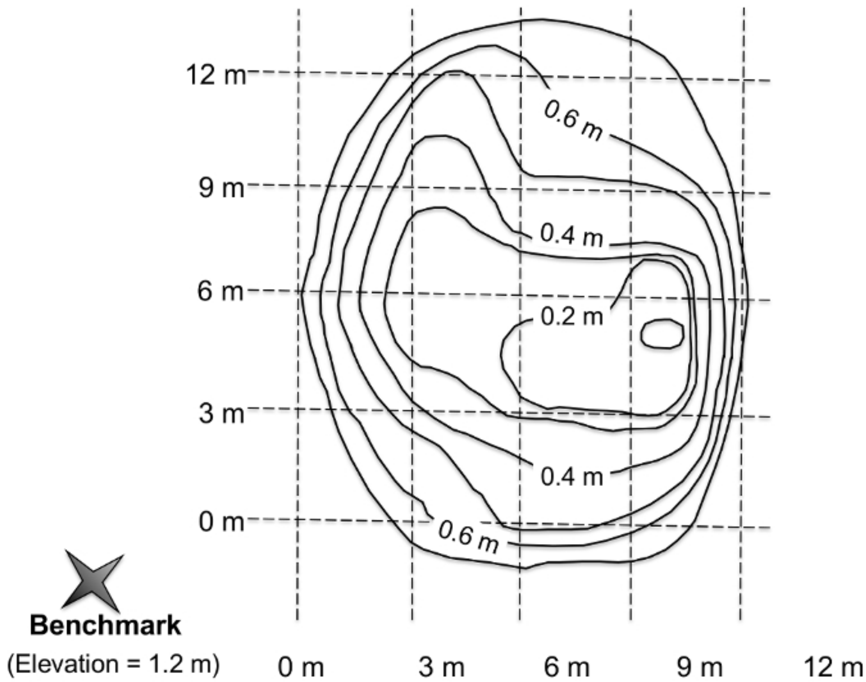

Figure 1: Example vernal pond morphology. Determined by conducting a profile leveling survey of a vernal pond in Central Pennsylvania. Contour lines are given at a 0.1-m interval. Please click here to view a larger version of this figure.

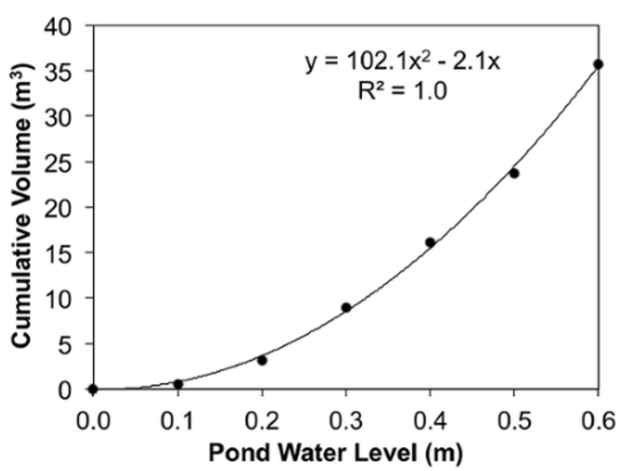

Figure 2: Example stage-storage curve for a vernal pond in Central Pennsylvania, USA. Pond water level is used to estimate the cumulative volume of water in a vernal pond in Central Pennsylvania. Please click here to view a larger version of this figure.

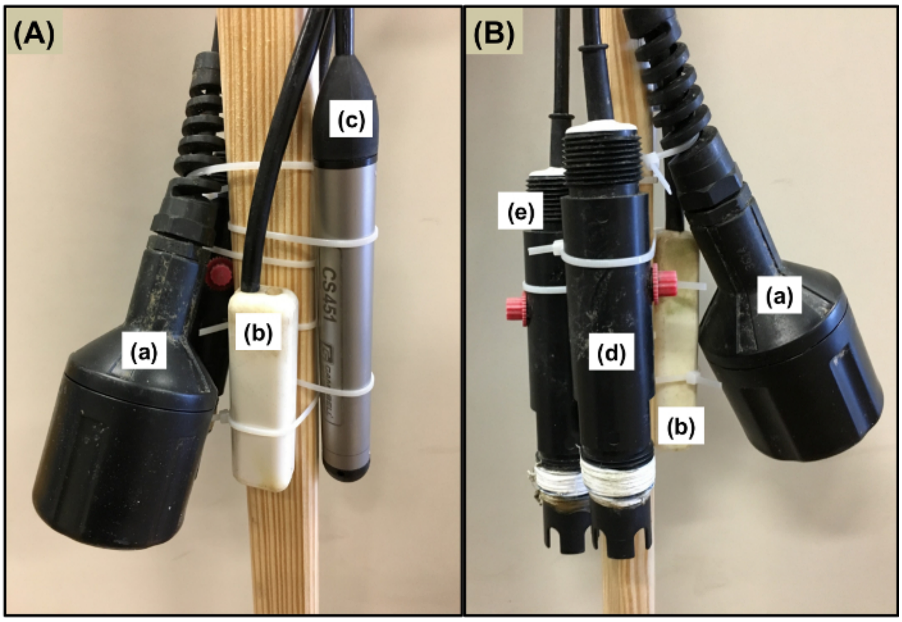

Figure 3: Mounting sensors for deployment. Sensors shown in views (**A**) and (**B**) include (a) dissolved oxygen sensor, (b) electrical conductivity probe, (c) pressure transducer, (d) pH probe, and (e) oxidation-reduction probe. Pressure transducer should be installed upright to accurately measure water level. Dissolved oxygen sensor should be installed at an angle to allow proper diffusion of oxygen across the sensor's membrane and to prevent bubbles from forming inside the sensor. Please click here to view a larger version of this figure.

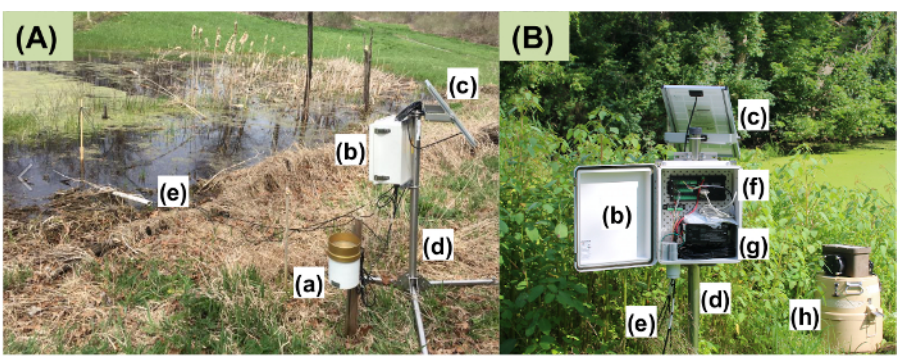

Figure 4: Monitoring stations deployed at vernal ponds in Central Pennsylvania, USA. (A) Side view, showing (a) rain gauge, (b) datalogger enclosure box, (c) solar panel, and (d) tripod, and (e) sensor wires going into the pond. **(B)** Front view with the datalogger enclosure box open, showing the (e) sensors connected to the (f) datalogger, with the (g) battery inside the box and an (h) automated sampler near the pond. Please click here to view a larger version of this figure.

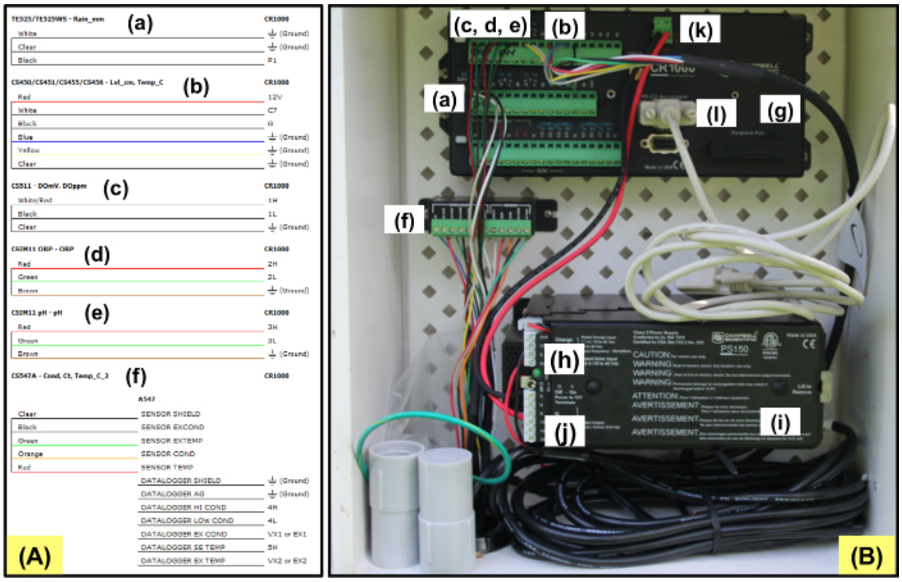

Figure 5: (A) Example wiring diagram and (B) sensor wires connected to datalogger. The sensors shown in the example wiring diagram are: (a) rain gauge, (b) pressure transducer, (c) dissolved oxygen sensor, (d) oxidation-reduction probe, (e) pH probe, (f) electrical conductivity sensor. Inside the enclosure box, the sensor wires are shown connected to the (g) datalogger. The solar panels are connected to the (h) voltage regulator on the (i) battery, which is then wired from the (j) power output on the battery to the (k) power input on the datalogger. A computer can be connected to the datalogger using a (l) serial cable. Please click here to view a larger version of this figure.

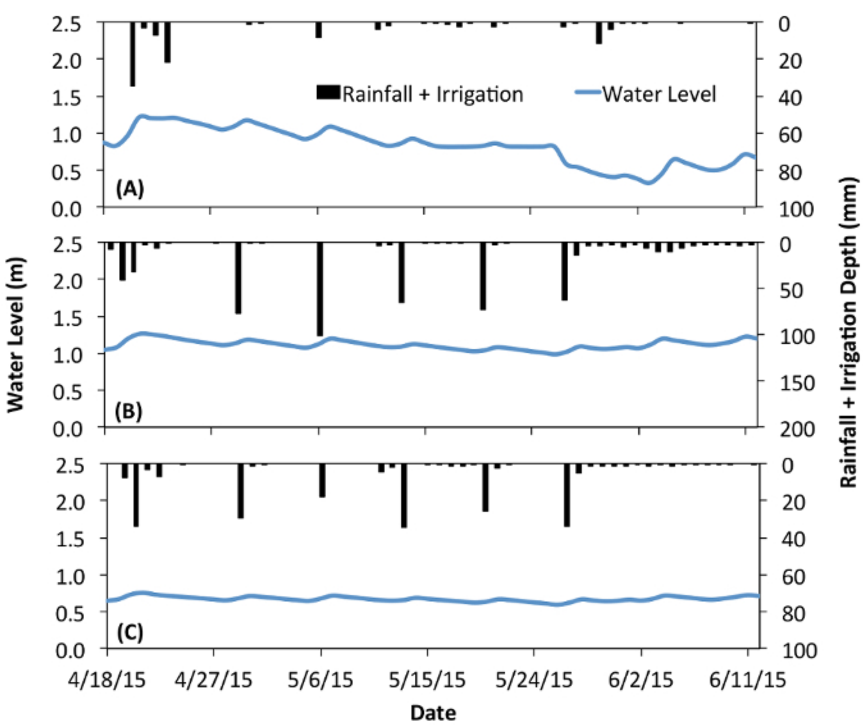

Figure 6: Hydrologic data collected at three vernal ponds (A, B, C) in Central Pennsylvania, USA. The sum of rainfall and wastewater irrigation (input) that reaches each vernal pond is shown across the top of each graph (secondary y-axis). The corresponding changes in the water level are shown on the primary y-axis. Please click here to view a larger version of this figure.

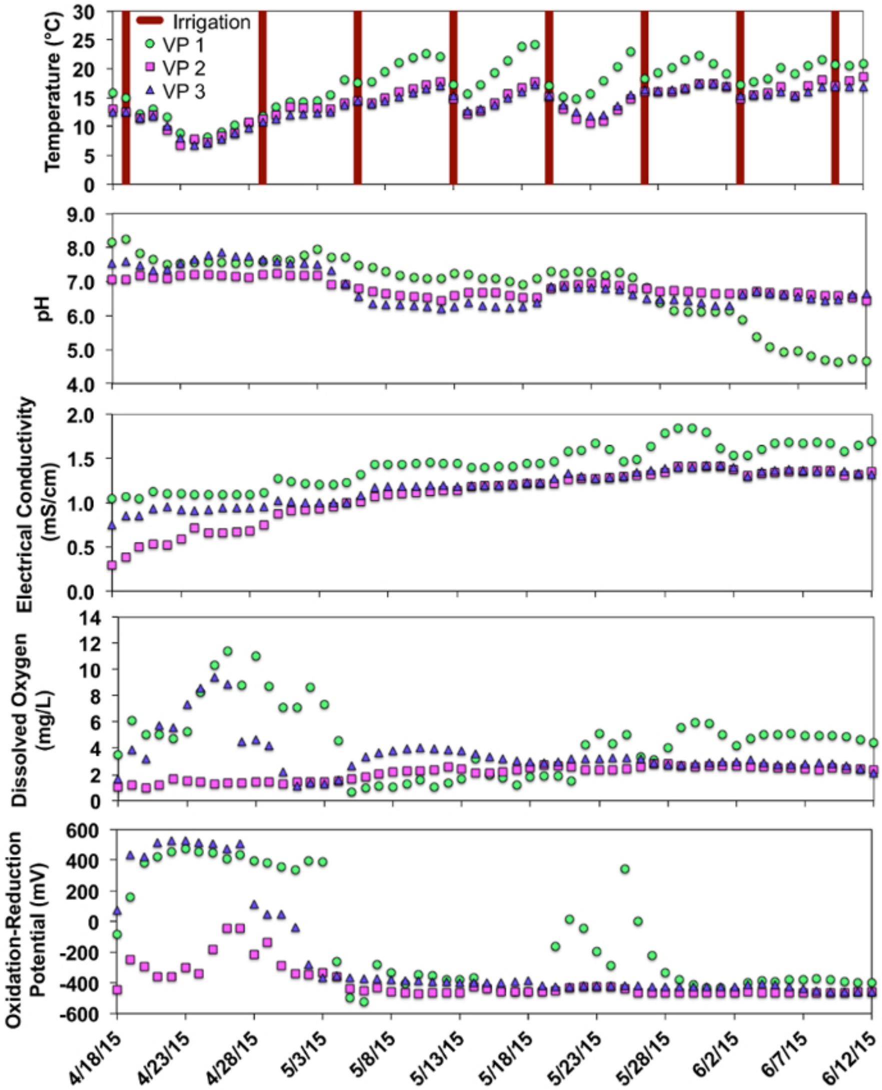

Figure 7: Physical and chemical properties of three vernal ponds (VP 1, VP 2, and VP 3) measured in real-time in Central Pennsylvania, USA. The parameters measured in real-time were temperature, pH, electrical conductivity, dissolved oxygen concentration, and oxidation-reduction potential. Please click here to view a larger version of this figure.

Pond Depth (m)	Area (m^2)	Average Area (m^2)	Contour Interval (m)	Change in Volume (m^3)	Cumulative Volume (m^3)
0.00	0.00				0.00
		6.10	0.10	0.61	
0.10	12.19				0.61
		24.91	0.10	2.49	
0.20	37.62				3.10
		58.60	0.10	5.86	
0.30	79.58				8.96
		72.39	0.10	7.24	
0.40	65.20				16.20
		75.65	0.10	7.57	
0.50	86.11				23.76
		118.91	0.10	11.89	
0.60	151.71				35.65

Table 1: Average end area method calculations for stage-storage curve development. Calculations were made for contour intervals of 0.1 m. The morphology is shown in **Figure 1** and the stage-storage curve is shown in **Figure 2**.

Discussion

Significance with Respect to Existing Methods

While monitoring of streams has well-established methodologies developed by the United States Geological Survey (USGS), no such widespread monitoring program exists for understanding vernal pond dynamics. This protocol seeks to provide guidance for how to begin to approach hydrologic and water quality monitoring research at a vernal pond site, with the goal of understanding how physical and chemical factors may be changing over time at a given site.

Limitations of the Technique

As described, the monitoring data collected may not be representative of the entire pond. Water quality parameters, particularly dissolved oxygen, and oxidation-reduction potential are unlikely to be homogenous within the pond. Multiple sensors distributed across the pond and at various depths may be needed to fully characterize physical and chemical parameters of interest that are likely to vary as a function of depth.

In situ monitoring data are likely to be insufficient for understanding water quality data in vernal ponds. Collecting grab samples either by hand or with automated sampling devices may provide valuable insight regarding a broader range of water quality. These samples can be brought back to an analytical laboratory to be analyzed for a suite of water quality parameters, including nutrients, pesticides, pharmaceuticals, and other contaminants of emerging environmental concern. Depending on the location of the vernal pond, salts and deicing agents may be a concern if the pond is receiving runoff from a nearby road[15]. However, the samples collected using grab sampling methodology provide data for only a specific point in time, and the concentrations are likely to change over time, particularly in response to snowmelt or rainfall events that trigger surface runoff. Therefore, sampling designed to capture events that are likely to result in changes in concentration should be conducted to more thoroughly understand the temporal variations of water quality parameters.

Modifications to the Protocol

Various options exist for designing monitoring stations for hydrology and water quality. The sensors described in Section 3 of the Protocol are not autonomous, meaning that they must be connected to an external datalogger for data to be recorded and downloaded. Various autonomous sensors do exist, particularly for water level and water temperature. The specific water level sensor that was selected for this application has a venting tube that enables the sensor to compensate for air pressure, and therefore, it does not require an additional sensor outside of the water. Some low cost *in situ* sensors are also available for a wide range of physical and chemical parameters beyond those described here, including a variety of dissolved ions (*e.g.*, nitrate, nitrite, ammonia, sodium).

Additionally, it may be desirable to collect measurements at various depths within the vernal pond or at various locations across the pond. Some of the parameters that are likely to vary by depth are temperature, dissolved oxygen, and oxidation-reduction potential. This protocol could be modified by adding replicate sensors to the monitoring network to examine variability across spatial transects (*e.g.*, every few meters across the pond) or vertically within the water column (*e.g.*, every few hundred cm within the water profile). For these applications, having one datalogger recording all date from the sensor network would be desirable over many autonomous sensors that require downloading from each individual sensor rather than from one central location at the vernal pond.

Future Applications

The advantage of the setup described in this protocol is that any variable of interest can be used to trigger an automated sampler by connecting a communication cable that can go from the datalogger to an automated sampler (*e.g.*, ISCO). The dataloggers use a programming language similar to C that enables novel sampling techniques to be employed. For example, Gall *et al.*[16,17] used flow data collected in real time to predict storm hydrographs and appropriately space flow-paced samples across the hydrograph, resulting in a novel storm-specific sampling protocol that adequately spaced samples over both small and large hydrographs. Examples of leveraging the data collected in this protocol for sampling could be using water level measurements to collect samples following a rain event that resulted in significant increase in the water level, or at the other extreme, triggered samples during a drought period when the vernal pond may rapidly lose water.

Another future application could be developing a real-time monitoring network of vernal ponds within a study area of interest. For example, vernal ponds across a human impact gradient could be selected, with each pond instrumented with the same water quantity and quality sensors. These stations could then communicate with each other via cell modems or radio networks, enabling data to be remotely accessible and making the data available to researchers in real time.

Given the global amphibian decline and the importance of vernal ponds as habitat for breeding and metamorphosis, this protocol seeks to address the dearth of continuous monitoring data for vernal ponds across a human impact gradient. Amphibians that utilize these vernal ponds can exhibit site fidelity[18,19,20], meaning that they return to breed at the same site (or within a relatively small distance) every year. Therefore, understanding the dynamics of these critical breeding habitats and using this knowledge to inform policy related to ephemeral wetlands is vital to their survival. It is critical to understand the hydrology and biogeochemical cycling of vernal ponds in order to better develop policies that restore degraded habitat and protect existing habitat.

Disclosures

The authors have nothing to disclose.

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