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RECYCLING IRRIGATION RESERVOIR STRATIFICATION AND IMPLICATIONS FOR CROP HEALTH AND PRODUCTION[1]

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ABSTRACT: Recycling irrigation reservoirs (RIRs) are an emerging aquatic ecosystem and water resource of global significance. This study investigated the vertical distribution of water temperature, dissolved oxygen (DO), and pH in eight RIRs at two nurseries each in Virginia and Maryland from 2011 to 2014. Monomictic thermal stratification was observed from April to October in all RIRs, despite their shallow depths (0.75-3.89 m). The strongest stratification had a top-bottom temperature difference of 21.53°C. The top-bottom temperature difference was positively correlated with water column depth, air temperature, and daily light integral ($p < 0.05$). Wind speed did not impact the thermal stratification, likely due to their relatively small surface areas. Thermal stratification affected the vertical distribution of DO and pH. The top-bottom differences in DO and pH were greater during stratification periods than nonstratification periods. Water pH in all RIRs was higher at the top than at the bottom with the greatest difference of 4.16 units. Discovery and characterization of thermal stratification in RIRs helps understand water quality dynamics in this novel ecosystem and promote safe and productive water reuse for irrigation. Specifically, water withdrawal depths should be adjusted according to variations in temperature, DO, and pH during the stratification and nonstratification periods to mitigate pathogen risk and improve water treatment efficacy and crop production.

(KEY TERMS: recycling irrigation reservoir; thermal stratification; recycled water quality; dissolved oxygen; pH; water management.)

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INTRODUCTION

Capturing and reusing runoff for irrigation in agricultural production is critical to conserving increasingly costly and scarce water resources. Recent droughts in the Great Plains have substantially depleted the Ogallala aquifer resulting in water shortages. Droughts in naturally arid lands, such as the western part of the United States, have greatly

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decreased surface water flows (CAST, 2009; PCAST, 2012). Water shortage will worsen with rising temperature and anticipated more frequent droughts (Dobrowolski *et al.*, 2004; Holdren, 2008; PCAST, 2012). Facing a future with less water available, it is of vital importance for agricultural production to reduce clean water use. Recycling irrigation reservoirs (RIRs) have been implemented to reclaim stormwater and irrigation runoff. The performance of RIRs relies heavily on the water quality within the system. It was reported recently that surface water quality in a RIR fluctuates dramatically over time and diurnally but its underlying mechanisms were not known (Hong *et al.*, 2009).

Thermal stratification plays an important role in water quality dynamics as it impacts many physical, chemical, and biological processes in aquatic ecosystems. It affects flow patterns, retention times and vertical exchange in dissolved oxygen (DO), nutrients, phytoplankton, and sediments (Fischer *et al.*, 1979). The presence of stratification can limit the transfer of oxygen within the water column and lead to anoxic conditions near the bottom. This process is often responsible for increasing eutrophication through release of phosphorus and ammonia from bottom sediments (Dodson, 2005; Elci, 2008; Escobar *et al.*, 2009; Jones *et al.*, 2011). The timing and magnitude of phytoplankton blooms are closely related to the temporal and spatial features of stratification. Stratification provides advantages for floating algal species to remain within the eutrophic zone (Sherman and Webster, 1994; Bormans and Condie, 1997; Wallace *et al.*, 2000) and appeared to be the key factor influencing the onset and demise of cyanobacterial blooms (Jones and Poplawski, 1998).

Three types of thermal stratification have been reported for deep lakes and reservoirs, depending on the climate zone. Lake Tinaroo (3,320 ha in surface area and 12.2 m in average depth) in Northern Queensland, Australia developed monomictic stratification from October to May which was occasionally disrupted by inflow from flood events (MacKinnon and Herbert, 1996). Dimictic stratification was often observed in lakes in the cooler parts of the temperate zone. For example, Lake Mendota, Wisconsin with a maximum depth over 23 m stratifies twice a year, once in summer and once in winter (Brock, 1985). Shallow lakes with intermediate depths, such as Lake Thonotosassa in Florida, are likely to experience polymictic stratification as disrupted by storms (Cowell *et al.*, 1975; Kerimoglu and Rinke, 2013).

Thermal stratification is also affected by a variety of environmental factors, including morphometric characteristics, such as shape, area, and depth (Sterner, 1990; Mazumder and Taylor, 1994; Dodson, 2005), meteorological variables, such as air temperature, short and long wave radiation and wind speed (Imboden and Wüest, 1995; Kalff, 2002; Kerimoglu and Rinke, 2013), as well as the biochemical characteristics of the water body. Investigations into lakes with comparable size and the maximum depth >20 m have shown that the thermal structure is related to water clarity (Can *et al.*, 1994). The penetration of short wave radiation depends on the particulate matter, such as clay, colloids, bacteria, phytoplankton, and other large particles in water (Casamitjana *et al.*, 2003). The thermocline development is related to the inflow of runoff containing sediment, turbidity, conductivity, and nutrients (Byun *et al.*, 2005) and water withdrawal at different layers (Milstein and Zoran, 2001).

Shallow lakes are often assumed to be well mixed vertically; however, this is not often true for turbid systems, where most of the solar radiation is absorbed close to the surface (~0.1 m) (Condie and Webster, 2002). A recent study of 45 urban ponds in southern Ontario revealed that most ponds were stratified during sampling periods (June and August), despite their shallow depth (0.5-2.8 m) (McEnroe *et al.*, 2013). Song *et al.* (2013) reported stratification in 10 shallow ponds in southern Ontario, Canada, with maximum depths of 2.5 m during the summer of 2010. Temperature variation was found depth-dependent even in a 6-m wide and 0.35-m deep pool in the Netherlands during the summer period, as reported by Jacobs *et al.* (1998). Thermal stratification was observed in a turbid water body located in southeastern Australia with the maximum depth of 1.6 m (Condie and Webster, 2002). Phytoplankton seasonal variation was observed in a shallow stratified eutrophic reservoir with a depth of just over 4 m (Fonseca and Bicudo, 2008). A shallow pond located within a marshland in the English Lake District (the maximum depth 3.5 m) was stratified during the summer (Folkard *et al.*, 2007).

Recycling irrigation reservoirs are different from natural lakes and urban ponds. RIRs typically are shallow and their surface areas are relatively small (1,012-16,997 m^2 in this study) compared to natural lakes (medium lake size 48,562-299,467 m^2) (Song *et al.*, 2013). RIRs are comparable to small urban ponds in size but they differ in terms of water inflow and water withdrawal regimes. RIRs receive agricultural runoff containing elevated concentrations of nutrients, organic matter, and sediments. Inflow to natural lakes is typically from streams or surface runoff depending on the landscape of the watershed. Inflow to urban ponds is from stormwater runoff and sewage overflow high in nutrients, sediment, and heavy metals (Walker *et al.*, 1999). In addition, water is withdrawn from RIRs at specific depths for irrigation. Withdrawal from natural lakes includes overflow, evaporation from the surface, and main flow into water channels. Urban ponds are mostly stagnant and water withdrawal is by evaporation from the surface and water drainage system. Whether stratification takes place in such shallow RIRs receiving agricultural runoff was unknown.

The overall goal of this study was to characterize the vertical distribution of temperature, DO, and pH in RIRs to further our understanding of the water quality dynamics in this emerging water resource of global significance. The specific objectives were to: (1) determine whether thermal stratification takes place in shallow RIRs and how it may be affected by environmental factors; (2) assess its impacts on the vertical distribution of DO and pH in the water columns. Their potential implications for recycled water management are also discussed.

MATERIALS AND METHODS

Site Description

Eight RIRs located in four nurseries (VA1, VA2, MD1, and MD2) in Virginia (VA) and Maryland (MD) were included in this study, as shown in Figure 1. Each nursery was given an alias name with the state of origin's initial followed by a number designating the nursery. The major characteristics of the reservoirs surveyed are shown in Table 1. Data from the reservoirs in Nursery VA2 are presented in detail in this article and that of the remaining nurseries (VA1, MD1, and MD2) is described in the supplementary information.

Nursery VA2 is located in Central VA. This nursery has three reservoirs built in sequence, VA21-22-23. VA21 is approximately 8,094 m^2 in surface area, 3.78 m in average depth at the reservoir center, and receives runoff from the entire production area. The water in VA21 overflows into VA22 when it reaches its full capacity, and overflows from VA22 into VA23 through a culvert. Water in VA23 is the source pumped for irrigation usage. VA22 is 16,187 m^2 in surface area and 2.98 m in average depth at the reservoir center. VA23 is 6,070 m^2 in surface area and 3.51 m in average depth at the reservoir center. Mature trees and natural shrubs surround the entire nursery.

Nursery VA1 is located in Eastern Virginia. The system setup of reservoirs VA11-12-13 is similar to VA21-22-23, except that VA11 is a small-sized sedimentation pond compared to other RIRs. Runoff from the production area flows into VA11 and then overflows into VA12. Water in VA12 was used for irrigation. Water in VA12 overflows into VA13 when its full capacity is reached. Occasionally VA12 is refilled by VA13 when the water level in VA12 is low.

Nursery MD1 and MD2 are located in Northern and Central Maryland. Both nurseries have a single reservoir recycling irrigation system. Irrigation runoff from the production area was channeled into MD11 or MD21 and the water is pumped from the same reservoirs for irrigation.

Data Collection

To investigate water quality, monthly field measurements were taken at the center of each reservoir between 12:00 and 16:00 from April 2011 to March 2014. Nine water quality parameters were measured

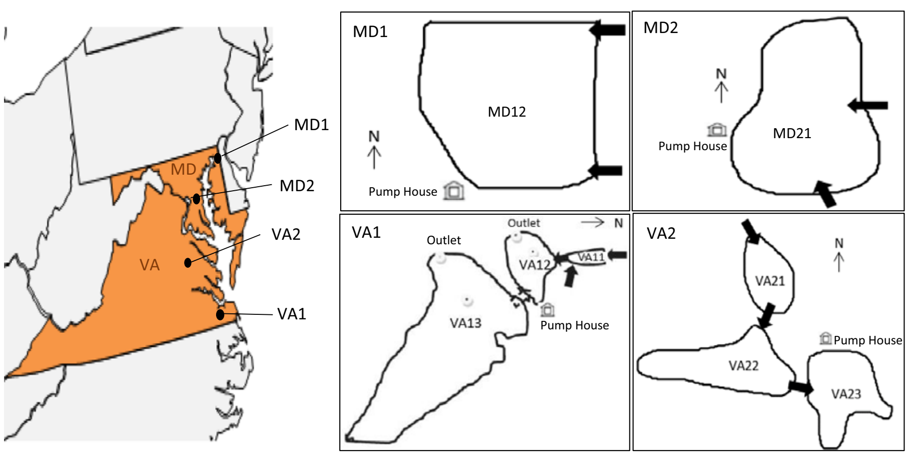

FIGURE 1. (a) Locations of All Four Nurseries VA1, VA2, MD1, and MD2 Studied and Schematic Layout of Eight Recycling Irrigation Reservoirs.

TABLE 1. Characteristics of Recycling Irrigation Reservoirs Included in This Study.

Nursery	Location	Reservoir ID	Surface Area (m^2)	Average Depth (m)	Minimum Depth (m)	Maximum Depth (m)
VA1	Eastern VA	VA11*	1,012	0.75	0.41	0.88
		VA12	8,094	2.28	1.95	2.57
		VA13	60,703	2.19	1.31	2.43
VA2	Central VA	VA21	8,094	3.78	3.23	4.05
		VA22	16,187	2.98	2.32	3.32
		VA23	6,070	3.51	2.05	3.89
MD1	Northern MD	MD11	16,997	1.80	1.36	2.02
MD2	Central MD	MD21	6,070	2.36	1.48	2.65

*VA11 is sedimentation pond with small surface area and shallow depth.

at 0.5-m intervals from surface to bottom of water columns using a 6600V2-4 Multiprobe (YSI Inc., Yellow Springs, Ohio). These parameters included temperature, dissolved oxygen (DO), pH, chlorophyll *a*, oxidation-reduction potential, electrical conductivity, salinity, total dissolved solids, and turbidity. Duplicate or triplicate measurements were taken at each depth. Meteorological data including air temperature, photosynthetically active radiation (PAR), precipitation, wind speed, and direction were recorded every five minutes via onsite weather stations. PAR represents solar radiance between wavelength 400 and 700 nm.

Data Analysis

Temperature, DO, and pH were the focus of analyses for this study. Vertical temperature profiles over time for each reservoir were plotted to determine seasonal stratification patterns. Top-bottom temperature differences (ΔT) were computed to further assess the time window and magnitude of stratification. Differences of >1°C between top and bottom water column temperature values were used as an indicator of thermal stratification (McEnroe *et al.*, 2013). One-way ANOVA was conducted in R (version 2.15.2) to determine if the temperature differences at various depths are statistically significant. Top-bottom temperature differences were plotted against depth to further define the association of depth and stratification in shallow RIRs. Pearson correlation coefficients were calculated to quantitatively describe the relationship. Similar analyses were carried out for DO and pH. Linear regression and Pearson correlation were performed in Minitab 17 statistical software (State College, Pennsylvania).

To determine the correlation between stratification and environmental factors, ΔT was plotted against air temperature, daily light integral (DLI), wind speed, and turbidity within synchronous timestamps. DLI represents the total amount of PAR received each day. Pearson correlation coefficients were also calculated between ΔT and these variables.

RESULTS

Thermal Stratification Pattern in Shallow RIRs

Vertical temperature differences were present in all RIRs**.** Stratified water has three layers; the upper epilimnion contains less dense warm water and the lower hypolimnion contains higher density cold water. In between, there is the thermocline where temperature rapidly changes. Figure 2a shows the vertical temperature profile of Reservoir VA21. In May 2013, water temperature was 29.18°C at the surface and it decreased to 9.16°C along the depth gradient. The temperature gradient was the highest from near surface to 0.5 m below surface with temperature changes at 15.40°C/m. The rate of temperature change was consistently high until the 2.5-m depth. The temperature gradient below 2.5-m depth was <2.80°C/m. The temperature profile in VA21 was representative of a wide thermocline, a narrow hypolimnion, and a nondistinctive epilimnion. Similar stratification structures were also observed in other reservoirs as illustrated in supplementary information.

Variation in water temperature in all RIRs was distinguished into two phases: (1) from April to October, when RIRs were stratified; and (2) the rest of year, when reservoirs were not stratified. The vertical contour plots in Figure 2b illustrate the temperature gradient with depth, and more colors and lines indicate a steeper gradient. Horizontal variation indicates the duration of stratification. In VA21, stratification began on April 3, 2012, reached its peak in June, and ended on October 25, 2012. This pattern repeated in 2013, with stratification existing from March 27 to October 31. A clear annual stratification pattern was also observed in VA22, VA23, VA11-12-13, MD11, and MD21 as presented in vertical temperature profiles in supplementary data. Top-bottom temperature difference (ΔT) was plotted for VA21-22-23 as shown in Figure 3a. The top-bottom temperature difference (ΔT) of each reservoir was summarized in Table 2.

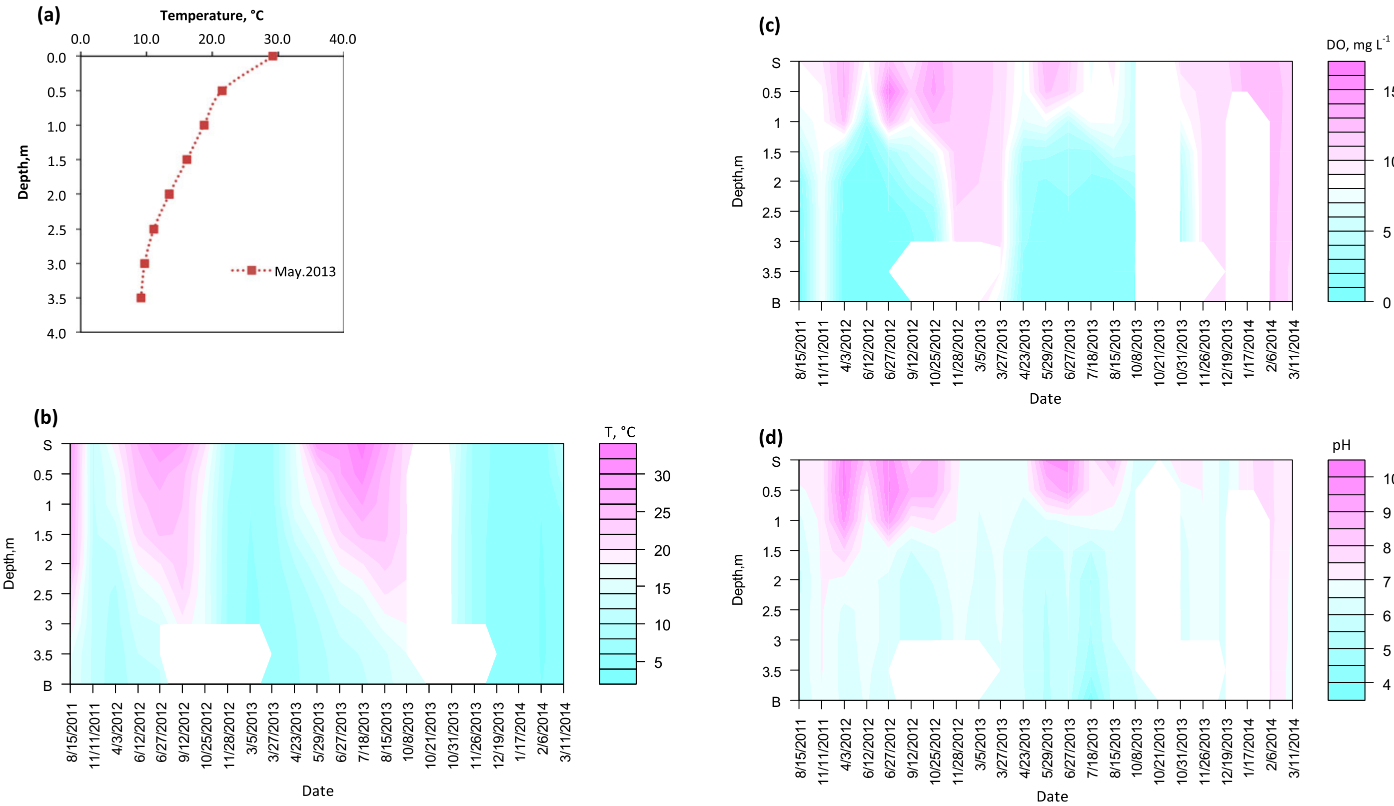

FIGURE 2. (a) Single-Day Vertical Water Temperature Profile; (b) Overall Vertical Water Temperature Profile; (c) Dissolved Oxygen (DO) Profile; and (d) pH Profile in Reservoir VA21 during the 2011-2014 Study Period (vertical profiles for all other RIRs were included in supplementary information).

Within each reservoir, the temperature differences during stratification periods were much higher than those during nonstratification periods. In VA21, 93% of the observations had $p < 0.05$; in VA22, all observations had $p < 0.05$; in VA23, all observations had $p < 0.05$, indicating that significant differences exist between water temperatures at different depths.

Correlation between Temperature Difference and Environmental Factors

Depth. Stratification occurred in all RIRs (VA11-12-13, VA21-22-23, MD11, and MD21), despite the shallow depths (0.75 m $\leq$ depth $\leq$ 3.89 m). The magnitudes of ΔT, however, varied from reservoir to reservoir and ranged from near 1.00 to 21.53°C. As shown in Table 2, in reservoirs with an average depth <2.5 m, such as VA11-12-13, MD11, and MD1, the average top-bottom ΔT ranged from 2.13 to 3.93°C. In contrast, reservoir VA21-22-23 had an average depth >2.5 m and a top-bottom ΔT from 10.79 to 11.58°C. ΔT from all reservoirs was plotted against depth to further define the relationship between these two variables during the stratification period, as shown in Figure 4. Although the variability of ΔT became larger as reservoir depth increased, ΔT generally was higher in the deeper reservoirs. Within the range of depths studied, ΔT positively correlated with depth with a Pearson correlation coefficient of 0.71 ($p < 0.05$).

Meteorological Variables. The top-bottom temperature difference ΔT was influenced by weather conditions. The maximum ΔT was 18.05 and 18.36°C in VA21 and VA23 in 2012; 21.53, 21.21, and 18.18°C in VA21, VA22, and VA23 in 2013, respectively. The corresponding air temperatures and DLI were 29.37°C and 62.04 moles/day in 2012, and 33.00°C and 50.76 moles/day in 2013. Both air temperature and DLI appeared to follow the trend of top-bottom ΔT, as shown in Figure 3b. Top-bottom ΔT was further plotted against meteorological variables for all reservoirs. Results for reservoir VA21 are displayed in Figure 5. Here ΔT was positively correlated with air temperature and DLI; ΔT was negatively correlated with wind speed, however, not at a significant level of $p > 0.05$.

The Pearson correlation coefficient between ΔT and air temperature was higher than between ΔT and DLI except for VA11, indicating a stronger influence on ΔT by air temperature (Table 3). In VA11,

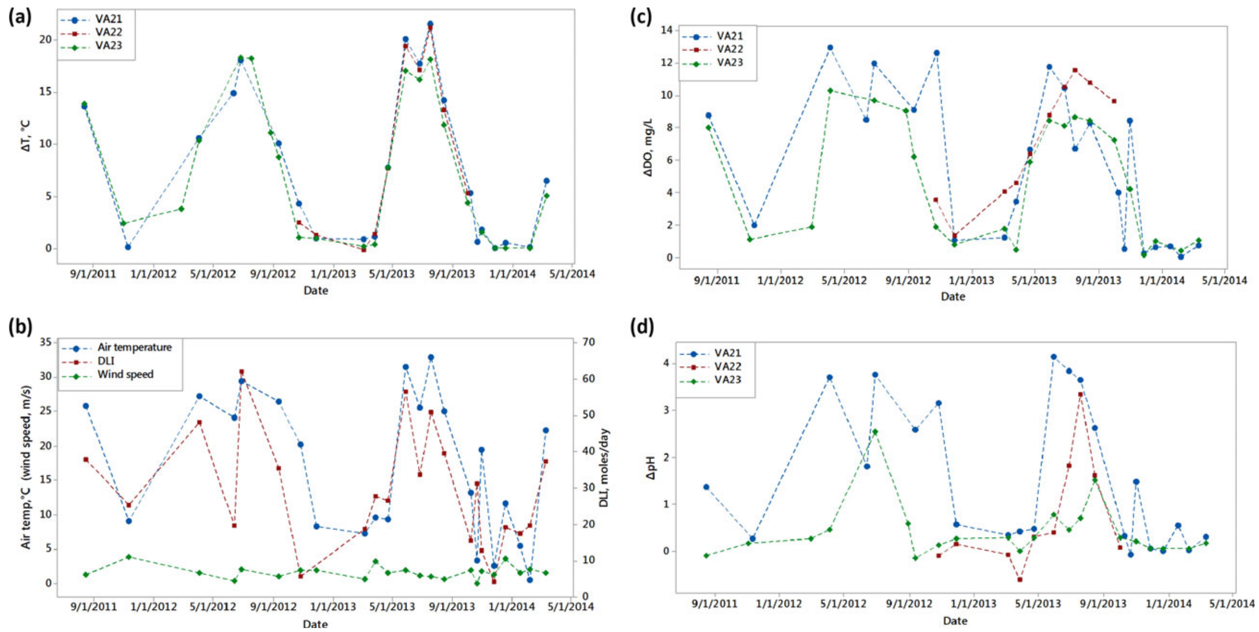

FIGURE 3. (a) Top-Bottom Temperature Difference (ΔT) in Reservoirs VA21, VA22, and VA23; (b) Variation in Air Temperature, Daily Light Integral (DLI), and Wind Speed during the 2011-2014 Study Period; (c) Top-Bottom Dissolved Oxygen (DO) Differences in Reservoirs VA21, VA22, and VA23 during the 2011-2014 Study Period; (d) Top-Bottom pH Differences in Reservoirs VA21, VA22, and VA23 during the 2011-2014 Study Period.

ΔT is significantly correlated with DLI only. Wind speed ranged from 0.80 to 4.83 m/s at Nursery VA1, 0 to 3.92 m/s at Nursery VA2, 0 to 5.10 m/s at Nursery MD1, and 0.07 to 4.07 m/s at Nursery MD2. Wind speed showed both positive and negative correlation with ΔT, but the correlation was not significant.

Turbidity. The RIRs receive runoff high in sediment from production areas. Turbidity levels in the majority of reservoirs fell within 10-50 NTU with some observations over 50 NTU. The correlation between ΔT and turbidity was either positive or negative, with p-values all >0.05 (Table 3). The magnitude of temperature differences was not correlated with turbidity levels within the range observed in this study.

Vertical Distribution of DO in Thermally Stratified Irrigation Reservoirs

The annual pattern of DO variation followed the same seasonal pattern as thermal stratification (Figure 2c). Surface water DO concentrations during the sampling period of 2011-2014 ranged from 5.00 to 13.95 mg/L in VA21, 4.48 to 12.40 mg/L in VA22, and 4.00 to 10.96 mg/L in VA23, respectively.

When the water column was not thermally stratified from November to March, the DO concentration was only slightly higher at the surface than at the bottom, as represented by the more uniform colors in the vertical contour profile. However, when thermal stratification took place from April to October, DO concentrations at the bottom were reduced to near zero. DO concentrations at the bottom were 0.06 to 3.02 mg/L in VA21, 0.27 to 0.93 mg/L in VA22, and 0.06 to 3.10 mg/L in VA23. The contrasting colors in Figure 2c show high DO concentrations in the upper layer and low DO concentrations at the bottom. Top-bottom DO differences (ΔDO) over time are shown in Figure 3c. During the stratification periods, the maximum ΔDO between surface and bottom were 12.97 mg/L in 2012 and 11.77 mg/L in 2013 in VA21; 11.57 mg/L in 2013 in VA22; 10.31 mg/L in 2012 and 8.66 mg/L in 2013 in VA23, respectively. The top-bottom DO differences over time for other RIRs are shown in supplementary information.

The p-values were calculated to determine the significance of DO concentration differences at various depths for each sampling date. Nighty-three percent of the observations in VA21, 100% of the observations in VA22, and 100% of the observations in VA23 had p-values <0.05, suggesting that DO concentrations differed significantly by depth throughout the sampling period.

Vertical Distribution of pH in Thermally Stratified Irrigation Reservoirs

The annual pH variation also coincided with the thermal stratification pattern (Figure 2d). When water was not stratified, the pH level at the surface

TABLE 2. Statistical Summary of the Mean Top-Bottom Temperature, Dissolved Oxygen (DO), and pH Differences during Stratification and Nonstratification Periods in Each Reservoir Studied.

Reservoir ID	Period*	Δ*T*, °C	ΔpH	ΔDO, mg/L
VA11	S	2.13 ± 1.82	0.28 ± 0.33	1.20 ± 1.85
	NS	0.66 ± 0.56	0.00 ± 0.11	0.45 ± 0.90
VA12	S	3.07 ± 1.71	1.27 ± 0.53	6.09 ± 3.38
	NS	1.25 ± 1.83	0.56 ± 0.65	0.38 ± 0.85
VA13	S	3.05 ± 1.93	1.87 ± 1.07	8.05 ± 6.24
	NS	0.66 ± 0.61	0.08 ± 0.36	0.98 ± 1.81
VA21	S	11.58 ± 6.62	2.35 ± 1.45	8.63 ± 3.44
	NS	1.25 ± 2.03	0.28 ± 0.22	1.14 ± 1.03
VA22	S	12.37 ± 7.30	1.07 ± 1.25	8.76 ± 2.85
	NS	0.91 ± 0.85	-0.17 ± 0.39	3.33 ± 1.74
VA23	S	10.79 ± 5.93	0.60 ± 0.73	7.41 ± 2.33
	NS	1.47 ± 1.86	0.15 ± 0.11	0.98 ± 0.59
MD11	S	3.93 ± 2.16	1.28 ± 1.08	7.66 ± 6.63
	NS	0.47 ± 0.45	0.06 ± 0.30	-0.27 ± 0.95
MD21	S	2.29 ± 3.08	0.64 ± 0.65	3.98 ± 7.28
	NS	0.08 ± 0.13	0.02 ± 0.12	-0.23 ± 0.67

*S represents stratification periods and NS represents nonstratification periods.

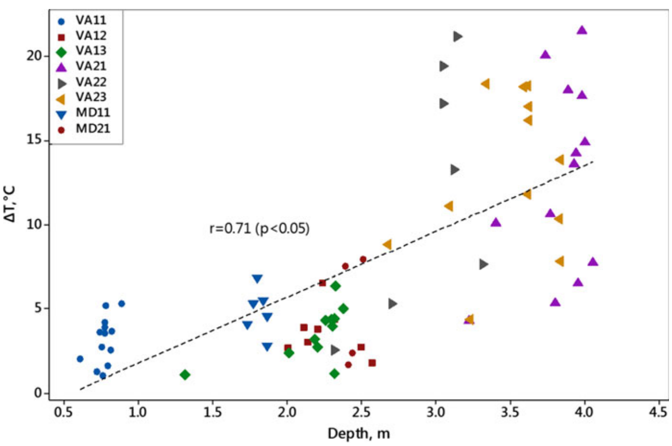

FIGURE 4. Scatterplot of Top-Bottom Temperature Difference (ΔT) and Depth during the Stratification Period (data from all reservoirs are included).

ranged from acidic to neutral (6.29 to 7.59 in VA21, 6.07 to 6.98 in VA22, and 5.74 to 6.67 in VA23) and was slightly higher than at the bottom. In contrast, when water was stratified, pH at the surface varied from acidic to basic (6.29 to 10.09 in VA21, 5.75 to 8.62 in VA22, and 6.06 to 9.03 in VA23) and was much higher than at the bottom. Top-bottom pH differences (ΔpH) over time are shown in Figure 3d. During the stratification period, the maximum ΔpH between surface and bottom was 3.77 in 2012 and 4.15 in 2013 in VA21; 3.35 in 2013 in VA22; 2.56 in 2012 and 1.53 in 2013 in VA23, respectively. The top-bottom pH differences over time for other RIRs are shown in supplementary information.

The *p*-values were calculated to determine whether pH values were significant by depth for each sampling date over the entire sampling period (2011-2014). Nighty-three percent of the observations in VA21, 100% of the observations in VA22, and 92% of the observations in VA23 had *p*-values <0.05, suggesting that the variation in pH at different depths was significant.

DISCUSSION

This study revealed for the first time existence of the thermal stratification in RIRs, an emerging aquatic ecosystem and irrigation water resource of global significance, and characterized its impacts on vertical profiling of pH and DO. The thermal stratification occurred yearly in all eight reservoirs with the shallowest reservoir being only 0.75 m deep. The stratification period in the Mid-Atlantic region generally is from April to October and this time window varied slightly depending upon water column depth, weather condition, and turbidity. These findings help understand the recycled water quality dynamics and its impacts on aquatic life in this novel ecosystem and develop agricultural runoff into a valuable water resource for irrigation.

Thermal stratification in RIRs generally is consistent with urban ponds. The stratification intensities in shallow RIRs (VA11-12-13, MD11, and MD21) are comparable with those in urban ponds, where top-bottom ΔT ranges between 1 and 6°C with depth between 0.5 and 2.5 m (McEnroe *et al.*, 2013; Song *et al.*, 2013). RIRs, such as VA21-22-23, that are deeper than 2.5 m have a much stronger stratification and the top-bottom ΔT was up to 21.53°C. In both RIRs and urban ponds, depth was found to influence thermal stratification, but such impact was weak for RIRs with shallower depths. VA11 had the least stratification compared to other RIRs, likely due to its small surface area and shallow depth. Runoff into VA11 was likely to cause turbulence in such a small water body and reduce thermal stratification stability.

The stratification pattern in these shallow RIRs was influenced by weather conditions and turbidity. There was a strong correlation with air temperature and DLI, but a weak correlation with wind speed, suggesting that the thermal structure in RIRs is due to radiative heat transfer rather than wind forcing. This was not unexpected as RIRs have smaller surface areas and are often surrounded with vegetation. The wind fetch is short compared to natural lakes, given the same wind speed, which is less likely to mix with the water completely (Xenopoulos and

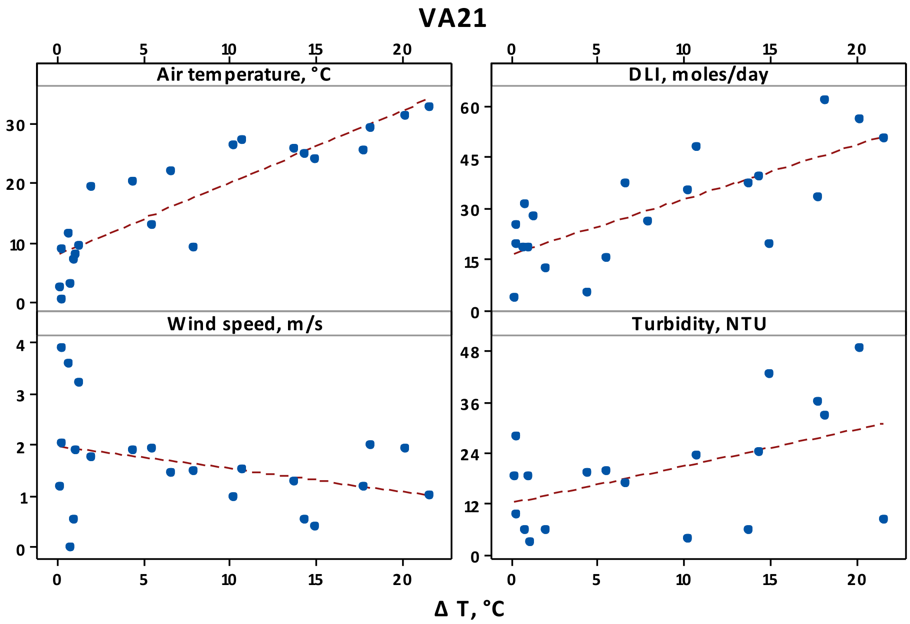

FIGURE 5. Scatterplot of Top-Bottom Temperature Difference *vs.* Air Temperature, Daily Light Integral (DLI), Wind Speed, and Turbidity in Reservoir VA21.

TABLE 3. Pearson Correlation Coefficients between Top-Bottom ΔT and Meteorological Variables in Each Reservoir.

Top-Bottom ΔT	Air Temperature, °C	DLI, moles/day	Wind Speed, m/s	Turbidity, NTU
VA11	0.51	0.76*	0.50	−0.15
	(p = 0.06)	(p = 0.00)	(p = 0.10)	(p = 0.65)
VA12	0.62*	0.45*	0.39	−0.09
	(p = 0.00)	(p = 0.00)	(p = 0.12)	(p = 0.71)
VA13	0.88*	0.81*	0.13	−0.09
	(p = 0.00)	(p = 0.00)	(p = 0.66)	(p = 0.75)
VA21	0.89*	0.76*	−0.34	0.28
	(p = 0.00)	(p = 0.00)	(p = 0.12)	(p = 0.24)
VA22	0.97*	0.86*	−0.28	0.49
	(p = 0.00)	(p = 0.01)	(p = 0.50)	(p = 0.32)
VA23	0.88*	0.86*	−0.34	0.42
	(p = 0.00)	(p = 0.00)	(p = 0.20)	(p = 0.15)
MD11	0.81*	0.30	−0.27	0.31
	(p = 0.00)	(p = 0.30)	(p = 0.36)	(p = 0.30)
MD21	0.68*	0.55*	0.34	0.16
	(p = 0.00)	(p = 0.02)	(p = 0.19)	(p = 0.56)

Notes: DLI, daily light integral.
*Represents statistical significance of correlations ($p < 0.05$).

Schindler, 2001). RIRs contain high concentrations of suspended solids such as soil particles and phytoplankton as indicated by turbidity levels. Water bodies with turbidity levels between 10 and 50 NTU are considered enriched with nutrients, supporting large plumes of planktonic life. The turbidity level in all RIRs is in this range. Higher turbidity results in higher temperatures in surface water as suspended particles or phytoplankton absorb heat from solar radiation. It also prevents sunlight from penetrating into the water column. The presence of phytoplankton at the surface also restricts water column mixing. Therefore, high turbidity is an important contributing factor for stratification in shallow RIRs as reported in other shallow systems (Condie and Webster, 2002; McEnroe *et al.*, 2013).

The occurrence of thermal stratification in RIRs impacted the vertical distribution of DO and pH in the water column. Both DO and pH levels were higher at the surface than at the bottom and these differences were much greater during the stratification periods than nonstratification periods. The hypolimnion layer became anoxic as DO concentration reached near zero and the maximum top-bottom pH difference was up to 4 units, resulting from restricted water exchange between top and bottom during the stratification periods. The vertical distribution of oxygen has been described in stratified deep and shallow water bodies, however, the vertical pH profile has not yet been studied, especially in RIRs, which is an important parameter in the decision-making of water management. The strong thermal stratification and subsequent DO differences could impact water chemistry in RIRs, particularly on phosphorous and nitrogen. Phosphorous is released from sediments under anaerobic hypolimnion created by thermal stratification (Wilhelm and Adrian, 2008; Song *et al.*, 2013, 2015), while such conditions could decrease the nitrogen availability due to denitrification in the water and sediment interface (Venterink *et al.*, 2003; Song *et al.*, 2013).

Discovery of thermal stratification furthers our understanding of the dramatic fluctuation of surface water quality in RIRs. As observed by Hong *et al.* (2009), surface water quality fluctuation is closely related to algal blooming and photosynthetic activities in the RIRs. Photosynthesis removes carbon dioxide, a weak acid, from RIRs while releasing oxygen into the same reservoirs, and this process begins in the morning and intensifies with time until evening, resulting in increased water pH and DO in the systems. An opposite process occurs during the night, driving both water pH and DO down. Such changes in hydrogen ion and oxygen at the surface water are limited within the epilimnion layer during the stratification periods as there is essentially no water mixing within the water column. In contrast, during the nonstratification periods, water mix freely and constantly within the water column and this mixing process reduces the fluctuation of water pH and DO at the surface.

Characterization of thermal stratification in RIRs helps understand the biology of important microbes, including plant pathogens in different parts of the water column. For example, approximately 30 *Phytophthora* species have been recovered from the RIRs. Among these high-temperature tolerant species, *P. aquimorbida*, *P. hydrogena*, *P. hydropathica*, *P. insolita*, *P. irrigata*, and *P. virginiana* have optimal growth temperature at 35°C (Hong *et al.*, 2008, 2010, 2012; Yang and Hong, 2014; Yang *et al.*, 2014). They may be more active in surface water when the temperature reaches 30°C during the stratification period between April and October, and less active at lower depths where the temperature decreases dramatically. Other frequently recovered species *P. gonapodyides* and *P. pini* have optimal growth temperatures between 20 and 25°C and cannot tolerate relatively high temperatures near 30°C (Buisman, 1927; Hong *et al.*, 2011). These species may survive at 25°C which occurs at the 1-m depth in Nursery VA2. All suggest that thermal stratification is likely to affect the abundance and diversity of *Phytophthora* species in RIRs. This conclusion is well supported by the fact that we recovered high-temperature tolerant *P. hydropathica* and *P. irrigata* much more frequently from the reservoir surface during warmer months, while *P. gonapodyides* and *P. syringae* were more abundant during cooler months (Ghimire *et al.*, 2011).

Profiling of DO concentrations during the annual thermal stratification period is a useful tool in determining the depth from which to pump irrigation water for pathogen risk mitigation. Zoospores of several *Phytophthora* species were found to survive best at DO concentrations of 5.3-5.6 mg/L, while levels outside this range enhanced the decline of zoospore survival over time (Kong and Hong, 2014). During the nonstratification periods, the majority of DO levels at all depths were higher than 7 mg/L, an unfavorable condition for zoospore survival. During the stratification period, the DO range (5.3-5.6 mg/L) often occurred between 1.0- and 1.5-m depths in Nursery VA2, which implies that zoospores may experience survival stress above or below these depths. Thus, water withdrawn from depths other than 1.0 to 1.5 m is likely to have lower concentrations of viable zoospores.

In addition to direct impacts on plant pathogen survival, low DO concentrations or anaerobic conditions in root zone substrate may impair a plant's resistance mechanism and increase its susceptibility to pathogenic invasion (Blaker and MacDonald, 1981; Wilcox and Mircetich, 1985; Fraedrich and Tainter, 1989). Increased susceptibility to infection by *Phytophthora cinnamomi* was observed for shortleaf and loblolly pine when exposed to DO concentrations of 0-0.25 mg/L (Fraedrich and Tainter, 1989). Several *Phytophthora* root and crown rots were developed for cherry seedlings after a long period of low oxygen availability (Wilcox and Mircetich, 1985). Oxygen deficiency resulted from flood stress can predispose normally resistant rhododendrons to root and crown rots caused by *Phytophthora cinnamomi* (Blaker and MacDonald, 1981). The DO concentrations in RIRs decrease dramatically from surface to the bottom during the stratification periods. Thus, water withdrawn should take place further away from the bottom to avoid low DO concentrations.

Profiling of pH levels during the annual thermal stratification period is very important in terms of pathogen risk mitigation and water treatment efficacy. *Phytophthora* species respond differently to various pH levels. Kong *et al.* (2009) reported on the variation in survival rates for zoospores of seven *Phytophthora* species at pH ranging from 3 to 11. Optimal survival for *P. citricola* and *P. tropicalis* is pH 9 and 5, respectively, and that of *P. citrophthora*, *P. insolita*, *P. irrigata*, *P. megasperma*, and *P. nicotianae* is pH 7. Germinants of *P. alni* and *P. ramorum* were more tolerant of basic conditions (pH as high as 11), while those of *P. kernoviae* were more acid tolerant (pH as low as 3) (Kong *et al.*, 2012). Depending on the pathogen of concern, water should be pumped from depths with pH levels that suppress pathogen survival. In addition, pH also affects water treatment efficacy such as chlorination which performs well at pH 5.0-6.5 (Wolfe *et al.*, 1976). During the nonstratification periods, most pH levels were acidic at all depths, as shown in Figure 2d, while during the thermal stratification periods, pH levels at the surface were neutral to basic, which could dramatically reduce water treatment efficacy. Therefore, avoiding pumping irrigation water from the surface is more likely to have low pH levels and improve the performance of chlorination.

Understanding vertical pH variation during the thermal stratification period also helps minimize the negative effects of high pH on crop quality and productivity. An increase in pH can negatively affect shoot and tuber weights (Valdez-Aguilar *et al.*, 2009). Varying pH levels can affect nutrient solubility and availability to plants. For example, the solubility of iron, manganese, zinc, boron, and phosphorus decreases with increasing pH. Phosphorous becomes less available to the plants when pH is above 7.2 (Argo and Fisher, 2002). In our study, the surface pH was higher than the bottom pH for most of the year and the difference was even greater during the stratification periods. Therefore, water pumped from lower depths during the stratification periods is more likely to have an acidic to neutral pH.

Profiling of three parameters provides quantitative support of pH as an indicator for monitoring water quality in RIRs. Many water quality parameters, including but not limited to temperature, DO, pH, electrical conductivity, oxidation-reduction potential, turbidity, chlorophyll *a*, and nutrients could impact crop health and production. It is not practical to regularly measure all parameters in order to determine water quality status for irrigation purposes due to time, expense, and accessibility of the reservoirs. Identification of a water quality indicator would facilitate water management while reducing monitoring cost. Such an indicator must be reliable, sensitive, and easy to measure. Water temperature, DO, and pH are relatively easy to assess. As discussed above, the vertical distribution of water DO and pH were closely tied into thermal stratification. Water pH is a measurement of hydrogen ion concentration and the 4.16 units in pH is equivalent to over 10,000 times top-bottom difference in hydrogen ion concentration, which is much greater in magnitude compared to the maximum top-bottom differences in 21.53°C for temperature and 12.97 mg/L for DO. This magnitude of pH variation (up to 4.16 units) could change the water condition from basic into acidic and this variation itself could strongly alter pathogen survival in water, water treatment efficacy and nutrient availability to crops. Thus, pH is potentially a good indicator for monitoring water quality in RIRs. Water pH should be measured from the depth where irrigation water is pumped during the stratification period while from the surface during nonstratification period to assess water quality, because dramatic vertical variation in pH occurs during stratification periods. The potential of pH as an indicator should be further evaluated against other water quality parameters such as chlorophyll *a*, oxidation-reduction potential, electrical conductivity, total dissolved solids, salinity, and turbidity to streamline water quality monitoring.

CONCLUSIONS

In our investigation of eight RIRs in the Mid-Atlantic region, we found monomictic thermal stratification occurred in all RIRs. Temperature, DO, and pH varied dramatically from surface to bottom during the stratification periods and the maximum differences were up to 21.53°C for temperature, 12.97 mg/L for DO, and 4.16 units for pH. Profiling of DO and pH levels during annual thermal stratification period has important practical implications in determining the depth at which irrigation water is withdrawn to mitigate pathogen risk and improve water treatment efficacy. The pH in RIRs has the greatest variation in the vertical and has a strong influence on pathogen survival, water treatment efficacy and crop productivity. The pH may be used as an indicator to assess irrigation water quality when constrained to monitoring cost. Discovery and characterization of the thermal stratification in RIRs help broaden the understanding of water quality dynamics and their impact on the biology of important microbes in this emerging aquatic ecosystem and help transform agricultural runoff into a valuable water resource.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Thermal stratification patterns and vertical distribution of DO and pH for reservoirs VA11-12-13, MD11, MD21, VA22, and VA23 were illustrated in Supplementary Information.

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