Agricultural Water Management 160 (2015) 76–83

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Characterization of water quality in stratified nursery recycling irrigation reservoirs

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ARTICLE INFO

Article history:
Received 12 November 2014
Received in revised form 16 June 2015
Accepted 30 June 2015
Available online 15 July 2015

Keyword:
Recycling irrigation reservoir
Stratification
Water quality
Electrical conductivity
Oxidation reduction potential
Chlorophyll *a*

ABSTRACT

Recycling irrigation reservoirs (RIRs) are an emerging aquatic ecosystem of global significance. Building upon the recent discovery of thermal stratification in these novel systems and its impacts on the vertical distribution of dissolved oxygen and pH, this study investigated the dynamics of chlorophyll *a* (CHLA), oxidation reduction potential (ORP), electrical conductivity (EC), and turbidity in the water columns of eight RIRs in the Mid-Atlantic region in USA over a 3-year period from 2011 to 2014. The vertical distribution of CHLA was associated with thermal stratification while ORP and EC were directly affected by thermal stratification. Specifically, CHLA concentration was greatest in the middle thermocline, followed by lower hypolimnion during the stratification period. ORP level was higher at the surface than bottom with differences up to 505.67 mv in Reservoir VA23. EC level was higher in the bottom than at the surface with the maximum difference of 0.90 dS m^{-1} in Reservoir VA22. The top–bottom ORP and EC differences increased when water was stratified. Turbidity was indirectly affected by stratification. The correlation of turbidity with total precipitation was stronger during the non-stratification period from November to March than during the stratification period from April to October, mainly due to restriction on water mixing. The characterization of these additional water quality parameters in the water columns of RIRs provides fundamental knowledge about this novel water system and will help in developing sound water quality management practices for improved crop health and production while reducing agriculture's environmental footprint. This study also provides additional evidence supporting pH as a significant indicator for monitoring water quality in RIRs.

1. Introduction

Capturing and reusing runoff for irrigation is of vital importance to the sustainability of agricultural production, given constraints on water availability, environmental initiatives and increasing regulation. Agriculture accounts for 80 percent of overall consumptive water use in the USA (USDA-ERS, 2013). Large amounts of water are pumped for irrigation while substantial proportions are lost in runoff. Elevated nutrient levels are present in the runoff due to irrigation and fertilization during plant development, especially in nursery production. The concentration of NO_3-N in nursery runoff ranged from 0.1 to 386.4 mg L^{-1} (Mangiafico et al., 2009; Taylor et al., 2006; Wilson et al., 2010; Wood et al., 1999; Yeager et al., 1993) while PO_4-P ranged from 0.01 to 20 mg L^{-1} (Alexander, 1993; Headley et al., 2001; Mangiafico et al., 2009; Taylor et al., 2006; Yeager et al., 1993). Most of these nutrient levels exceed water quality standards and could impact water quality dynamics in the receiving water bodies. Recycling irrigation reservoirs (RIRs) have been built to collect storm and irrigation runoff in order to conserve increasingly limited and costly water resources needed and reduce nutrient discharges into natural water bodies. However, water quality dynamics within these aquatic systems is largely unknown.

Water quality parameters have been studied for their impacts on the survival of *Phytophthora* species, a group of destructive plant pathogens. First, different species of *Phytophthora* responded to pH

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http://dx.doi.org/10.1016/j.agwat.2015.06.027
0378-3774/

Table 1
Characteristics of recycling irrigation reservoirs included in this study.

Nursery	Location	Reservoir ID	Surface area, ha	Average depth[a], m	Minimum Depth[a], m	Maximum Depth[a], m
VA1	Eastern VA (36°46′03.2″N, 76°38′21.3″W)	VA11	0.10	0.75	0.41	0.88
		VA12	0.81	2.28	1.95	2.57
		VA13	6.07	2.19	1.31	2.43
VA2	Central VA (37°46′52.3″N, 77°27′28.9″W)	VA21	0.81	3.78	3.23	4.05
		VA22	1.62	2.98	2.32	3.32
		VA23	0.61	3.51	2.05	3.89
MD1	Northern MD (39°29′28.9″N, 75°47′18.0″W)	MD11	1.70	1.80	1.36	2.02
MD2	Central MD (38°57′05.4″N, 76°39′04.1″W)	MD21	0.61	2.36	1.48	2.65

[a] Depth was measured at the reservoir center.

stress differently in a simulated aquatic environment (Kong et al., 2009). Some species were favored by acidic conditions while others were favored by slightly basic pH. Second, these pathogens are aerobic and they survived at the greatest rates in water at dissolved oxygen (DO) concentrations of 5.3 to 5.6 mg/L and at reduced rates above or below those DO concentrations (Kong and Hong, 2014). Third, *Phytophthora ramorum*, *P. alni* and *P. kernoviae*, all of quarantine significance, survived better in water at ECs greater than 1.89 dS m^{-1} than at ECs below 0.41 dS m^{-1} (Kong et al., 2012). Fourth, the impact of oxidation-reduction potential (ORP) on plant pathogens is not known. It is known that ORP values above 650 can inactivate human pathogens, such as *Escherichia coli* O157:H7, *salmonella* spp., *L. monocytogenes* and thermotolerant coliform (Suslow, 2000).

Water quality may also influence crop health and productivity. Elevated EC and pH negatively affected shoot and tuberous root weight (Valdez-Aguilar et al., 2009). pH levels can also affect nutrient solubility and availability to plants (Argo and Fisher, 2002).

Characterization of water quality dynamics in irrigation reservoirs is a critical step to understanding its potential implications for crop health and productivity. Thermal stratification is known to regulate numerous physical, chemical and biological processes in aquatic ecosystems and affects water quality in reservoirs. Thermal stratification affects the vertical exchange of DO, nutrients, phytoplankton and sediments (Fischer et al., 1979).

Stratification provides advantages for floating algal species to remain within the eutrophic zone (Bormans and Condie, 1997; Sherman and Webster, 1994; Wallace et al., 2000) and appeared to be the key factor influencing the onset and demise of cyanobacterial blooms (Jones and Poplawski, 1998). In a recent study, we observed monomictic thermal stratification from April to October in shallow RIRs of the Mid-Atlantic region in USA and demonstrated its relationship to vertical distribution of DO and pH (Zhang et al., 2015). However, whether and how thermal stratification may affect the other water quality parameters of chlorophyll *a* (CHLA), ORP, EC and turbidity in RIRs have not yet been analyzed.

The primary objective of this study was to analyze water quality data collected from eight RIRs in the Mid-Atlantic region in USA over a 3-year period from 2011 to 2014 and characterize the vertical distribution of CHLA, ORP, EC and turbidity with respect to thermal stratification. The implications of resultant findings for recycled water management are discussed.

2. Materials and methods

2.1. Site description

Six irrigation reservoirs located in two nurseries in Virginia (VA1, VA2) and two in Maryland (MD1 and MD2) were included in this study. The major characteristics of these reservoirs are shown in Table 1. Data from the reservoirs in nursery VA2 are presented in detail in this paper and that of the remaining nurseries (VA1, MD1, and MD2) are described in Supplementary information.

Nursery VA2 is located in central VA. This nursery has three reservoirs built in sequence, VA21, VA22 and VA23 as illustrated in Fig. 1. Runoff water from all production areas is channeled via a single entrance into VA21. When VA21 reaches its full capacity, water overflows into VA22, and similarly, from VA22 into VA23 through a culvert. Recycled water from VA23 is pumped to irrigate ornamental plants. Mature trees and natural shrubbery surround the entire nursery. The surface area and average depth of each reservoir investigated are summarized in Table 1.

2.2. Data collection

To investigate water quality within each reservoir, monthly measurements were taken between 12:00 and 16:00 h at the geometric center from April 2011 to March 2014. Nine water quality parameters were measured vertically at 0.5-m intervals from surface to bottom using a 6600V2-4 Multiprobe (YSI Inc., OH, USA). These parameters included temperature, DO, pH, CHLA, ORP, EC, total dissolved solids, salinity and turbidity. Triplicate measurements were taken at each depth for all parameters. Temperature, DO and pH were analyzed in a previous study (Zhang et al., 2015). This study focused on CHLA, ORP, EC and turbidity. Precipitation data was recorded every five minutes using onsite weather stations (Decagon Devices, Inc., Pullman, WA). Data outliers or errors due to malfunction of the instrument were excluded from the data analyses below.

2.3. Data analysis

To uncover the seasonal pattern of water quality variations in RIRs, the vertical profile of each water quality parameter (CHLA, ORP, EC and turbidity) was plotted against time for each reservoir. The range of water quality and time window for water quality variations were determined. Top–bottom water quality differences were also computed by sampling date for each reservoir to examine the magnitude of variations in the water columns. One-way analysis of variance (ANOVA) was conducted in R (Version 12.5.2) to determine if water quality difference were affected by depths (null hypothesis H0: water quality parameters at all depths are equal). *P* value less than 0.05 is considered statistically significant to reject the null hypothesis.

To further determine whether and how CHLA, ORP, EC and turbidity in water columns may be affected by thermal stratification from April to October, top–bottom differences of individual parameters were plotted against top–bottom temperature differences. Pearson correlation coefficients were calculated to quantitatively describe their association. As turbidity is weather-dependent (Hong et al., 2009) and normally affected by soil erosion and sediment re-suspension from seasonal runoff, the impact of precipitation was also examined in this study.