Agricultural Water Management 187 (2017) 131–139

Contents lists available at ScienceDirect

Agricultural Water Management

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

Seasonal water quality changes in on-farm water storage systems in a south-central U.S. agricultural watershed

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ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form 27 February 2017
Accepted 8 March 2017

Keywords:
On-farm water storage systems
Tailwater recovery ditch
Agricultural runoff
Nutrient reduction
BMP

ABSTRACT

The objective of this study was to investigate the ability of on-farm water storage (OFWS) systems to mitigate off-site nutrient movement in a south-central U.S. agricultural watershed. We examined the seasonal water quality changes in an OFWS system by measuring several physical and chemical constituents at multiple sampling points throughout the system. Water quality sampling occurred every three weeks during the growing season and every six weeks during the dormant season from February 2012 to December 2014. The collected data were grouped into four seasons and then analyzed using boxplots along with the Wilcoxon and Kruskal-Wallis rank-sum tests for detecting changes in nutrient concentrations. Significant water quality changes were observed in the OFWS system by season and nutrient species, indicating a variation in downstream nutrient reduction with season. The in-ditch median removal efficiency, from the center of the tailwater recovery ditch to the outlet, was 54% during winter and 50% during spring for NO_3-N; 60% during spring for NH_3-N; 26% during autumn and 65% during winter for ortho-P; and 31% during winter and 10% during spring for TP. The in-pond median concentration removal efficiency was ~77% during summer for NO_3-N, while the concentration remained stable during winter, spring and autumn; 53% from winter to spring and 58% from spring to summer for NH_3-N; 70% from winter to spring for ortho-P, while remaining stable during the other seasons; and 28% from winter to spring and 55% from spring to summer for TP. Our results support the hypothesis that OFWS systems could mitigate downstream nutrient-enrichment pollution, especially during spring. The results obtained from this study offer a better insight into the behavior of OFWS systems and help enhance the management of agroecosystems from an ecological and hydrological perspective for water quality pollution control and water resource conservation.

1. Introduction

It is widely accepted that agricultural practices have become a significant contributor of pollutants that adversely alter the natural cycle of nutrients, especially for nitrogen and phosphorus (Schlesinger, 1991; Vitousek et al., 1997; Smith et al., 1999). This alteration is derived in large part from the dramatic increase in the use of fertilizers needed to maintain agricultural profitability and higher yields, which is required to feed a growing global population (*i.e.*, roughly 77 million individuals per year according to the US Census Bureau, 2015). In 2012, the world consumption of fertilizers reached nearly 120 and 46.5 million tons of nitrogen and phosphorus per year, respectively (FAO, 2015). The increasing use of fertilizers could be detrimental to aquatic ecosystems as a substantial portion of the nutrient inputs is transported from croplands to groundwater *via* percolation and to adjacent waterbodies *via* surface and irrigation runoff (Ongley, 1996; Carpenter et al., 1998; Sims et al., 1998; Hollinger et al., 2001; Rabalais et al., 2002b), often reaching coastal ecosystems (Nixon, 1995; Rabalais, 2002; Seitzinger et al., 2002). The over enrichment of nutrients in waterbodies stimulates eutrophication, which is the most common leading factor in the deterioration of aquatic ecosystems. Additional nutrients result in the excessive growth of phytoplankton, macrophytes, and toxic algal blooms, and dissolved oxygen is consumed and depleted as bacteria decompose carbon in the dead plant material. The depletion of oxygen can cause hypoxia and as a consequence a shift in the benthic population and its related food chain, resulting in fish kills, loss of aquatic biodiversity, and many other adverse ecological effects (Carpenter et al., 1998; Smith et al., 1999; Smith, 2009).

Agriculture in the southern United States, specifically in the Mississippi Delta region (MDR), faces two major challenges to

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http://dx.doi.org/10.1016/j.agwat.2017.03.014
0378-3774/

maintain a high level of productivity while preserving the surrounding ecosystem's health: (1) off-site movement of nutrients contributing to the development of the hypoxic zone in the northern Gulf of Mexico, especially during the spring season, and (2) the declining groundwater levels in the Mississippi River Valley Alluvial Aquifer (MRVAA). According to Rabalais et al. (2002a), an average of roughly 1 million metric tons per year of nitrate, 67% of which originates from agricultural sources, are released into the Gulf of Mexico, causing devastating ecological effects such as "the dead zone" due to hypoxia phenomenon. Similarly, phosphorus has also been suggested as a major contributor to the Gulf hypoxia problem (USEPA, 2007; Sylvan et al., 2006). In addition, the overuse of groundwater from the MRVAA is, on average, nearly 530 m^3 ha^{-1} yr^{-1} (Kebede et al., 2014; Massey, 2010; Wax et al., 2008). To address these complex environmental issues, stakeholders and the scientific community have been promoting control measures such as the implementation of Best Management Practices (BMPs) at the field and watershed scale. One of these BMPs is the on-farm water storage (OFWS) system, which has been gaining popularity in agriculturally-dominated regions such as the MDR. By combining tail-water recovery (TWR) ditches and on-farm reservoirs, an OFWS system becomes a structural BMP that collects and stores surface runoff and irrigation tail water from farmed lands. Because of its inherent features, researchers have suggested that OFWS systems have the potential of (1) reducing nutrients exported from agricultural watersheds to receiving waterbodies and (2) providing an alternative source of water for the irrigation of cropped fields.

Over the past decade, many researchers have investigated the role of ditches as an individual structural BMP because of their crucial function of linking agricultural watersheds to external ecosystems (Herzon and Helenius, 2008; Ahiablame et al., 2010). Dollinger et al. (2015) collated the vast majority of scientific contributions focused on the benefits of implementing ditches for agroecological management. Their study classified these benefits into waterlogging control, soil erosion prevention, water quality improvement, flood control, aquifer recharge, and biodiversity conservation. While several studies have addressed the role of ditches in nutrient movement, little attention has been paid to the combined effect of TWR ditches and on-farm reservoirs (*i.e.*, an OFWS system) or their performance as a BMP on agricultural lands. Popp et al. (2004) cited increased profitability and reduced dependence on groundwater when using on-farm reservoirs and tail-water recovery systems in conjunction with other BMPs. Later, preliminary results from Carruth et al. (2014) and Pérez-Gutiérrez et al. (2015) indicated that OFWS could reduce nutrient runoff from farms and also that the stored water could be used for irrigation needs. In a recent study, Moore et al. (2015) observed no statistical differences in water quality among sampling points in an intensively used on-farm storage reservoir and its surrounding ditches in the Northeast Arkansas Delta. While these investigations examined OFWS systems, there are still many questions regarding the systems' nutrient removal effectiveness and seasonal water quality variation, which are helpful for making better agricultural management decisions. Therefore, it is important to monitor and analyze the water quality changes in these systems to improve our understanding of how this emerging BMP impacts the environment in terms of downstream nutrient control and water conservation.

The objective of this study was to investigate the mitigation of nutrient runoff from a south-central U.S. agricultural watershed implementing an OFWS system, by examining the spatial and temporal variations of water quality occurring at sampling points located throughout the system. With the goal of measuring downstream nutrient reduction, we tested the hypothesis of water-quality statistical differences between the sampling points by season, using a suitable non-parametric approach.

Table 1
Hydro-geometric characteristics of the monitored OFWS system.

Hydro-geometric feature	Value	Units
TWR ditch (Trapezoidal shape)		
Length	818.8	m
Side slope	1.5:1	–
Channel bed slope	0	–
Bottm width	3.6	m
Flow depth	1.8	m
Freeboard	0.3	m
Storage volume	13,320	m^3
On-farm reservoir		
Depth	2.4	m
Side slope	3:1	–
Surface area	4.45	ha
Bottom width	3.6	ha
Storage volume	114,700	m^3

2. Materials and methods

2.1. Study area

The monitored OFWS system is implemented on a farm located in the central portion of the MDR within the headwater region of the Porter Bayou watershed (PBW; Fig. 1), north of Indianola, Mississippi. The PBW extends from latitude 33° 26′ 41″ to 33° 51′ 40″ north and longitude 90° 48′ 54″ to 90° 31′ 34″ west, covering nearly 506.2 km^2, most of which are cultivated, producing mainly soybeans and corn (MDEQ, 2012). The topography of PBW is relatively flat with elevations ranging from 90 to 150 m. From 2012–2014, the observed total monthly precipitation ranged from about 200–600 mm and primarily occurred from early autumn to late spring (Fig. 2), when the runoff was usually high. The monthly average temperature ranged from 16.7 °C during winter to 26.7 °C during summer (Fig. 2). More information about the watershed can be found at MDEQ (2008, 2012).

The soils on the 110-ha fields surrounding the monitored system are comprised of several soil types namely, Alligator silty clay loam (24.1%), Forestdale silty clay loam (21.1%), Dowling overwash phase (17.9%), Forestdale silt loam (14.9%), and Dowling clay (13.9%). The soils are exposed during the dormant season, and a soybean-corn crop rotation with conventional and non-tillage practices covered the farm during the growing season for the monitoring period. Typically, nitrogen was applied during early spring, while phosphorus was applied during the fall.

2.2. Field sampling and analytical techniques

For water quality data acquisition, an edge-of-field monitoring network was established in 2012 in the OFWS system at our study site (Fig. 1). The network consists of four sampling points within the system: (1) the inlet, M1; (2) TWR ditch, M2; (3) the outlet, M3; and (4) the pond, MP. Table 1 provides the main characteristics of the monitored OFWS system. Sample collection was conducted from March 2012 to December 2014 every three weeks during the growing season (March–October) and every six weeks during the dormant season.

Manual samples were collected in high density polyethylene bottles according to EPA Method 600/4-82-029 (USEPA, 1982). Samples were analyzed *in situ* for potential of hydrogen, pH (pH units); electrical conductivity, EC (mS cm^{-1}); dissolved oxygen, DO (mg L^{-1}); temperature, T (°C); and *ex situ* for nitrate nitrogen, NO_3-N (mg L^{-1}); ammonia nitrogen, NH_3-N (mg L^{-1}); orthophosphate, ortho-P (mg L^{-1}); total phosphorus, TP (mg L^{-1}); total kjeldahl nitrogen, TKN (mg L^{-1}); and total suspended solids, TSS (mg L^{-1}). *In situ* parameters were measured using a Thermo Scientific Orion Star A329 Portable Multiparameter meter (Thermo Fisher Scientific