Potential for recycling of suspended solids and nutrients by irrigation of tailwater from tailwater recovery systems

ABSTRACT

Within the Lower Mississippi Alluvial Valley, conservation practices are being utilized to mitigate nutrient loading to streams from agricultural landscapes. This study was conducted to determine the potential to use solids, phosphorus (P) and nitrogen (N) captured by tailwater recovery (TWR) systems for reuse onto production fields through irrigation applications. Seven TWR systems were assessed for seasonal changes in nutrient concentrations and application loads. Samples were collected every three weeks from 2013 to 2015 for seasonal analyses and weekly during the 2014 and 2015 growing seasons for nutrient load analyses. Water samples collected in spring contained greater concentrations of solids than samples collected in winter and summer. In addition, spring samples contained greater concentrations of nitrate–nitrite than samples collected in all other seasons, and spring samples also contained higher ammonium than summer and fall samples. Mean nutrient loads per hectare recycled onto the landscape for an irrigation season were 325.10 kg ha$^{-1}$ solids, 0.86 kg ha$^{-1}$ P, and 7.26 kg ha$^{-1}$ N, with the N being 77% organic. TWR systems can be used to recycle solids, P and N onto agricultural landscapes through irrigation events; however, nutrient loads will not be sufficient to alter agronomic fertilizer recommendations.

Key words | best management practices, irrigation, water quality, water quantity, water reuse

INTRODUCTION

Documentation, awareness, and understanding of agricultural impacts on the environment have led to increased implementation of conservation practices to mitigate local and national water quality degradation. One region in which large amounts of Federal and private funds are focused on the implementation of conservation practices is the Lower Mississippi Alluvial Valley in Mississippi, hereafter referred to as ‘the Delta’. This region is economically important due to its highly productive alluvial soils. Agricultural practices required to maintain maximum yields are concomitant to two predominant environmental issues facing producers in the Delta. The first is that intensive agricultural practices have resulted in increased surface water transport of nutrients, contributing to eutrophication in receiving waters and to the increased size of the Gulf of Mexico hypoxic zone (Rabalais et al. 1996; Turner & Rabalais 2003; Rabalais & Turner 2017). The second issue is the unsustainable water withdrawal from the Lower Mississippi River Valley Alluvial Aquifer for irrigation during the growing season during which precipitation is typically minimal in this area (Clark et al. 2011).

Irrigation for agriculture in the Delta accounts for the largest use (98%) of the Mississippi Aquifer (Thornton 2012). Years of withdrawals from the aquifer at rates faster than groundwater recharge have resulted in a cone of depression in the central Delta (Barlow & Clark 2011). This unsustainable use of groundwater has raised awareness about water conservation and the need to reduce use or create new surface water supplies for irrigation.
An important best management practice (BMP) aimed at addressing both water quality and water quantity issues is surface water capture-and-irrigation reuse systems, also known and further referred to as tailwater recovery (TWR) systems. TWR systems are a combination of a ditch which captures surface water, an on-farm storage (OFS) reservoir to store additional captured surface water, and pumps to re-lift surface water from the ditch into the OFS reservoir. Pumps are also used to irrigate water from the OFS reservoir onto fields. The shape and size of TWR systems vary, and are further described in Prince Czarnecki et al. (2017). The United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) has financially assisted with installation of over 180 TWR systems in the Delta under Practice 436 in the state of Mississippi (USDA NRCS 2016). Of those 180 systems, 123 have been implemented within the aquifer cone of depression to alleviate groundwater withdrawal (P. Rodrigue, NRCS, personal communication, 2015). However, the capacity of TWR systems to mitigate nutrient loss to downstream waters, irrigate those nutrients onto the landscape, and alleviate groundwater withdrawals has yet to be investigated. Assessing benefits of these systems is important to (1) justify the continued expenditure of Federal and private funds on these systems and (2) adaptively manage these systems.

Currently, TWR systems are hypothesized as a practice that allows for the application of nutrients with irrigation water, therefore allowing producers to reduce fertilizer inputs (Carruth et al. 2014); however, no scientific evidence is available to support this hypothesis. Quantification of nutrient concentrations and loads in TWR systems are needed, with consideration of seasonal differences. Therefore, the objective of this study was to determine the potential to recycle and reuse suspended solids, P and N captured by TWR systems back onto production fields through irrigation applications.

MATERIALS AND METHODS

Sample collection

Samples were collected from seven TWR systems, comprising six TWR ditches and five OFS reservoirs on five separate farms in the Mississippi Delta region. The Mississippi Delta region is shown in Figure 1 shaded in dark grey and counties outlined in black. The bottom right of Figure 1 depicts TWR system locations represented as dots and labeled with letters corresponding to Table 1, and Delta counties outlined and labeled in black. One TWR system consisted of only a ditch and in another TWR system only the OFS reservoirs were sampled (Table 1). A TWR system diagram is provided as a visualization tool in Figure 2 (Figure 2

Figure 1 | Map of the Delta region of Mississippi and this study’s TWR system locations.
### Table 1 | Characteristics of TWR systems sampled

<table>
<thead>
<tr>
<th>Farm</th>
<th>TWR Layout</th>
<th>Volume (m³)</th>
<th>Crop rotation</th>
<th>Catchment area (ha)a</th>
<th>Soil type</th>
<th>Other best management practices b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A TWRD</td>
<td>115,900</td>
<td>Rice</td>
<td>74.3</td>
<td>100% SC</td>
<td>irrigation land leveling (zero grade rice) (342), water control structure (riserboard pipes) (410) and grade stabilization (field perimeter pads) (587)</td>
</tr>
<tr>
<td>2</td>
<td>B TWRD</td>
<td>7,700</td>
<td>Rice–Soybeans, Corn–Soybeans</td>
<td>155.6</td>
<td>73% TN, 27% SC</td>
<td>90% TN, 10% SC</td>
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<tr>
<td>3</td>
<td>C TWRD</td>
<td>25,500</td>
<td>Corn–Soybeans</td>
<td>639.8</td>
<td>95% DC, 5% SC</td>
<td>90% FD, 10% DC</td>
</tr>
<tr>
<td>4</td>
<td>D TWRD</td>
<td>37,000</td>
<td>Corn–Soybeans</td>
<td>123.8</td>
<td>42% DC, 26% FD, 20% DN, 12% DB</td>
<td>56% DN, 18% FD, 15% DC, 11% DB</td>
</tr>
<tr>
<td></td>
<td>E TWRD</td>
<td>17,800</td>
<td>Corn–Soybeans</td>
<td>68.2</td>
<td>46% DC, 31% DB, 13% DN, 11% FD</td>
<td>irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)</td>
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<tr>
<td>5</td>
<td>F TWRD</td>
<td>50,600</td>
<td>Rice–Soybeans</td>
<td>80.4</td>
<td>100% AC</td>
<td>irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)</td>
</tr>
<tr>
<td></td>
<td>G OFS</td>
<td>197,400</td>
<td>Rice–Soybeans</td>
<td>57.2</td>
<td>100% AC</td>
<td></td>
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</tbody>
</table>

TWRD is the tailwater recovery ditch.

aThe area of the catchment draining into the TWRD. Crops in crop rotation include: rice (Oryza sativa), soybeans (Glycine max) and corn (Zea mays).


Soil types: AC, Alligator clay (very-fine, smectitic, thermic Chromic Dystraquerts); DC, Dowling clay (very-fine, smectitic, nonacid, thermic Vertic Endoaquepts); DB, Dubbs silt loam (fine-silty, mixed, active, thermic, Typic Hapludalfs); DN, Dundee loam (fine-silty, mixed, active, thermic Typic Endoaqualfs); FD, Forestdale silty clay loam (fine, smectitic, thermic Typic Endoaqualfs); SC, Sharkey clay (very-fine, smectitic, thermic, Chromic Epiaquerts); TN, Tensas silty clay (fine, smectitic, thermic, Chromic Vertic Epiaqualfs). Descriptions for each soil series from the USDA-NRCS Soil Survey Division, Official Soil Series Description, [http://soilseries.sc.egov.usda.gov/](http://soilseries.sc.egov.usda.gov/).

### Figure 2 | Diagram of a TWR system.
modified from Baker et al. (2017), and is not inclusive of all TWR systems. TWR systems may differ by only containing a large TWR ditch and no OFS reservoir and different pumps and service pipes. Pipes leaving fields are often slotted to allow control of the water leaving the field. In addition, pipes leading from the TWR ditch to the field have a valve (not pictured) which does not allow surface water into the ground water. The pump can only pump from either surface water or groundwater.

Water samples were collected from 2013 to 2015 from both TWR ditches and OFS reservoirs to assess seasonal changes in water nutrient concentrations and were collected every 3 weeks throughout the year (hereafter described as ‘seasonal’ samples). Additionally, to assess nutrient loads onto irrigated fields, water samples were collected from 2014 to 2015 on a weekly basis during the growing season (May–September) from source TWR system locations used for irrigation (either TWR ditches or OFS reservoirs) (hereafter described as ‘irrigation’ samples). Seasonal samples were collected from A and B locations, and irrigation samples were collected from A or B locations depending on where surface water was being irrigated from (Figure 2).

All samples were collected at consistent locations and were comprised of two, 1 L grab samples collected 0.3 m below the water’s surface 3.7 m from shoreline. One of the two 1 L samples was immediately acid-preserved with 2 ml of 49% sulfuric acid solution for nutrient analyses. Samples were collected, labeled, placed on ice and transported within 24 h according to USEPA QA/QC guidelines (USEPA 2002) to the Mississippi Department of Environmental Quality (MDEQ) laboratory for analyses.

Sample analyses

Samples were analyzed for total suspended solids (TSS) and nutrient concentrations including total phosphorus (TP), total Kjeldahl nitrogen (TKN), nitrate plus nitrite (NO\textsubscript{3}-NO\textsubscript{2}), and ammonium (NH\textsubscript{4}). TSS were determined using method 2540D described in Eaton et al. (1998). Prior to nutrient analyses, samples were filtered using vacuum filtration through a 0.45 μm cellulose nitrate membrane filter (Whatman Co., Dassel, Germany). Following filtration, a LACHAT Flow Injection Analyzer 8500 Series 2 (LACHAT Instrument Co., Loveland, CO) was used to analyze TP, NH\textsubscript{4}\textsuperscript{+} and NO\textsubscript{3}-NO\textsubscript{2} (i.e. NO\textsubscript{x}) according to the standard methods of persulfate digestion, Berthelot reactions, and cadmium reduction, respectively (Eaton et al. 1998). TKN was analyzed using metal catalyzed digestion, distillation, and automated colorimetry (Eaton et al. 1998). Total nitrogen (TN) was calculated as the sum of TKN and NO\textsubscript{3}-NO\textsubscript{2}, and organic nitrogen (ON) was determined as the difference between TKN and NH\textsubscript{4}\textsuperscript{+}.

Water quantity monitoring

Water depth was also monitored in TWR ditches and OFS reservoirs using OTT pressure level sensors (OTT Hydromet Ltd, Germany). Sensors were connected to A755 addWAVE general packet radio service remote transmitting units (ADCON Telemetry, Klosterneuburg, Austria) powered by a Solar Set 4 (ADCON Telemetry). Surface water capture volumes were calculated based on water depth and system dimensions (obtained from local USDA NRCS personnel). For TWR ditches, volume was calculated using a standard trapezoidal geometry, and for OFS, volume was calculated using domain decomposition of four inverted pyramids (corners), four triangular prisms (sides and ends) and a cuboid (center) (Prince Czarnecki et al. 2017). The volume of water used for irrigation was monitored at each location using flow meters installed in the surface water irrigation pipelines (McCrometer, Hemet, California).

Statistical analysis of seasonal samples

All sample analyte concentration non-detects (i.e. results below a methods quantitation limit) were treated with the method described by Hornung & Reed (1990) where one-half of the quantitation limit was equal to 2, 0.01, 0.01, 0.05, and 0.02 mg L\textsuperscript{-1} and substituted for TSS, TP, NO\textsubscript{3}-NO\textsubscript{2}, TKN, and NH\textsubscript{4}, respectively. Statistical analysis for routine samples consisted of a multivariate analysis of variance (MANOVA) to detect differences between site and seasons for each analyte. Dependent variable data for all analytes was found using the Shapiro–Wilks test to be non-normally distributed and was log base-10 transformed to meet MANOVA assumptions. Homogeneity of variances was checked using Levene’s test and found to be not significant (alpha = 0.05). Independent variables consisted of year.
(2012–2015), season, and TWR system body (TWR ditch or OFS reservoir). Site (i.e. farm) was included as a random effect. Samples were pooled by year to see if annual precipitation differences influenced TWR system concentrations. Seasons were defined as winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November). These months were grouped to represent distinctly different phases of agricultural management activity, biological activity, and climatic conditions. Models were run using the ‘manova’ function in R version 3.2.2 Statistical Software (R Development Core Team 2015). A subset of the MANOVA test was used to evaluate differences between seasons. An alpha value of 0.05 was used of MANOVAs and was adjusted for experiment-wise error with multiple comparisons among seasons using a false discovery rate (FDR) technique (Benjamini & Hochberg 1995).

**Quantification of nutrient loads (irrigation samples)**

Nutrient loads irrigated were estimated using two different parameters. The first, available loads recycled (ALR), represents the potential nutrient load within the available surface water for irrigation back onto the landscape and is the total water captured prior to the irrigation season (before May 1) in both the TWR ditch and OFS reservoir, multiplied by the average irrigation season nutrient concentrations from the respective TWR ditch or OFS reservoir irrigation samples by:

\[
\text{Available loads recycled} = \sum_{i=1}^{n} \left( \text{volume of runoff collected} \right) \times \frac{1}{n} \sum_{i=1}^{n} \text{irrigation sample concentration}_i
\]  

(1)

The purpose of calculating ALR is to consider the nutrient recycling potential of the systems, regardless of the amount of irrigation used, which is dependent upon growing season (May–September) precipitation.

The second parameter is the estimated nutrient loads within surface water that were irrigated (ELI) onto the landscape, which represents the nutrient loads producers recycled back onto tillable acreage from irrigating surface water by:

\[
\text{Estimated loads irrigated} = \sum_{i=1}^{n} \left( \text{water irrigated} \right) \times \frac{1}{n} \sum_{i=1}^{n} \text{irrigation sample concentration}_i
\]  

(2)

Water irrigated is multiplied by the average concentration of the irrigation season’s samples (Equation (2)). ALR and ELI were calculated for the 2014 and 2015 growing seasons.

**RESULTS AND DISCUSSION**

**Seasonality of analytes in TWR systems**

Monthly precipitation (Figure 3) estimates were calculated using methods in Dyer (2008) and verified by Dyer (2009). Irrigation volumes (Figure 3) were measured using methods used in Omer (2017). There were differences \( F_{3,18} = 2.09, p < 0.005 \) in analyte concentrations among years (2013–2015); however, pairwise comparisons with FDR adjustment showed no differences \( p < 0.05 \). The \( F \)-test statistic being closer to 1 means no significant difference and the greater the statistic the more significant the result, as well as \( p \) values less than 0.05 showing a significant result. Differences \( F_{3,18} = 12.58, p < 0.0001 \) in concentrations over seasons were observed across all analytes (Figure 4). Mean seasonal analyte concentrations are shown in Figure 4,
with shaded boxes representing the middle 50 percent of the population concentrations, error bars representing standard error, dotted lines representing means, solid lines representing medians, and different letters above boxes representing significant differences between each seasons’ samples (MANOVA, alpha of 0.05 adjusted using FDR technique; $n = 324$). Because the majority of irrigation takes place in the summer season (June, July, and August), availability of nutrients during those months would be advantageous to producers using surface water sources. However, results of
this study show most analyte concentrations were greater in spring than summer ($p < 0.0001$), with the exception of ON ($F_1 = 12.58$, $p < 0.0001$), which increased with the growing season and was greater in summer than in spring (Figure 4). Inorganic nitrogen is assimilated by biota for growth thereby increasing the amount of ON throughout the growing season.

TSS concentrations were greater in spring than in summer ($F_1 = 20.55$, $p < 0.0001$) and in fall than in summer ($F_1 = 8.52$, $p < 0.01$), with mean differences of 0.30 mg L$^{-1}$ and 0.18 mg L$^{-1}$. This study’s observations are similar to those of Carruth et al. (2014), who sampled two TWR systems in the Delta and showed similar numerical results with the greatest concentrations of TSS in the spring to early summer (March to June) then increasing in late fall (October). High suspended solids concentrations are most likely explained by heavy precipitation events resulting in erosion and runoff, many of which occur in the spring in the Delta (Pennington 2004; Baker et al. 2016).

TP concentrations were greater in spring compared with summer ($F_1 = 18.87$, $p < 0.0001$), with mean differences of 0.16 mg L$^{-1}$. TP observed by Carruth et al. (2014) showed relatively steady concentrations, with the exception of a few samples being higher due to winter precipitation events. Likewise, Karki et al. (2015) sampled a TWR system located in east Mississippi and observed the highest TP concentrations in winter and spring. Observations of the highest TP concentrations occurring in winter and spring are similar to the observations of Pennington (2004), Shields et al. (2009), and Baker et al. (2016), who found the greatest TP concentrations in Delta surface waters in spring.

No significant differences ($F_3 = 1.19$, $p > 0.1$) in seasonal TN concentrations in TWR systems were observed. Apart from brief periods when there is flow into the TWR system during a runoff event, TWR systems remain largely stagnant with no loss of sediment or solutes from the system. The lentic nature of TWR systems may result in TWR system N-cycling without increase or decrease in TN, but changes in TN constituents. This study’s results show ON was greater in fall than winter ($F_1 = 16.71$, $p < 0.0001$), spring ($F_1 = 36.81$, $p < 0.0001$), and summer ($F_1 = 8.46$, $p < 0.01$) with the overall average in fall being 0.24 mg L$^{-1}$, 0.19 mg L$^{-1}$ and 0.02 mg L$^{-1}$ greater than in winter, spring, and summer, respectively. Summer concentrations of ON were also greater than in the spring by 0.17 mg L$^{-1}$ ($F_1 = 15.63$, $p < 0.0001$). That ON was greatest in the fall and increased progressively from winter through spring and summer is consistent with the growth of phytoplankton (Wetzel 2000).

Increased concentrations of NH$_4^+$ and NO$_3$NO$_2^-$ in TWR systems in the spring were most likely due to reduced ground cover and increased fertilizer loss following spring applications and precipitation events (Pennington 2004). In addition, increased NH$_4^+$ and NO$_3$NO$_2^-$ concentrations may be a result of lower water temperature and lower solar radiation in winter into spring compared with summer and fall. During the summer and fall seasons NH$_4^+$ and NO$_3$NO$_2^-$ may be readily used and thereby converted into ON. Ammonium concentrations were greater in the spring than summer by 0.24 mg L$^{-1}$ ($F_1 = 17.29$, $p < 0.0001$) and the fall by 0.20 mg L$^{-1}$ ($F_1 = 7.59$, $p < 0.01$). Ammonium concentrations were also greater in the winter than summer by 0.25 mg L$^{-1}$ ($F_1 = 20.15$, $p < 0.0001$) and in the fall by 0.21 mg L$^{-1}$ ($F_1 = 12.39$, $p < 0.001$). In addition to NH$_4^+$, NO$_3$NO$_2^-$ was greater in the spring by 0.35 mg L$^{-1}$ than in the winter ($F_1 = 13.04$, $p < 0.001$), by 0.73 mg L$^{-1}$ than in the summer ($F_1 = 68.44$, $p < 0.0001$) and by 0.91 mg L$^{-1}$ than in the fall ($F_1 = 114.42$, $p < 0.0001$). Numerical observations by Carruth et al. (2014) showed similar results to this study, with the greatest concentrations of NH$_4^+$ and NO$_3$NO$_2^-$ in the spring to early summer (March to June). In addition, Karki et al. (2015) observed the highest NO$_3$ concentrations in the winter and spring (January to March). In this study, fall concentrations of NO$_3$NO$_2^-$ were less than winter ($F_1 = 36.08$, $p < 0.001$) by 0.56 mg L$^{-1}$ and summer ($F_1 = 10.27$, $p < 0.01$) by 0.12 mg L$^{-1}$. Results of this study and Carruth et al. (2014) contrast with Moore et al. (2015), where samples from one TWR system in the Arkansas Delta region numerically showed summer and fall NO$_3$NO$_2^-$ and P nutrient concentrations to be greater than spring concentrations, which may be a result of differing fertilizer application rates and timing in the catchment in which the only irrigated crop was rice.

Analyses between TWR ditches and OFS reservoirs routine samples found greater concentrations in TWR ditches than in OFS reservoirs ($F_{1.6} = 31.43$, $p < 0.0001$), with pairwise comparisons of TSS ($F_1 = 69.19$, $p < 0.0001$), TP ($F_1 = 114.02$, $p < 0.0001$), TN ($F_1 = 4.99$, $p < 0.05$),
NO$_3$NO$_2$ ($F_1 = 19.29$, $p < 0.0001$), and NH$_4^+$ ($F_1 = 28.02$, $p < 0.0001$) with differences of 0.57 mg L$^{-1}$, 0.27 mg L$^{-1}$, 0.06 mg L$^{-1}$, 0.25 mg L$^{-1}$, and 0.18 mg L$^{-1}$, respectively. This was expected because TWR ditches receive nutrient and sediment load directly from fields, while OFS reservoirs are filled slowly with water during and post precipitation events. In addition, water added to OFS reservoirs is diluted by a larger amount of previously stored water. The remaining analyte, ON ($F_1 = 0.02$, $p > 0.05$), showed no differences between TWR ditches and OFS reservoirs.

**Nutrient loads within TWR system water**

Estimated mean TSS, P and N loads available to be irrigated with surface water during the 2014 and 2015 growing seasons are shown in Table 2. Four sites show mixed results due to special circumstances. The first site, System B, during the 2014 and 2015 irrigation seasons required maintenance and therefore no collected surface water was used for irrigation. Other sites including systems E, F, and G were still being built in the spring of 2014 and were unable to save their capacity of surface water prior to the irrigation season on May 1. The majority of TWR systems’ water irrigated exceeded the water available (i.e. the water available in TWR systems prior to May 1 and therefore the irrigation season) due to collection and irrigation of water during the irrigation season after May 1 (Table 2). On average, the seven TWR systems monitored achieved recycling of TSS (325.1 kg ha$^{-1}$), TP (0.86 kg ha$^{-1}$) and TN (7.26 kg ha$^{-1}$) onto the landscape, thereby reducing potential detrimental impacts to receiving waters (Table 2). Mean amounts of available TP (0.86 kg ha$^{-1}$) and TN (7.26 kg ha$^{-1}$) are most likely too low to justify reducing fertilizer application rates. In the Delta, the average elemental P and N application rates for four crop species (soybeans (*Glycine max*), rice (*Oryza sativa*), cotton (*Gossypium spp.*) and corn (*Zea mays*)) during the 2014 and 2015 growing seasons were 22 and 170 kg ha$^{-1}$, respectively (MSU 2014, 2015). The average of these TWR systems could only provide 3.90% and 4.24% of the required P and N for typical crops in the Delta.

<table>
<thead>
<tr>
<th>TWR Description</th>
<th>Year</th>
<th>Water available (m$^3$)</th>
<th>Water irrigated (m$^3$)</th>
<th>Land irrigated (ha)$^a$</th>
<th>TSS (kg ha$^{-1}$)</th>
<th>TP (kg ha$^{-1}$)</th>
<th>TN (kg ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A TWR</td>
<td>2014</td>
<td>75,850</td>
<td>153,210</td>
<td>27.42</td>
<td>217.60</td>
<td>439.50</td>
<td>2.85</td>
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<tr>
<td></td>
<td>2015</td>
<td>83,450</td>
<td>226,020</td>
<td>30.17</td>
<td>505.77</td>
<td>1,369.93</td>
<td>3.70</td>
</tr>
<tr>
<td>B$^b$ TWR &amp; OFS</td>
<td>2014</td>
<td>74,290</td>
<td>0</td>
<td>26.86</td>
<td>87.70</td>
<td>0.00</td>
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<td>75,270</td>
<td>0</td>
<td>27.21</td>
<td>72.89</td>
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<td>3.97</td>
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<td>2014</td>
<td>170,180</td>
<td>114,940</td>
<td>61.53</td>
<td>83.14</td>
<td>56.15</td>
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<td>2015</td>
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<td>198,450</td>
<td>62.14</td>
<td>88.24</td>
<td>101.88</td>
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<td>418.65</td>
<td>637.61</td>
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<td>34,060</td>
<td>65,910</td>
<td>12.31</td>
<td>281.26</td>
<td>527.74</td>
<td>4.12</td>
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<tr>
<td>E TWR &amp; OFS</td>
<td>2014</td>
<td>35,040</td>
<td>52,310</td>
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<td>221.28</td>
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<td>136,510</td>
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<td>Mean (SD)</td>
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<td>94,050</td>
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<td>189.36</td>
<td>325.10</td>
<td>4.15</td>
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<tr>
<td></td>
<td></td>
<td>(53,790) (69,250)</td>
<td>(19.44) (372.70)</td>
<td>(132.01) (372.70)</td>
<td>(0.31) (0.75)</td>
<td>(1.69) (11.09)</td>
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<tr>
<td>Median</td>
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<td>74,780</td>
<td>76,910</td>
<td>27.04</td>
<td>143.14</td>
<td>184.08</td>
<td>3.83</td>
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</tbody>
</table>

SD is standard deviation.

$^a$Land irrigated with available surface water was calculated based on the average surface water applied in the Mississippi Delta during June and July of 2015, which equated 2,770 m$^3$/ha (Yazoo Mississippi Delta Joint Water Management District 2015) and the total amount of water either available or irrigated. For the water available, this assumes that the TWR system is designed to irrigate the water it can store.

$^b$Producer did not irrigate surface water for 2014 and 2015 growing seasons.
When considering the value of nutrients applied to agricultural crops, the form (i.e. species) of N is important to consider. The N species concentrations in irrigation samples from TWR system samples in Figure 5 show the majority of N in the samples was organic in form. The mean percentages of the species of total N present were 77% ON, 19% NO$_3$NO$_2$, and 4% NH$_4$ during the 2014 and 2015 irrigation seasons. Two of the TWR systems D and E, both on farm 4, had a numerically greater amount of NO$_3$NO$_2$ than the other sites due to fertilizer loss and lack of aquatic growth in the systems, which were younger than the other TWR systems. ON is not readily available for uptake by crops (Foth & Ellis 1997). Thus, only an average of 23% of the N in TWR system water is readily available. This means that of the 7.26 kg ha$^{-1}$ N available to be put back onto tillable land, only 1.67 kg ha$^{-1}$ is immediately available for plant assimilation. Based on the average nutrient applications to grow the four dominant crop species in the Delta, only 0.98% plant-available N could be supplied using TWR system water, although ON may become available in the following seasons after further degradation.

CONCLUSIONS

TWR systems in the Mississippi Delta capture surface water and allow for producers to use water for irrigation, thereby irrigating nutrients back onto the agricultural landscape. Nutrients irrigated onto the landscape were not lost to downstream systems. Concentrations of nutrients in TWR system water were highest in spring; however, summer is when the majority of water is irrigated. Mean nutrients available to be irrigated back onto the landscape during the 2014 and 2015 growing seasons were 0.86 kg ha$^{-1}$ P and 7.26 kg ha$^{-1}$ N, with the majority (77%) of N organic in form. However, these application rates being only 3.9% and 0.98% of typical P and N applications to crops in the Delta are most likely too low to justify lowering synthetic fertilizer applications. This study only investigated the potential for nutrient recovery by use of TWR systems. Further investigation is needed to quantify the additional benefits of TWR systems which include, but are not limited to, water quantity conservation and reducing nutrient pollution of receiving waters. In addition, an economic analysis comparing costs to benefits of TWR systems would be beneficial.

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