# Characterizing nitrogen outflow from pre-harvest rice field drain events

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## ARTICLE INFO

## ABSTRACT

Tailwater recovery systems (TWR) provide an excellent testbed for examining nutrient loading from agriculture non-point sources, such as pre-harvest rice (*Oryza sativa* L.) field drains, on receiving waters. In this study, the focus was to use continuous sampling of nitrate–nitrogen ($NO_3^--N$) concentration, paired with discrete grab samples of water which were analyzed for total nitrogen and inorganic nitrogen species to (1) assess if rice paddies are a source of nitrogen loading to downstream systems; (2) monitor the diel cycles in $NO_3^--N$ of rice paddies and TWR; and (3) describe the nitrogen capture capacity of TWR during these events. Five rice paddies within the Mississippi Delta with adjoining TWR were selected as case study locations. Both paddy and TWR were instrumented to continuously monitor nitrate, pH, dissolved oxygen, specific conductivity, and water temperature; discrete grab samples of water were also taken at deployment and collection. During the study, most TWR had total nitrogen concentrations <1 mg L$^{-1}$; the majority of nitrogen present at drain was organic (>51% for paddies, and >88% for TWR). The percent change in total nitrogen concentrations between draining paddies and post-drain TWR ranged from −14 to +178%; the percent of organic nitrogen increased between 5 and 24% in TWR following rice drains. Both nitrogen accumulation and dilution in TWR were observed during drain events. Diel cycles were apparent and were in phase with dissolved oxygen (average values between 3.7 and 13.2 mg L$^{-1}$). The average peak-to-peak amplitude in TWR was 0.101 mg $NO_3^--N$ L$^{-1}$. Total nitrogen captured by TWR ranged from 0.009 to 0.610 kg ha$^{-1}$. Increases in $NO_3^--N$ concentrations were observed in several TWR during drain events, but concentrations remained low and loads were determined to be of little consequence; this suggests limited detrimental impact of rice drains downstream.

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## 1. Introduction

There is growing public awareness of nutrient loading from production agriculture systems. Within the United States alone, over 160,000 km of rivers and streams and over 400,000 ha of lakes, reservoirs, and ponds are impaired by excess nutrients (USEPA, 2014). Excessive nitrate–nitrogen ($NO_3^--N$) in agricultural runoff has been identified as a primary driver for the annual Gulf of Mexico hypoxic zone (Turner and Rabalais, 2003). As such, there remains a need for strategic implementation of scientifically-validated conservation practices within the agriculture landscape. A unique opportunity exists to quantify the ability of tailwater recovery systems (TWR) to mitigate nutrient loading from agriculture non-point sources. Tailwater recovery systems (described under National

Resources Conservation Service practice code 447) are a conservation practice designed to capture surface water runoff and store the captured water for subsequent irrigation; it is anticipated they will additionally capture nutrients leaving the landscape. Tailwater recovery systems, when coupled with rice fields, provide an excellent testbed for examining the impact of rice (*Oryza sativa* L.) field outflows on receiving waters. Typical water levels are greater than 5 cm within the field during the growing season. Prior to harvest, rice fields must be drained, but the fate of downstream water quality resulting from rice drain events has not been investigated fully.

Moreover, studies on conservation practice efficacy typically measure $NO_3^--N$ in agricultural runoff through use of grab samples, resulting in discrete "snapshots" of water quality. Stelzer and Likens (2006) have pointed to problems of bias associated with coarse sampling frequency due to the relationship between dissolved concentration and discharge. *In-situ* equipment, which allows for continuous data collection, can now be utilized and presents a more comprehensive picture of nutrients in field runoff.

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An understanding of diel cycles for $NO_3^-$-N could have implications for development of conservation practices in agriculture catchments (Pellerin et al., 2009). Diel $NO_3^-$-N cycles have been observed in larger aquatic systems including oceans (Johnson et al., 2006), rivers (Heffernan and Cohen, 2010), and streams (Pellerin et al., 2009) but have not yet been investigated in TWR. In this study, the focus was to use continuous sampling of $NO_3^-$-N concentration, paired with discrete samples which were analyzed for total nitrogen and inorganic nitrogen species to (1) assess if rice paddies are a source of nitrogen loading to downstream systems; (2) monitor the diel cycles in $NO_3^-$-N of rice paddies and TWR; and (3) describe the nitrogen capture capacity of TWR during these events.

## 2. Methods and materials

Five rice paddies with adjoining TWR were selected as case study locations within the Mississippi Delta, a region in northwest Mississippi created by alluvial deposition from the Mississippi and other rivers. These case study locations represent multiple areas within the Delta, with one site each in Humphreys, Bolivar, and Tunica Counties, and two sites in Sunflower County. Hectares drained and TWR dimensions were provided by producers and local National Resources Conservation Service personnel (Table 1). Predominant soil type for each catchment area was attained from the United States Department of Agriculture's Web Soil Survey (Table 1). Local weather conditions were obtained from the closest National Resources Conservation Service Soil and Climate Analyses Network and the National Oceanic and Atmospheric Administration's National Climatic Data Center monitoring locations for the dates represented by each study site (Table 2). All paddies in the study have been land leveled, surrounded with elevated berms, and outfitted with slotted pipes with removable riser boards by producers.

For data collection, both paddy and TWR were instrumented with a Submersible Ultraviolet Nitrate Analyzer V2 $NO_3^-$-N meter (Sea-bird Coastal, Bellevue, WA) and a Hydrolab DS5 water quality multiprobe equipped with pH, dissolved oxygen (DO), specific conductivity, and water temperature sensors (Hach Company, Loveland, CO). Nitrate meters were powered with 12 V–12 amp hour batteries, with a solar panel and supply regulator. Nitrate meters were deployed from a floating buoy within TWR; when floating was not possible (occasionally in TWR, but always in paddies), $NO_3^-$-N meters were deployed on a stable mount. Equipment was deployed in each paddy within the rice stand, away from outflow pipes; deployment in TWR was near the thalweg, away from sumps and inflow pipes. Due to the potential for damage from flowing debris, $NO_3^-$-N meters were encased in plastic housing when deployed on a stable mount. The housing did not interfere with optics or wiper function and was open on each end and porous enough on the top and sides to avoid creating a microcosm by allowing adequate flow-through. Several locations in this project are monitored for other research projects and were already instrumented with OTT PLS pressure sensors (OTT Hydromet Ltd., Germany) which provide continuous water depth measurements of TWR. Other TWR which had no such mechanism and rice paddies used Hobo water level loggers (Onset, Bourne, MA), mounted similar to pressure sensors, directly (15.2 cm) above the sediment surface for water depth measurements. Pre-monitoring was done to attain baseline water quality levels and diel patterns of nitrate. All sites were monitored for a 4-to-5 day period prior to drain events.

Immediately prior to drain events, sites were re-instrumented with the same equipment. Nitrate meters and multiprobes (and level loggers, where necessary) were placed only in the TWR for the drain events. It was reasoned that continuous monitoring of paddies during the drain event was not as essential as the ability to monitor two simultaneous drain events; thus only TWR were continually monitored with nitrate meters during drain. However, discrete water samples collected from paddies where instruments had previously been located were assumed to indicate water quality immediately prior to the drain.

Discrete water samples of 250 ml were taken at instrument deployment and collection for both pre-monitoring and drain events. Unfiltered samples were collected and placed on ice before transport to the Water Quality Laboratory at Mississippi State University. Samples were analyzed for total nitrogen with TNT 826 kits (Hach Company, Loveland, CO). Samples were additionally filtered using 0.45-μm Whatman nitrate–cellulose membranes and preserved with sulfuric acid for analysis with a flow injection analyzer (Lachat FIA 8500, HACH, Loveland, CO). The flow injection analyzer was used to determine concentrations of nitrite ($NO_2^-$-N), $NO_x^-$-N ($NO_2^-$-N + $NO_3^-$-N), and ammonia ($NH_3$-N) in water samples. Concentrations of $NO_2^-$-N and $NO_x^-$-N were determined using the cadmium reduction method (QuickChem method 10-107-05-1-B, HACH, Loveland, CO). Nitrate concentrations were derived by subtracting the determined concentrations of $NO_2^-$-N from the determined concentrations on $NO_x^-$-N. Inorganic nitrogen was the summation of $NO_x^-$-N and $NH_3^-$-N. Organic nitrogen was attained by subtracting inorganic nitrogen (FIA) from total nitrogen (TNT kits).

Calculations for water holding and capture capacities were performed by applying dimensionality to depths. It was assumed that rice field would have a uniform flood depth of 10.16 cm (typical flood depth) immediately prior to draining. This depth was multiplied by the total paddy hectares drained into the TWR (reported in Table 1) to obtain the volume of *potential* water captured from fields. This value would represent the maximum volume of water leaving the field during the rice drain. As it may not be the case that a producer drains a field with average or above average flood depths, the volume of *actual* water captured from fields (i.e., the difference in TWR volume post-drain minus TWR volume pre-drain) was also calculated using system dimensions and recorded water depth change in TWRs.

Water holding capacities were coupled with average nutrient concentrations for each location to calculate loads. Multiplying the average total nitrogen concentration by the perceived maximum outflow volume of water (i.e., the potential water captured from field), the potential total nitrogen load was calculated. Additionally, the average total nitrogen concentration was multiplied by the total water holding capacity of the system to obtain the potential nutrient capture capacity of the TWR. These two values help to put the third calculation, representing actual total nitrogen load captured, into perspective. Actual total nitrogen load was calculated as the product of average total nitrogen concentration and actual water captured from fields by the TWR. These values were normalized by hectares drained (as specified in Table 1) for comparison purposes.

Finally, percent differences between system holding capacities for potential and actual total nitrogen load captured were compared to the total nitrogen holding capacity of the TWR to get a sense of the efficiency of each system. Potential efficiencies assume that TWR are empty at the commencement of drain events.

## 3. Results and discussion

### 3.1. Nutrient and dissolved oxygen concentrations

Mississippi rice fertility guidelines suggest split application of nitrogen, one-half to two-thirds prior to initial flooding, with the rest applied mid-season. Typical rates range from 168 to 202 kg

**Table 1**
Site characteristics for each study location.

| Site | Total area of rice paddy drained into tailwater recovery systems (ha) | Tailwater recovery systems holding capacity (ML) | Predominate soil types[a] | Type of rice irrigation |
|---|---|---|---|---|
| Bolivar | 108.9 | 46.9 | Alligator, Dowling, and Sharkey silty clays | Contour levee |
| Humphreys | 70.8 | 32.3 | Alligator clay | Straight levee side inlet |
| Sunflower 1 | 60.7 | 15.2 | Dowling clay, Dundee very fine sandy loam, Forestdale silt clay and Forestdale silty clay loam | Straight levee |
| Sunflower 2 | 106.0 | 31.1 | Dowling clay, Forestdale silt clay loam, and Forestdale fine sandy loam | Straight levee |
| Tunica | 59.5 | 117.2 | Sharkey clay and Sharkey silty clay | Zero-grade |

[a] Source: Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/. Accessed (2/5/2015).

**Table 2**
Precipitation and average ambient air temperature during monitoring periods.

| Site | Timing | Monitoring period[a] | Average temperature (°C) | Cumulative precipitation (cm) |
|---|---|---|---|---|
| Bolivar[b] | Pre-Drain | August 12–15 | 24.1 | 5.0 |
| | Drain | September 1–4 | 26.7 | 1.1 |
| Humphreys[c] | Pre-Drain | August 7–12 | 26.1 | 1.5 |
| | Drain | August 26–September 1 | 26.4 | 2.4 |
| Sunflower 1[b] | Pre-Drain | August 18–22 | 27.5 | 0.3 |
| | Drain | August 26–September 1 | 27.1 | 1.9 |
| Sunflower 2[b] | Pre-Drain | August 22–26 | 28.5 | 0.0 |
| | Drain | September 4–9 | 26.5 | 0.3 |
| Tunica[d] | Pre-Drain | September 1–4 | 27.2 | 1.8 |
| | Drain | October 1–6 | 23.1 | 0.5 |

[a] All dates are from 2014.
[b] NRCS Soil and Climate Analysis Network Station ID 2019 Sandy Ridge.
[c] NRCS Soil and Climate Analysis Network Station ID 2032 Beasley Lake.
[d] NOAA National Climatic Data Center Location Mississippi-Tunica 2N.

**Table 3**
Mean values for nitrogen from discrete water samples taken from paddies and tailwater recovery systems pre-drain and at drain.

| Site | Timing | Total nitrogen (mg L$^{-1}$) | Ammonia[a] (mg L$^{-1}$) | Nitrate[b] (mg L$^{-1}$) | Total inorganic nitrogen[c] (mg L$^{-1}$) | Total organic nitrogen[c] (mg L$^{-1}$) |
|---|---|---|---|---|---|---|
| Bolivar Paddy | Pre-Drain | 0.62 | 0.03 | <MDL[d] | 0.05 (8.06) | 0.57 (91.94) |
| Bolivar TWR | Pre-Drain | 0.91 | 0.09 | 0.08 | 0.17 (18.68) | 0.74 (81.32) |
| Bolivar TWR | Drain | 0.82 | <MDL | 0.05 | 0.05 (6.10) | 0.77 (93.90) |
| Humphreys Paddy | Pre-Drain | 0.50 | 0.07 | <MDL | 0.11 (22.00) | 0.39 (78.00) |
| Humphreys TWR | Pre-Drain | 0.51 | 0.07 | <MDL | 0.09 (17.65) | 0.42 (82.35) |
| Humphreys TWR | Drain | 1.39 | 0.05 | 0.05 | 0.10 (7.19) | 1.29 (92.81) |
| Sunflower 1 Paddy | Pre-Drain | 1.20 | 0.05 | <MDL | 0.08 (6.67) | 1.12 (93.33) |
| Sunflower 1 TWR | Pre-Drain | 0.66 | 0.06 | <MDL | 0.08 (12.12) | 0.58 (87.87) |
| Sunflower 1 TWR | Drain | 0.73 | 0.00 | <MDL | 0.04 (5.48) | 0.69 (94.52) |
| Sunflower 2 Paddy | Pre-Drain | 1.22 | 0.13 | 0.06 | 0.19 (15.57) | 1.03 (84.43) |
| Sunflower 2 TWR | Pre-Drain | 0.79 | 0.02 | <MDL | 0.06 (7.59) | 0.15(28.85) |
| Sunflower 2 TWR | Drain | 0.76 | <MDL | <MDL | 0.02 (2.63) | 0.74 (97.37) |
| Tunica Paddy | Pre-Drain | 0.78 | 0.03 | 0.35 | 0.38 (48.72) | 0.40 (51.28) |
| Tunica TWR | Pre-Drain | 0.52 | 0.04 | 0.11 | 0.15(28.85) | 0.37 (71.15) |
| Tunica TWR | Drain | 0.67 | 0.05 | <MDL | 0.08 (11.94) | 0.59 (88.06) |

[a] NH$_3$-N.
[b] NO$_3$$^-$-N.
[c] Values in parentheses represent percentage of total nitrogen.
[d] Value below minimum detection level, 0.01 mg L$^{-1}$ for ammonia, 0.05 mg L$^{-1}$ for nitrate.

of N ha$^{-1}$ (MSU, 2008). Mid-season applications are generally two months prior to drain. During both pre-drain and drain, with the exception of Humphreys, study TWR had total nitrogen concentrations of less than 1 mg L$^{-1}$ in discrete samples (Table 3); average concentrations of total nitrogen in TWR for the five systems investigated were 0.68 mg L$^{-1}$ for pre-drain and 0.87 mg L$^{-1}$ at drain (standard deviation of 0.17 mg L$^{-1}$ and 0.29 mg L$^{-1}$, respectively). The percent change in total nitrogen concentrations of discrete grab samples between paddy pre-drain and TWR drain ranged from −14 (Tunica) to +178% (Humphreys), with the remaining sites calculated at −39, −38 and +32% (reported in order for Sunflower 1, Sunflower 2, and Bolivar). Shields et al. (2009) found between 1.5 and 2.0 mg L$^{-1}$ total nitrogen and 0.2–0.4 mg NO$_x$$^-$-N L$^{-1}$ (NO$_2$$^-$-N + NO$_3$$^-$-N) in surface water in Mississippi Delta Streams during August, September and October. These findings are also similar to Fernández-Valiente and Quesada (2004) who observed water in Valencian rice paddies to contain an average of 0.12 mg L$^{-1}$ NO$_3$$^-$-N during the months of June, July and September. Average concentrations of total nitrogen in paddies for the five systems investigated were 0.86 mg L$^{-1}$ pre-drain (standard deviation of 0.33 mg L$^{-1}$). Average water temperatures and pH levels observed in continuous data collection from paddies and TWR were conducive to biologic activity and physical processes for nitrogen cycling (Foth and Ellis, 1997) (Table 4). Although temperature and pH were conducive to processes of nitrogen cycling, the majority of nitrogen present in paddies and TWR at drain was organic (>51% for paddies, and >88% for TWR). The percent of organic nitrogen increased between 5 and 24% in TWR following rice drains, with the lowest rate at Sunflower 2 and the highest rate at Tunica. Two locations, Bolivar and Humphreys, increased in NO$_3$$^-$-N concentration, suggesting

**Table 4**
Mean values for nitrogen from continuous water samples taken from paddies and tailwater recovery systems pre-drain and at drain.

| Site | Timing | Nitrate[a] (mg L$^{-1}$) | | | Dissolved oxygen (mg L$^{-1}$) | | | Water temperature (C) | | | pH | | |
|------|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | | Avg | Max | Min | Avg | Max | Min | Avg | Max | Min | Avg | Max | Min |
| Bolivar Paddy | Pre-Drain | 0.13 | 0.154 | 0.001 | 4.0 | 8.6 | 2.6 | 25.4 | 28.5 | 22.6 | 6.6 | 7.2 | 6.1 |
| Bolivar TWR | Pre-Drain | 0.24 | 0.305 | 0.035 | 4.7 | 9.8 | 1.0 | 26.5 | 34.8 | 18.9 | 7.0 | 8.9 | 5.1 |
| Bolivar TWR | Drain | 0.13 | 0.139 | 0.111 | NA[b] | NA | NA | NA | NA | NA | NA | NA | NA |
| Humphreys Paddy | Pre-Drain | NA | NA | NA | 3.7 | 10.7 | 0.9 | 26.2 | 28.8 | 24.2 | 7.1 | 7.3 | 6.9 |
| Humphreys TWR | Pre-drain | 0.11 | 0.140 | 0.033 | 9.7 | 18.8 | 5.1 | 29.8 | 35.3 | 23.4 | 8.0 | 8.6 | 7.0 |
| Humphreys TWR | Drain | 0.18 | 0.257 | 0.152 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Sunflower 1 Paddy | Pre-Drain | 0.11 | 0.121 | 0.051 | 4.7 | 8.6 | 2.0 | 26.9 | 34.5 | 27.9 | 7.1 | 7.5 | 6.8 |
| Sunflower 1 TWR | Pre-Drain | 0.09 | 0.116 | 0.010 | 8.2 | 9.8 | 4.5 | 27.1 | 35.5 | 18.9 | 7.5 | 10.4 | 2.0 |
| Sunflower 1 TWR | Drain | 0.13 | 0.157 | 0.010 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Sunflower 2 Paddy | Pre-Drain | 0.14 | 0.150 | 0.132 | 5.6 | 6.9 | 4.8 | 25.5 | 33.5 | 23.8 | 7.3 | 7.4 | 7.1 |
| Sunflower 2 TWR | Pre-Drain | 0.11 | 0.114 | 0.100 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Sunflower 2 TWR | Drain | 0.15 | 0.165 | 0.077 | 13.2 | 16.9 | 5.6 | 29.6 | 32.7 | 27.2 | 7.7 | 8.0 | 7.1 |
| Tunica Paddy | Pre-Drain | 0.20 | 0.868 | 0.098 | 5.8 | 9.2 | 4.1 | 27.2 | 37.9 | 25.9 | 7.1 | 7.9 | 6.8 |
| Tunica TWR | Pre-Drain | 0.18 | 0.202 | 0.080 | 7.8 | 9.8 | 6.0 | 25.5 | 29.2 | 21.9 | 7.9 | 8.3 | 7.5 |
| Tunica TWR | Drain | 0.18 | 0.204 | 0.197 | 7.0 | 9.6 | 2.55 | 22.5 | 39.4 | 19.1 | 7.8 | 8.3 | 6.5 |

[a] NO$_3^-$-N.
[b] Data not available.

nitrogen accumulation in TWR during draining; while the decrease at the other sites suggests dilution during draining (Table 3). The low levels of NO$_3^-$-N suggest little detrimental impact of rice drains on downstream NO$_3^-$-N. Additionally, with the exception of Humphreys paddy, all TWR and paddies had DO in sufficiently high concentrations (>4 mg L$^{-1}$, the Mississippi Department of Environmental Quality-mandated total maximum daily load lower limit for DO in receiving streams) (Table 4), indicating little detrimental impact of rice drains on downstream DO.

### 3.2. Diel cycles

Diel cycles of nutrient (Fig. 1A–D) and DO were observed over the course of the study with regular patterns apparent within several TWR and rice paddies. Dissolved oxygen data is not available for all sites for the complete duration of the study due to equipment malfunction; a similar problem was incurred on a few occasions with the NO$_3^-$-N meter during pre-drain paddy data collection. Data lost were not crucial, but do represent a limitation in this study in that these data were not available for analysis and comparison.

Two distinct patterns were observed within study locations. A diel cycle, characterized by an increase in NO$_3^-$-N during the day, a late-afternoon peak, and decrease at night (Fig. 1A–C), was observed during pre-drain monitoring at Humphreys TWR, Sunflower 2 TWR, and Bolivar paddy and TWR, and during drain events for Humphreys TWR, Sunflower 2 TWR and Bolivar TWR. This trend has been identified in similar studies on natural systems (Gammons et al., 2011; Harris and Smith, 2009; Harrison et al., 2005; Johnson et al., 2002; Laursen and Seitzinger, 2004; Smith et al., 2009; Warwick, 1986). It is hypothesized this is the result of diurnal changes in delivery from hyporheic zones or diurnal redox cycles. It is possible that anthropogenic disturbances which increase the turbidity (thereby decreasing the photic zone and biologic production) are influencing the system; in a previous study, Laursen and Seitzinger (2004) attributed increased NO$_3^-$-N to turbidity which decreased benthic algal production. The opposite cycle was observed for pre-drain Sunflower 2 paddy, suggesting assimilation by rice plants during the day. These cycles showed diel cycling in NO$_3^-$-N characterized by a decrease during the day and increase at night (Fig. 1D). Previous authors showed evidence of a similar diel nitrate cycle (Brick and Moore, 1996; Burns, 1998; Heffernan and Cohen, 2010; Hessen et al., 1997; Johnson and Tank, 2009; Manny and Wetzel, 1973; Mulholland, 1992; Roberts and Mulholland, 2007; Rusjan and Mikoš, 2010; Scholefield et al., 2005) and suggested that diel patterns of NO$_3^-$-N were due to biological processes such as assimilation by primary producers, with ampli-
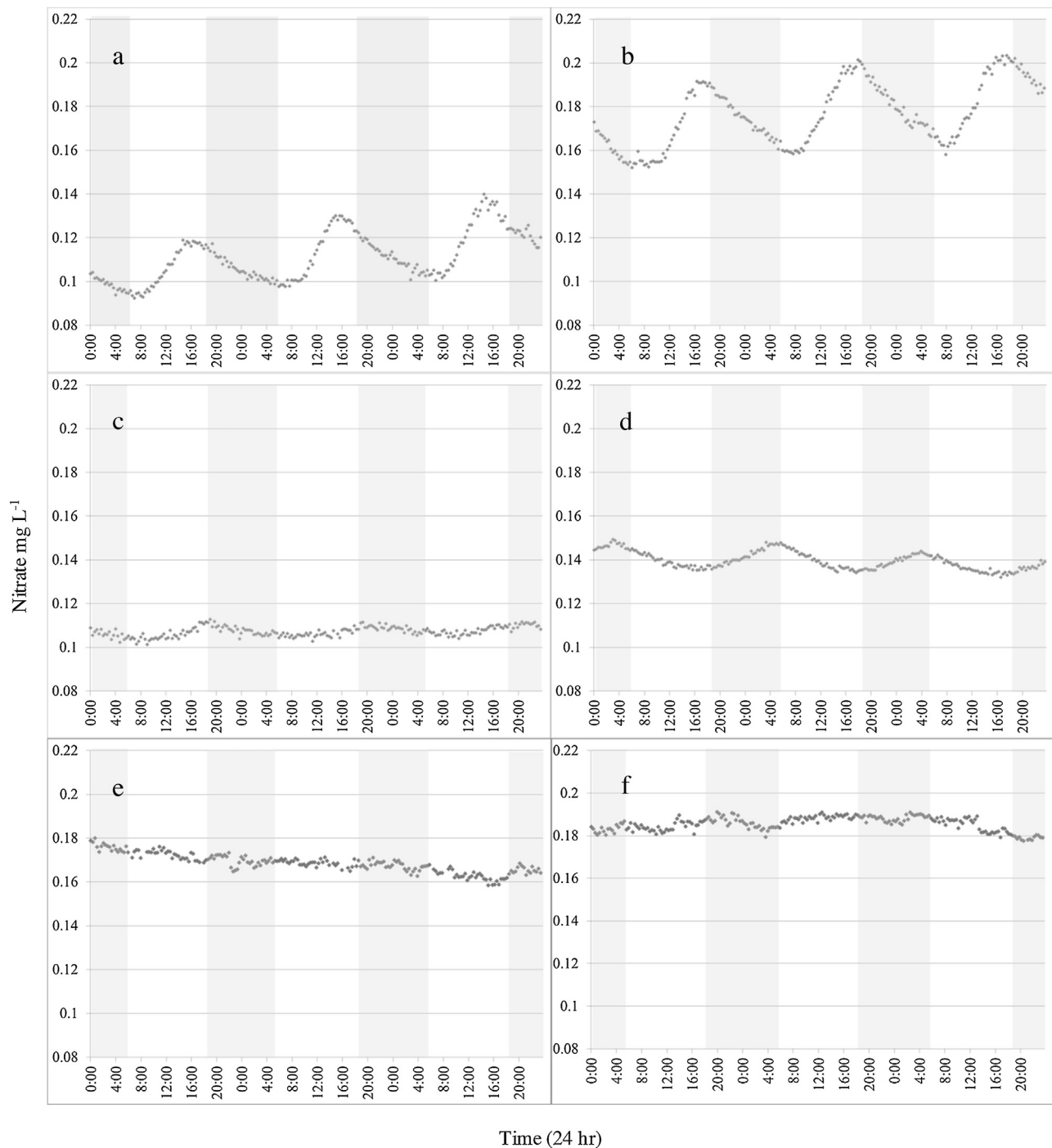
tude dependent on light and temperature (Johnson et al., 2006; Nimick et al., 2011).

In contrast, Pellerin et al. (2009) noted changing nitrate values, but no distinct diel pattern, which was seen in this study for pre-drain Tunica paddy and TWR and Sunflower 1 TWR and drain events for Tunica and Sunflower TWRs (Fig. 1E,F). Pellerin et al. (2009) concluded this was due to anthropogenic activities such as upstream diversions and nutrient loading. An additional observation is that high levels of turbidity (100–20,000 NTU), typical of the Delta region, may alter diel patterns by altering the balance between nitrification and denitrification (Nimick et al., 2011). It should also be noted, immediately prior to draining the Sunflower 1 location, the producer augmented paddy flood waters with pumped groundwater, which may have diluted nitration concentration (because of the increased volume of paddy flood water), concealing patterns.

Stelzer and Likens (2006) and Pellerin et al. (2009) suggest cycles in nitrogen concentrations may decrease accuracy of non-point source pollution assessment and BMP development and analyses. For TWR which showed diel cycles, the average peak-to-peak amplitude was 0.101 mg NO$_3^-$-N L$^{-1}$. Midpoints of wave period coincide with midday or midnight hours. While the shifting values seen in this study do not show great variability from a chemical analysis perspective, for systems which are currently under investigation and may someday fall under regulation, it is important to consider the potential range in nitrate values if discrete samples are used.

### 3.3. Capture capacity

All estimates for capacities are presented in Table 5; it was not possible to calculate capacity estimates for Sunflower 1 due to data limitations. Total nitrogen captured by TWR ranged from 0.009 to 0.610 kg ha$^{-1}$ (Table 5). Low levels of nitrogen outflow from rice paddies have previously been reported in literature. Takeda and Fukushima (2006) observed average outflow of between 10 and 25 kg ha$^{-1}$ yr$^{-1}$ total nitrogen from rice paddies due to irrigation for months of May through September over an 8-year period. A different Japanese study measured average total nitrogen runoff from August to September from 1.0 to 1.2 kg ha$^{-1}$ d$^{-1}$ (Yoshinaga et al., 2007). Comparing the potential loading from rice paddies against the amount of total nitrogen captured indicates efficiency between 2 and 5% of actual to potential total nitrogen captured from fields during rice drains in the current study, with an outlier at Tunica of 77%. The Tunica TWR has considerably more water holding capacity than other sites in the study. Additionally, a wet summer reduced the amount of irrigation during the 2014 growing season (thus

**Fig. 1.** Selected illustrative diel nitrate cycles from (a) Humphreys TWR Pre-Drain (b) Humphreys TWR Drain (c) Sunflower 2 TWR Pre-Drain (d) Sunflower 2 Paddy (e) Tunica TWR Pre-Drain (f) Tunica TWR Drain. Day (white) and night (gray) are determined from sunrise/sunset data from the US Naval Observatory Astronomical Applications Department. Banded zones are approximate; sunrise 05:30, sunset 18:30.

increasing water levels in TWR through both incoming rainfall and decreased pumping from TWR for irrigation); this resulted in TWR with higher water levels than would normally be expected. Tunica TWR was, however, almost empty at the time drain commenced as this water had been used for irrigation as intended. The low water levels in the TWR, combined with the large holding capacity, likely account for the outlier nature of Tunica TWR.

This point applies to all TWR in general. In a dry year, TWR would likely be nearly empty by the fall season (August–October) because of use for irrigation. During a drier year when TWR are empty at drain, potential capacities show the capability to capture between

29 and 194% of recorded total nitrogen outflow from rice drains. The gap between actual and potential nitrogen captured means the nutrient reduction benefit of these systems could be substantially improved by commencing rice drain events with lower water depths within the TWR. If systems are full at drain, the systems would overflow, thus forfeiting anticipated benefits of water quality associated with these systems. Additional capture capacity is available to locations in this study (with the exception of Tunica) within on-farm storage reservoirs, which are often linked to a TWR. In absence of a reservoir however, there is no means by which a producer could reduce the amount of water in the TWR. This could

**Table 5**
Potential and actual water and total nitrogen captured in tailwater recovery systems during rice drain events.

| Site | Depth of water within tailwater recovery system at the onset of drain (m) | Potential water outflow during drain event (ML)[a] | Actual water captured by tailwater recovery system (ML)[a] | Potential total nitrogen load (kg) | Potential total nitrogen captured by tailwater recovery system (kg) | Actual total nitrogen captured by tailwater recovery system (kg) | Normalized nitrogen captured by tailwater recovery system (kg ha$^{-1}$) | Potential nitrogen capture efficiency (%) | Actual nitrogen capture efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|
| Bolivar | 2.13 | 110.6 | 3.0 | 68.6 | 29.1 | 1.8 | 0.017 | 42.4 | 2.7 |
| Humphreys | 0.23 | 72.0 | 1.3 | 36.0 | 16.2 | 0.6 | 0.009 | 44.9 | 1.7 |
| Sunflower 1 | 2.13 | 61.7 | NA[b] | 74.0 | 18.2 | NA | NA | 24.6 | NA |
| Sunflower 2 | 1.30 | 107.7 | 5.8 | 131.4 | 37.9 | 7.1 | 0.067 | 28.9 | 5.4 |
| Tunica | 0.18 | 60.4 | 46.5 | 47.1 | 91.4 | 36.3 | 0.610 | 193.9 | 77.0 |

[a] All values are rounded to the nearest 0.1 ML.
[b] Data not available.

mean in a wet year that the ability to capture nutrient–laden runoff would be diminished.

## 4. Conclusions

*In-situ* monitoring showed advantages over discrete sampling to help assess mechanisms acting on nutrients in these systems, particularly when diel cycles were present. Increases in $NO_3^-$-N concentrations were observed in several tailwater recovery systems during drain events, but concentrations remained low and loads from these events were inconsequential. Much literature supports the ability of rice fields to serve as sinks, rather than sources, for nitrogen; this study suggests limited detrimental nitrogen remains in flood waters to be released to surface waters during drain events. This study provides a glimpse into nitrogen dynamics within tailwater recovery systems. Were this study to be repeated, recommendations would include looking at longer periods of *in-situ* monitoring post-drain to investigate nitrogen fate with increased hydraulic residence time, as well as stratified placement of nitrate probes in tailwater recovery systems for sufficiently deep systems.

## Acknowledgements

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