

ARTICLE

Climatology & Water Management

Alternate wetting and drying reduces aquifer withdrawal in Mississippi rice production systems

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Abstract

Water level declines in the Mississippi River Valley Alluvial Aquifer (MRVAA) are attributed largely to withdrawals for rice (*Oryza sativa* L.) irrigation. This study was performed to determine if alternative irrigation strategies for rice could reduce withdrawal from the MRVAA without having an adverse effect on yield and profitability. Research was conducted at 19 on-farm locations across the Delta region of Mississippi from 2014 through 2016 to determine the effects of irrigation water management practice, i.e., conventional flood via cascade (CONV), multiple side inlet (MSI), and MSI coupled with alternate wetting and drying (AWD), on aquifer withdrawal, rough rice grain yield, irrigation water use efficiency (IWUE), and net returns above irrigation costs. Compared to CONV and MSI, up to 39% less water was applied to AWD ($P < .0001$). Rice grain yield for AWD was not different from either CONV or MSI ($P = .1343$), despite substantial reductions in water use. Relative to standard irrigation strategies, AWD maintained or increased net returns up to \$238 ha⁻¹ for pumping depths from 5.5 m to 122 m and diesel prices from \$0.42 L⁻¹ to \$0.98 L⁻¹ ($P \leq .0003$). Irrigation water use efficiency was up to 59% greater for AWD relative to conventional systems due to the positive effects of the former on water use while maintaining yield ($P = .0034$). These data demonstrate that AWD can reduce withdrawal from the MRVAA while maintaining or improving yield and net returns relative to irrigation strategies currently employed across the midsouthern USA rice belt.

1 | INTRODUCTION

The Mississippi River Valley Alluvial Aquifer is the primary source of water for the irrigation of crops in the midsouth-

ern USA (Massey et al., 2017). For over 50 years, agricultural withdrawal from the MRVAA has exceeded long-term recharge rates, causing a decline in water levels of 0.15 to 0.45 m yr⁻¹ (ARNC, 2019; Massey et al., 2017; Wax, Pote, & Merrell, 2008). Continued reliance on the MRVAA raises concerns regarding the long-term sustainability of irrigated, row-crop agriculture in the midsouthern USA (Wax et al., 2008).

Abbreviations: AWD, alternating wetting and drying; CONV, conventional flood via cascade; IWUE, irrigation water use efficiency; MRVAA, Mississippi River Valley Alluvial Aquifer; MSI, multiple side inlet.

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Rice irrigation accounts for almost half of the agricultural withdrawal from the MRVAA. Irrigated hectareage for major row crops in the Lower Mississippi River Valley includes 590,000 ha rice, 1.6 million ha soybean, 508,000 ha corn, and 342,000 ha cotton (USDA-NASS, 2018a). Per hectare, irrigation applied to rice, soybean, corn, and cotton was determined to be 9200, 2800, 3100, and 1800 m³ ha⁻¹ yr⁻¹, respectively, over a 12-yr period in the Delta region of Mississippi (Massey et al., 2017). Irrigation practices are similar across the midsouthern USA; therefore, the irrigation rates of Massey et al. (2017) are an acceptable estimate for the entire region (Massey, Smith, Adviento-Borbe, Reba, & Avila, 2019). Assuming 90% of row crop irrigation in the Lower Mississippi River Valley is supplied from the MRVAA, estimated withdrawal is approximately 4.9×10^9 m³ yr⁻¹ for rice, 1.4×10^9 m³ yr⁻¹ for corn, 4.0×10^9 m³ yr⁻¹ for soybean, and 0.6×10^9 m³ yr⁻¹ for cotton (Massey et al., 2017; Massey et al., 2019; USDA-NASS, 2018a). Development and implementation of rice production systems that maintain productivity with less applied water per hectare will improve sustainability of the MRVAA.

In the midsouthern USA, rice is grown in a drill seeded, delayed-flood production system on contour-levee and/or precision-leveled straight-levee fields. In contour-levee fields, levees are constructed perpendicular to the native slope (Smith et al., 2007; Street & Bollich, 2002). In straight-levee fields, levees are constructed 50–70 m apart perpendicular to a consistent slope of 0.1–0.2%, while zero grade rice is grown on level basin fields (Mississippi State University, 2008; Smith et al., 2007). On both contour-levee and precision-leveled fields, upland conditions are preserved until approximately 40–45 d after emergence, at which point a 5- to 10-cm flood is established and maintained until two weeks prior to harvest. Water is either cascaded across the field from a single irrigation point source or to multiple paddies simultaneously via disposable lay-flat polyethylene tubing, i.e., multiple side-inlet irrigation (Massey et al., 2017).

The water required to produce rice in the drill seeded, delayed-flood production system is a function of field preparation and irrigation delivery technique. Contour-levee, cascade flood and straight-levee, cascade flood require similar water inputs of 10,371 m³ ha⁻¹ (1,037 mm) and 9,806 m³ ha⁻¹ (981 mm), respectively, but are greater than the 7,950 m³ ha⁻¹ (795 mm) for straight-levee, MSI (Massey et al., 2017). Zero-grade requires 5,738 m³ ha⁻¹ (574 mm), which is less than the previously mentioned field preparation and irrigation delivery techniques (Massey et al., 2017). The majority of rice hectareage in the midsouthern USA is cascade flooded and requires 76% more water than zero-grade systems, which account for only 10% of rice production. Irrigation strategies that reduce the amount of water applied to rice are needed to improve sustainability of the MRVAA.

Core Ideas

- Flood management in rice affects water use and profitability.
- Alternate wetting and drying can decrease total water applied in rice production.
- Alternate wetting and drying maintained or improved rice grain yield and net returns.
- Benefits of alternate wetting and drying increase with well depth and diesel price.

An irrigation management practice for rice that may reduce withdrawal from the MRVAA while maintaining profitability is alternate wetting and drying (Carrijo, Lundy, & Linquist, 2017; Lampayan, Rejesus, Singleton, & Bouman, 2015; Massey, Walker, Anders, Smith, & Avila, 2014). In AWD, the flood is allowed to subside after each irrigation resulting in alternating cycles of saturated and unsaturated soil conditions. Reported benefits of AWD include the potential to reduce greenhouse gas emissions, rice grain arsenic concentrations, and water use, although yield response is variable (LaHue, Chaney, Adviento-Borbe, & Linquist, 2016; Linquist et al., 2018; Nalley, Linquist, Kovacs, & Anders, 2015). Small plot data indicate that AWD can reduce water use in rice by two-fold compared to a conventional flood; however, AWD must be validated at the production scale prior to widespread adoption (Gholson, 2020; Massey et al., 2014). The objectives of this research were to determine the effects of AWD on rice water use, grain yield, IWUE, and net returns above irrigation cost compared to MSI and CONV rice irrigation in the Delta region of Mississippi.

2 | MATERIALS AND METHODS

2.1 | Research location and design

Research was conducted in the Delta region of Mississippi from 2014–2016 on 19 sites, each consisting of three adjacent fields with the same cultivar, soil texture (Soil Survey Staff, 2020), planting date, and management practices (Table 1; Figure 1). Three irrigation treatments, straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, MSI, alternate wetting and drying (AWD), were investigated in this research. Each treatment was randomly assigned to one of the three fields at each location. For the CONV treatment, irrigation was established and maintained via water entering the field in the uppermost paddy and cascaded into subsequent rice paddies by gravity flow through a levee gate set at 10 cm above the soil surface. Under

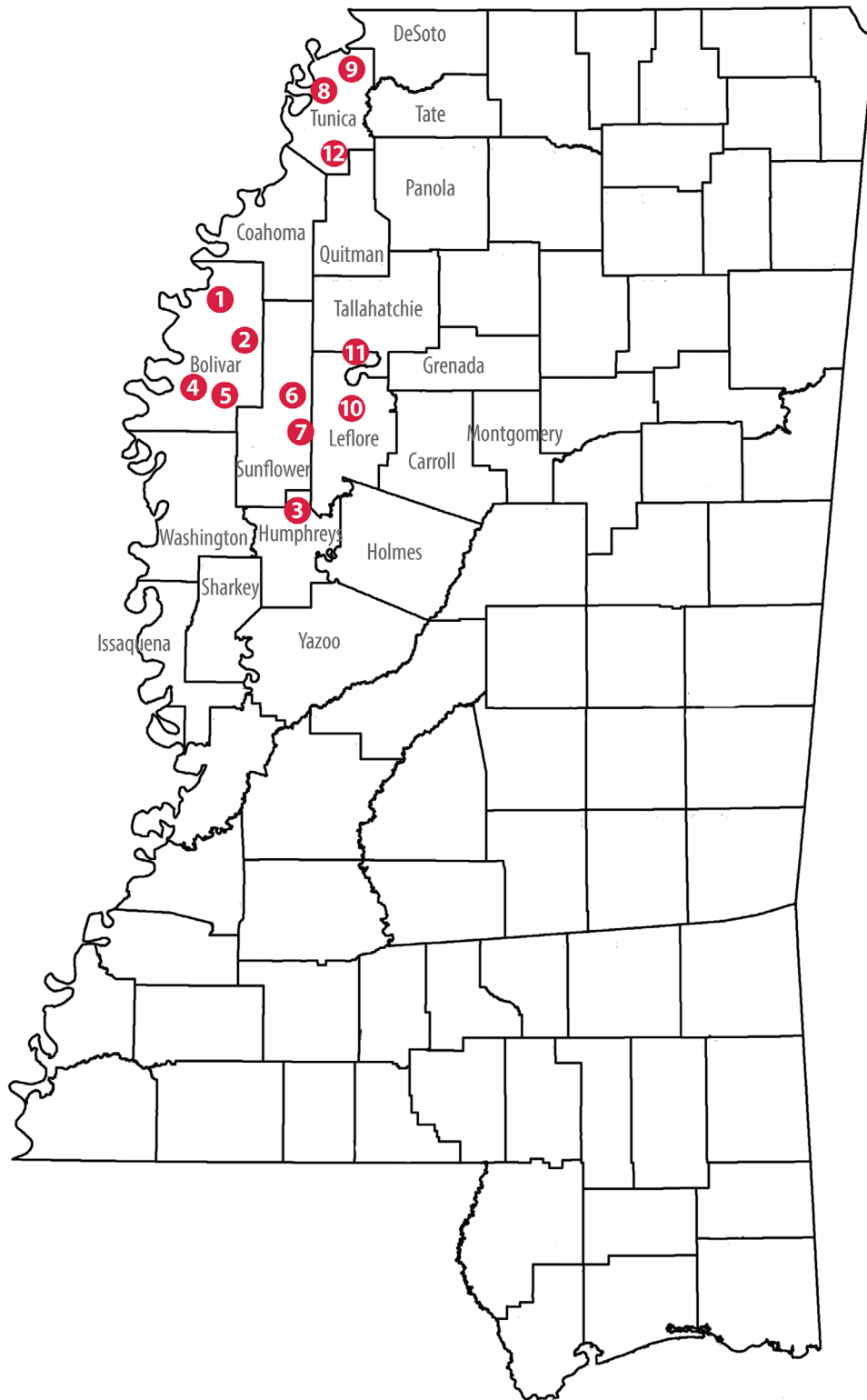


FIGURE 1 On-farm research locations for a study that assessed rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) in the Delta region of Mississippi during the 2014 through 2016 growing seasons

TABLE 1 Year, county, soil texture, and size for fields where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons. Site numbers refer to those shown in Figure 1

Year	Farm	Site no.	County	Soil texture	CONV	MSI	AWD
					ha		
2014	1	1	Bolivar	Silty clay loam	8.9	14.0	24.1
	2	2	Bolivar	Silty clay	14.0	14.5	14.6
	3	3	Humphrey	Clay	16.7	15.0	18.9
2015	1	1	Bolivar	Silty clay loam	10.0	9.6	9.7
	2	4	Bolivar	Silty clay	6.4	8.8	15.8
	3	5	Bolivar	Clay	14.0	18.5	14.2
	4	5	Bolivar	Clay	17.8	15.3	15.0
	5	6	Sunflower	Silty clay	7.2	6.3	7.5
	6	7	Sunflower	Silt loam	16.4	17.9	19.0
	7	8	Tunica	Clay	10.3	8.7	9.3
	8	9	Tunica	Clay	20.0	31.2	33.5
2016	1	4	Bolivar	Clay	29.7	26.5	30.0
	2	5	Bolivar	Clay	42.0	15.8	13.2
	3	5	Bolivar	Clay	20.2	21.6	20.1
	4	1	Bolivar	Silty clay loam	23.8	14.5	15.2
	5	2	Bolivar	Silty clay	11.2	10.0	5.5
	6	10	Leflore	Clay	7.5	14.0	14.4
	7	11	Tallahatchie	Clay	17.0	17.0	17.2
	8	12	Tunica	Clay	30.6	27.4	31.8

MSI irrigation management, a 10-cm flood was maintained by delivering water simultaneously to each paddy via polyethylene tubing placed perpendicular to the levees through the center or along the perimeter of the field. The rate of water distribution to an individual paddy was calculated as described by Thomas, Street, and Tacker (2004):

$$\text{Paddy Flow (L min}^{-1}\text{)} = \frac{\text{Paddy Area (ha)} \times \text{Well Output (L min}^{-1}\text{)}}{\text{Field Size (ha)}}$$

Alternate wetting and drying utilized the MSI delivery technique; however, from three weeks after initial flood establishment to rice flowering, and from the end of rice flowering until two weeks prior to harvest, the flood subsided to 10 cm below the soil surface after each irrigation before the 10-cm flood was reestablished. On average, approximately three drying events per season initiated flood reestablishment, with a range of two to six per season. Throughout rice flowering, a 5- to 10-cm flood was maintained. Paddy water level in fields managed under AWD were monitored with one perforated PVC tube installed in the middle of the rice paddy that was located approximately one-third from the top of the

field (Lampayan et al., 2015). Seepage through levees separating the paddies resulted in field conditions up slope and down slope of the perforated PVC tube to be slightly drier and wetter, respectively, than at the location where water level was monitored. The placement of the water level monitoring tube was selected to reduce the area in which flood abatement exceeded 10 cm below the soil surface, while concurrently allowing the flood to subside in lower paddies.

Prior to flood establishment, a McCrometer flow tube with attached McPropeller bolt-on saddle flowmeter (McCrometer, Hemet, CA) was placed at the inlet of each field to monitor irrigation water applied. Cooperating producers mechanically harvested fields, reported rice grain yield using calibrated onboard yield monitors, and verified the accuracy of reported yields with scale tickets. Rice grain yields were adjusted to 12% moisture content. Irrigation water use efficiency was calculated as described by Vories, Tacker, and Hogan (2005):

$$\text{IWUE} = \frac{Y}{\text{IWA}}$$

where IWUE is irrigation water use efficiency (kg ha-mm⁻¹), Y is rice grain yield (kg ha⁻¹), and IWA is irrigation water applied (mm).

2.2 | Economic analysis

The irrigation costs used in this research incorporated irrigation enterprise budgets developed by utilizing the Mississippi State University Budget Generator. Net returns were calculated as rice grain yield multiplied by rice price, less total specified costs. The rice price was held constant at \$0.27 kg⁻¹, the average price reported by USDA at Greenville, MS for the August, September, and October harvest periods for the 2014, 2015, and 2016 crop years (see Mississippi portal for rice at <https://www.ers.usda.gov/data-products/commodity-costs-and-returns/commodity-costs-and-returns>). Total specified costs varied according to irrigation treatment, diesel price, and well depth.

Total specified costs vary by irrigation treatment because of differences in irrigation delivery technique and water management. For each treatment, irrigation costs are divided into diesel, other direct, and total fixed costs (Table 2; Supplemental Tables S1 and S2). Diesel costs vary among irrigation treatments as a function of fuel costs for pumping. Other direct costs and fixed costs for each irrigation treatment are associated with irrigation set up and application costs (Mississippi State University, 2013, 2014, and 2015). For all treatments, the irrigation set up costs included costs for labor, fuel, repair and maintenance of equipment, supplies and interest associated with surveying and marking levees, building levees, installing gates, removing gates, removing levees, and capital recovery costs associated with land forming, well, pump and engine. Irrigation setup for MSI and AWD also included costs for polyethylene tubing, labor to install and remove the polyethylene tubing, and repair and maintenance costs on machinery associated with installing and removing the polyethylene tubing. Irrigation application costs included irrigation labor to apply water.

Diesel price is a major variable cost associated with pumping, therefore a sensitivity analysis was conducted to evaluate a baseline, high, and low diesel price. The baseline diesel price was \$0.70 L⁻¹, which was the average diesel price used in MSU budgets for 2014, 2015, and 2016 crop years (Mississippi State University, 2013, 2014, 2015). Diesel prices for the high- and low-price scenarios were taken from the USDA Prices Paid Survey for the 2007-2016 timeframe for the Delta States region (USDA-NASS, 2018b). The maximum annual average reported diesel price for the 2007-2016 timeframe of \$0.98 L⁻¹ was used in the high-price scenario, and the lowest price of \$0.42 L⁻¹ was used in the low-price scenario. Diesel prices effect the unit price of diesel, while well depth effects the quantity of diesel used in pumping.

Both total direct and total fixed costs vary according to well depth. Deeper well depths require greater diesel consumption per unit volume of water lifted than shallower well depths, which increases total direct costs for deeper well depths. To evaluate the effect of well depth on net returns, four different

depths were considered: Relift of 5.5 m, standard well depth of 42.6 m, deep well depth of 61 m, and SPARTA depth of 122 m. Irrigation was assumed to be supplied at 590 m³ h⁻¹ for the Relift alternatives, 454 m³ h⁻¹ for the 42.6-m Standard Depth well alternatives, 409 m³ h⁻¹ for the Deep Depth 61-m well alternatives, and 284 m³ h⁻¹ for the Sparta Depth 122-m well alternatives. Total fixed costs vary among water-lifting depths according to pump, well depth, and power unit (Table 2; Bryant et al., 2017). The values for purchase price and fuel consumption are based on personal communications with Mississippi Delta-region irrigation equipment input and service providers. The Relift alternatives utilize a 75-hp tractor as a power unit, with all other alternatives using a 100-hp stationary diesel engine for power.

2.3 | Statistical analysis

All data were subjected to ANOVA using the GLIMMIX procedure of SAS (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, NC). For water use, yield, and IWUE analyses, irrigation treatment was considered a fixed effect with year, farm nested within year, and year × irrigation as random effects. For the analysis of net returns, irrigation treatment and well depth were fixed effects while year, farm, and their interactions with irrigation treatment and well depth were considered random effects. Degrees of freedom were estimated using the Kenward-Roger method (Kenward & Roger, 1997). Least-square means were calculated for all data and differences were considered significant at $\alpha = .05$.

3 | RESULTS AND DISCUSSION

3.1 | General site statistics

During the three-year study (2014–2016), data for comparisons were collected from 19 sets of fields ranging from 5.5 to 42.0 ha (Table 1). Farms in this study were dispersed throughout the Delta region of Mississippi, USA. The soil textures of the experimental units at each location included silt loam, silty clay, silty clay loam, and clay, which represented 5%, 16%, 21%, and 58% of the sites, respectively.

3.2 | Environmental, agronomic, and economic implications for AWD

A central hypothesis of this research was that managing rice under AWD would decrease total water applied while having no adverse effect on yield, IWUE, or net returns

TABLE 2 Estimated irrigation costs per hectare at estimated least square means of water pumped and low, baseline, and high diesel prices for an experiment where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons

Diesel Scenario	Irrigation Method	Cost	Water-lifting depth			
			Relift	Standard well	Deep well	SPARTA
			(5.5 m)	(42.6 m)	(61 m)	(122 m)
\$ ha ⁻¹						
Low diesel ^a	CONV ^b	Diesel	93.27	113.74	125.62	180.95
		Other direct	121.94	108.68	110.51	117.23
		Total fixed	177.00	187.47	192.88	212.77
	MSI	Total specified	392.21	409.90	429.01	510.94
		Diesel	74.94	90.80	100.21	143.88
		Other direct	103.07	93.66	95.49	102.21
		Total fixed	181.55	192.02	197.43	217.31
		Total specified	359.56	376.48	393.13	463.40
		AWD	Diesel	57.72	70.17	77.43
	Other direct		91.54	85.44	87.27	93.98
	Total fixed		181.55	192.02	197.43	217.31
	Total specified		330.81	347.63	362.13	422.39
Baseline diesel	CONV		Diesel	155.07	189.08	208.86
		Other direct	121.94	108.68	110.51	117.23
		Total fixed	177.00	187.47	192.88	212.77
		Total specified	454.01	485.23	512.25	630.84
	MSI	Diesel	124.61	150.94	166.58	239.19
		Other direct	103.07	93.66	95.49	102.21
		Total fixed	181.55	192.02	197.43	217.31
		Total specified	409.23	436.62	459.49	558.71
	AWD	Diesel	95.96	116.66	128.74	184.71
		Other direct	91.54	85.44	87.27	93.98
		Total fixed	181.55	192.02	197.43	217.31
		Total specified	369.04	394.11	413.43	496.00
High diesel	CONV	Diesel	215.68	263.03	290.52	418.47
		Other direct	121.94	108.68	110.51	117.23
		Total fixed	177.00	187.47	192.88	212.77
		Total specified	514.62	559.18	593.91	748.46
	MSI	Diesel	173.32	209.97	231.74	332.71
		Other direct	103.07	93.66	95.49	102.21
		Total fixed	181.55	192.02	197.43	217.31
		Total specified	457.94	495.65	524.65	652.23
	AWD	Diesel	133.48	162.28	179.10	256.95
		Other direct	91.54	85.44	87.27	93.98
		Total fixed	181.55	192.02	197.43	217.31
		Total specified	406.56	439.73	463.79	568.25
	MSI	Total specified	514.62	559.18	593.91	748.46
		Diesel	173.32	209.97	231.74	332.71
		Other direct	103.07	93.66	95.49	102.21
		Total fixed	181.55	192.02	197.43	217.31

^aLow, baseline, and high diesel prices used in the analysis were \$0.42 L⁻¹, \$0.70 L⁻¹, and \$0.98 L⁻¹, respectively.

^bEstimated least square means for water pumped in CONV, MSI, and AWD were 896, 708, and 546 mm, respectively.

TABLE 3 Estimated least square means for rice grain yield, irrigation water applied, and irrigation water use efficiency (IWUE) for an experiment where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons

Irrigation strategy	Yield	Irrigation water applied	Irrigation WUE
	kg ha ⁻¹		
CONV	8,295 ± 1,017 ^a	896 ± 320 a ^b	10.5 ± 4.4 c
MSI	8,482 ± 795	708 ± 233 b	13.2 ± 4.7 b
AWD	8,510 ± 709	546 ± 159 c	16.7 ± 4.7 a
P _r > F	.1343	< .0001	.0034

^aValues shown are the mean ± standard deviation.

^bWithin columns, means followed by the same letter are not significantly different according to LSD (.05).

TABLE 4 Estimated least square means for net returns for four water-lifting depths at a baseline rice price of \$0.27 kg⁻¹ and low, baseline, and high diesel prices of \$0.42, \$0.70, and \$0.98 L⁻¹, respectively, for an experiment where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons

Diesel scenario	Irrigation method	Water-lifting depth			
		Relift (5.5 m)	Standard well (42.6 m)	Deep well (61 m)	SPARTA (122 m)
		– \$ ha ^{–1}			
Low diesel	CONV	1,842 ± 298 b ^{ab}	1,825 ± 300 b	1,805 ± 302 b	1,723 ± 314 b
	MSI	1,925 ± 21 5a	1,909 ± 215 a	1,892 ± 216 a	1,821 ± 219 a
	AWD	1,961 ± 188 a	1,945 ± 188 a	1,930 ± 187 a	1,870 ± 188 a
	<i>P</i> -value	.0003	.0002	.0001	<.0001
Baseline diesel	CONV	1,780 ± 310 b	1,748 ± 314 b	1,722 ± 318 b	1,603 ± 340 c
	MSI	1,875 ± 217 a	1,847 ± 219 a	1,825 ± 220 a	1,726 ± 227 b
	AWD	1,923 ± 187 a	1,897 ± 187 a	1,878 ± 188 a	1,795 ± 189 a
	<i>P</i> -value	<.0001	<.0001	<.0001	<.0001
High diesel	CONV	1,720 ± 322 b	1,676 ± 330 b	1,641 ± 337 c	1,486 ± 369 c
	MSI	1,827 ± 221 a	1,790 ± 223 a	1,760 ± 226 b	1,633 ± 240 b
	AWD	1,886 ± 188 a	1,852 ± 188 a	1,828 ± 189 a	1,724 ± 194 a
	<i>P</i> -value	<.0001	<.0001	<.0001	<.0001

^aValues shown are the mean ± standard deviation.

^bWithin a diesel scenario and water-lifting depth column, means followed by the same letter are not significantly different according to LSD (.05).

relative to CONV and MSI. Managing the flood via AWD in a straight-levee system reduced the amount of water applied 39 and 23% relative to CONV and MSI, respectively ($P < .0001$; Table 3). Relative to a continuous flood, AWD had no adverse effect on rice grain yield ($P = .1343$; Table 3), but increased IWUE up to 58% ($P < .0001$). Alternate wetting and drying management of the flood either maintained or improved net returns relative to standard regional flood management strategies. In comparison to CONV, AWD had greater net returns at all diesel prices and well depths. Net returns for AWD were similar to MSI except at a baseline diesel price of \$0.70 L⁻¹ and well depth of 122 m and a high diesel price of \$0.98 L⁻¹ and well depth ≥ 61 m ($P \leq .0003$; Table 4). Results from this on-farm research affirm that AWD can reduce the amount of

water applied without having an adverse effect on yield, net returns, and IWUE.

The adoption of AWD in the midsouthern USA could reduce total withdrawal from the MRVAA. Similar to the present study, small-plot research indicated that an irrigation threshold of 10 cm below the soil surface reduced consumptive water use in AWD 32% relative to CONV (Gholson, 2020). A threshold of 60 or 40% of saturated volumetric water at 5 cm below the soil surface decreased water use 18 to 44% in AWD compared to a constant flood (Linquist et al., 2015). Converting from a continuous flood to AWD reduced consumptive water use 24 to 71% in Bangladesh, China, Philippines, and Vietnam (Lampayan et al., 2015; Pan et al., 2017). The reduction in water use under AWD irrigation

management is largely due to improved rainfall capture (Massey et al., 2019). Conventional rice flood management constitutes constructing outlets, i.e., levee gates, in each levee to impound water to a depth of 10 cm at the bottom of the paddy. The flood is maintained at 10 cm above the soil surface; therefore, rainfall that increases the water level above 10 cm is lost as surface runoff. Drying events in AWD produce a free-board to capture rainfall, thereby increasing the flood depth without irrigation.

Increased rainfall capture in rice fields managed under AWD in the midsouthern USA should moderate withdrawal on the MRVAA and increase compliance with state-mandated withdrawal limits. Pooled over land formation practice and irrigation delivery technique, $5.4 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ is applied to rice in the midsouthern USA with approximately $4.9 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ originating from the MRVAA (Massey et al., 2019). Data from the present study indicate that adoption of AWD on the landscape would reduce withdrawal from the MRVAA 1.1 to $1.9 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$, contingent on the current proportion of CONV and MSI hectareage. In Mississippi, the permitted well withdrawal limit for rice is 914.4 mm yr^{-1} . Rice managed under AWD never exceeded permitted withdrawal throughout the duration of the study. Conversely, rice irrigation managed under MSI and CONV exceeded 914.4 mm yr^{-1} 31% and 53% of the time, respectively. Alternate wetting and drying in rice production can improve the sustainability of the MRVAA and increase compliance with state laws. However, producers will not adopt AWD if the best management practice adversely effects productivity (Asci, Borisova, & Van Sickle, 2015).

This study suggests that converting from CONV or MSI to AWD will maintain rice grain yield in the midsouthern USA. Similar to this research, intermittent flooding at the small plot and field scale maintained or improved rice grain yield in the midsouthern USA up to 11% relative to CONV (Gholson, 2020; Massey et al., 2014). Moreover, across a range of environments, that is, temperature, humidity, precipitation, soil texture, and farming practices, converting from continuous flooding to AWD maintained or improved yield up to 15% in Bangladesh, Vietnam, and the Philippines (Lampayan et al., 2015). In Arkansas, an AWD threshold of 40% saturated volumetric water at a depth of 5 cm plus a continuous flood from reproductive growth stages through the remainder of the season maintained yield (Linguist et al., 2015). Similar or increased grain yield for rice in AWD systems may be attributed to the compounding effects of reduced “cold water effects” (Mississippi State University, 2008), lower flood depths (Zeng, Lesch, & Grieve, 2003), increased N mineralization (Reddy & Patrick, 1975), and enhanced N uptake relative to CONV (Dillon et al., 2011). Maintaining yield with a corresponding decrease in water application improves efficiency of water use.

Increased IWUE under AWD relative to continuous flood in this study are in accord with research from major rice-growing countries across the world. In China, IWUE was increased up to 81.9% relative to continuous flooding (Xue et al., 2013; Ye et al., 2013). A meta-analysis determined that total water use efficiency, defined as rice grain yield divided by total irrigation and precipitation input, was increased 24.2% in AWD relative to continuous flooding (Carrijo et al., 2017). These data affirm that amount of rice grain yield per unit of water applied is improved under AWD compared to maintaining a flood.

Alternate wetting and drying management of rice irrigation either maintains or improves net returns relative to standard regional flood management strategies. For pumping depths ranging from 5.5 m to 122 m and diesel prices ranging from $\$0.42 \text{ L}^{-1}$ to $\$0.98 \text{ L}^{-1}$, managing rice under AWD increased net returns $\$119 \text{ ha}^{-1}$ to $\$238 \text{ ha}^{-1}$ relative to CONV. Net returns under AWD were not different than MSI except at a baseline diesel price of $\$0.70 \text{ L}^{-1}$ and well depth of 122 m and a high diesel price of $\$0.98 \text{ L}^{-1}$ and well depth $\geq 61 \text{ m}$. Thus, the advantage of AWD increased as the variable costs of pumping increased. The full results are presented in Table 4. These findings are consistent with research in Vietnam, the Philippines, and Bangladesh, which report increases in farm-level income up to 17, 32, and 38%, respectively, for AWD-managed rice compared to conventional water management (Lampayan et al., 2015). Small-plot research in the midsouthern USA also demonstrated that profitability is either maintained or improved by converting from a constant-flood rice production system to AWD (Gholson, 2020; Nalley et al., 2015).

The decrease in diesel, repair and maintenance, and labor costs were the major contributing factors to greater net returns under AWD. Total water applied was 23 and 39% less in AWD than MSI and CONV, respectively, which directly influences the cost of diesel associated with pumping that water. At the baseline diesel price of $\$0.70 \text{ L}^{-1}$ and well depths from 5.5 m to 122 m, diesel costs for AWD were $\$59.11 \text{ ha}^{-1}$ to $\$116.14 \text{ ha}^{-1}$ less than CONV and $\$28.65 \text{ ha}^{-1}$ to $\$54.48 \text{ ha}^{-1}$ less than MSI (Table 2). As depth to water and diesel price increase, the economic advantage of pumping less water is magnified. Relatedly, less water translates to lower repair and maintenance costs on water-lifting equipment. Although both AWD and MSI have greater fixed expenses associated with laying and removing polyethylene tubing, labor requirements are less for these two systems compared to CONV. Decreased pumping and labor costs of AWD compared to CONV offset the greater fixed costs. These decreased costs and the maintenance of yield result in greater net returns under AWD than CONV for all scenarios examined. The pumping cost savings under AWD resulted in greater net returns than MSI when diesel price and well depth were high. Because AWD does

not have an adverse effect on yield or profitability, midsouthern USA producers are more likely to adopt this technology (Asci et al., 2015).

4 | CONCLUSIONS

This research was conducted to determine if AWD irrigation in rice can reduce withdrawal from the MRVAA without having an adverse effect on yield or profitability at the field-scale. Intermittent flooding decreased total water use while maintaining or improving rice grain yield and profitability relative to a traditional, continuous flood. Alternate wetting and drying is one of the most promising, current water-saving practices in midsouthern USA rice production. Potential barriers to adoption include a perceived negative effect of AWD on yield, profitability, nitrogen use efficiency, and weed control; however, this research demonstrates that properly managed AWD can improve the sustainability of the MRVAA while preserving or enhancing on-farm profitability.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Atwill RL, Krutz LJ, Bond JA, et al. Alternate wetting and drying reduces aquifer withdrawal in Mississippi rice production systems. *Agronomy Journal*. 2020;112:5115–5124. <https://doi.org/10.1002/agj2.20447>