Published online August 17, 2017

Surge Irrigation Reduces Irrigation Requirements for Soybean on Smectitic Clay-Textured Soils

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Abstract

The Mississippi River Valley Alluvial Aquifer is declining precipitously due to irrigation withdrawal for row crop production. Currently, 25% of the soybean (*Glycine max* L.) acres in the Mid-South are planted on clay-textured soils and furrow-irrigated using conventional continuous flow (CONV), the least efficient irrigation delivery system. The objective of this research was to determine the effect of surge irrigation (SURGE) on amount of water applied, soybean grain yield, irrigation water use efficiency (IWUE), and net return above irrigation costs when implemented on clay-textured soils. The research was conducted during the 2013 through 2015 growing seasons in Stoneville, MS and consisted of paired fields, with the same cultivar, soil texture, planting date, and management practices used on both sites. Paired fields were randomly assigned as SURGE or CONV. Water applied to each field was monitored with flowmeters, and irrigations were initiated based on soil moisture sensor thresholds. Relative to CONV, SURGE reduced the amount of water applied per irrigation event by 22% and total water applied in season by 24% ($P \leq 0.0349$). Soybean grain yield averaged 66 bu/acre and was not different between delivery systems ($P = 0.7711$), but SURGE increased IWUE by 29% compared with CONV ($P = 0.0076$). Net return above irrigation cost was not different between CONV and SURGE, regardless of diesel price or pumping depth ($P \geq 0.1149$). Results from this research indicate that soybean producers in the Mid-South and other regions that irrigate using lay-flat polyethylene tubing can adopt SURGE for soybean on clay-textured soils without adversely affecting yield or on-farm profitability while concurrently decreasing the demand on depleted groundwater resources.

The number of permitted agricultural wells and subsequent water withdrawals from the Mississippi River Valley Alluvial Aquifer (MRVAA) have increased from 2,823 in 1987 to 19,410 in 2015, a 6.8-fold increase (Sam Mabry, personal communication, 2017). In Arkansas County, Arkansas, withdrawals increased from 133 million gal d^{-1} in 1965 to 581 million gal d^{-1} in 2000, a 396% expansion (Halberg and Stephens, 1966; USDA/NASS, 2013). Agricultural withdrawal from MRVAA exceeds the aquifer's recharge rate, thereby causing a decline in groundwater levels (Guzman et al., 2014). The Mississippi Department of Environmental Quality has responded to declining MRVAA levels by requiring withdrawal

Crop Management

Core Ideas

- Surge irrigation reduced the amount of water applied per irrigation event by 22%
- Surge irrigation reduced the total amount of seasonal irrigation water application by 24%
- Surge irrigation increased irrigation water use efficiency by 29%

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Received 3 Apr. 2017.
Accepted 5 July 2017.

Abbreviations: COMV, continuous flow; IWUE, irrigation water use efficiency; MRVAA, Mississippi River Valley Alluvial Aquifer; SURGE, surge irrigation

Conversions: For unit conversions relevant to this article, see Table A.

Published in Crop Forage Turfgrass Manage. Volume 3. doi:10.2134/cftm2017.04.0026

Table A. Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
3.8	gallons per minute, gpm	liters per minute, lpm
2.54	inch	centimeter, cm
0.405	acre, ac	hectare, ha
10.2616	Acre-inch, ac-in	Hectare-millimeter, ha/mm
67.25	Bushels/acre, bu/acre	Kilograms/hectare, kg/ha
6.535	Bushels/acre-inch, bu/acre-in	Kilograms/hectare-millimeter, kg/ha-mm

permits, implementing maximum allowable permitted withdrawal values, and mandating that prescribed irrigation water management (IWM) practices be implemented on permitted wells.

Conventional continuous flow furrow irrigation (CONV) is the predominant delivery system used for soybean grown on clay-textured soils across the Mid-South. Practitioners of CONV utilize lay-flat polyethylene tubing, which is attached to the well or riser and then laid perpendicular to the furrows at the upper end of the field. Holes are punctured in the tubing to facilitate the continuous flow of water down each furrow. The method quickly moves water over large amounts of land, but application efficiency with CONV is only 55% (Israeli, 1988). Poor irrigation application efficiency with CONV on clay-textured soils is attributed to deep percolation losses (infiltration exceeds irrigation requirements), tail-water runoff (surface runoff from irrigation), and slow wetting front advance time (Goldhamer et al., 1987; Varlev et al., 1995; Eid et al., 1999; Matter, 2001). Currently, CONV-irrigated soybean planted on clay-textured soils (2:1 shrink-swell capacity) accounts for approximately 25% of the Mid-South's irrigated acres (Heatherly et al., 2002, USDA-NASS, 2015). Improving irrigation application efficiencies on clay-textured soils will reduce the amount of water withdrawn from MRVAA, which is imperative if furrow irrigation in the Mid-South is to continue.

Surge irrigation (SURGE) is a technique that may improve furrow irrigation application efficiency on clay-textured soils. During SURGE, water is applied intermittently to furrows in a series of relatively short, on and off time periods (Bryant et al., 2017). During the advance phase, water is cycled "on" and "off" to different portions of the field such that the water front advances progressively down the furrow. During the "off" cycle, water supplied to the first portion infiltrates into the soil profile while water is being applied to the second portion of the field. Water applied during a following "on" cycle advances rapidly across the wetted soil due to reduced infiltration rate. Once the water has reached the end of the furrow, a soak phase is utilized to reduce runoff by using shorter "on" cycles, allowing the field to be irrigated to the desired depth. The intermittent application of water with SURGE on clay-textured soils reduces infiltration and deep percolation losses, increases furrow advance time, decreases total irrigation water applied, and improves irrigation application efficiency (Goldhamer et al., 1986; Israeli, 1988; Musick et al., 1987; Eid et al., 1999; Testezlaf et al., 1987; Bishop et al., 1981; Izuno et al., 1985). Surge flow irrigation has not been evaluated on clay-textured soils in the Mid-South. The objective of this research was to determine the effect of SURGE on the amount of irrigation water applied, soybean grain yield, irrigation water use efficiency (IWUE), and net return above irrigation cost when implemented on clay-textured soils.

Site Description and Experimental Design

The study was conducted at the Delta Research and Extension Center in Stoneville, MS on Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts) during the 2013 through 2015 growing seasons. Experimental design was a randomized complete block with two treatments and six blocks. Blocks consisted of two fields in 3 yr, for a total of six fields each containing both treatments. The Sharkey series consists of very deep, poorly and very poorly drained, very slowly permeable soils that formed in clayey alluvium with a maximum rooting depth of 4 ft (Soil Survey Staff, 2017). The research consisted of paired fields, with the same cultivar, planting date, and management practices in each field. All paired fields were planted at 140,000 seed acre^{-1} on 40-inch raised seed beds. Paired fields were randomly assigned with one being CONV and the other as SURGE (Table 1). All fields were managed for weed and insect pests according to Mississippi State University Extension Service recommendations.

Computerized Hole Selection and Surge Flow Irrigation

Lay-flat polyethylene tubing (Delta Plastics, Little Rock, AR) was utilized for the experiment. For Field 1 in 2013 and 2014, 15-inch by 9-mil lay-flat polyethylene tubing was used. For all other year and field combinations, 12-inch by 9-mil lay-flat polyethylene tubing was evaluated. Computerized hole selection was used on both CONV and SURGE fields (Kebede et al., 2014). Input parameters for computerized hole selection include accurate elevation of the crown profile, that is, the location where lay-flat polyethylene tubing will be installed, accurate water output (gpm), furrow spacing (ft), furrow length (ft), diameter of lay-flat polyethylene tubing, furrow flow rate (gpm) required for soil to be effectively irrigated, and wall thickness (mils) and allowable pressure (ft of head) of selected lay-flat polyethylene tubing (Kebede et al., 2014). Flow rate at the field inlet was determined with a McCrometer flow tube with attached McPropeller bolt-on saddle flowmeter (McCrometer

Table 1. Fields used in the research located at the Delta Research and Extension Center in Stoneville, MS, comparing surge flow irrigation (SURGE) with conventional flow irrigation (CONV) of soybean grown on clay-textured soils during the 2013 through 2015 growing seasons.

Year	Field	Variety	Tillage practice	Previous crop	Max furrow length (ft)	Field size (acre)	
						Irrigation method	
						CONV	SURGE
2013	1	HBK LL4850	Fall/Reduced Till	Soybean	540	18.0	18.0
2013	2	HBK LL4850	Fall/Reduced Till	Rice	900	15.0	15.0
2014	1	Halo 4:65	Fall/Reduced Till	Soybean	540	14.2	14.2
2014	2	P 45T77	Fall/Reduced Till	Rice	1,600	7.8	6.7
2015	1	HBK LL4950	Fall/Reduced Till	Rice	1,600	6.3	7.6
2015	2	HBK LL4950	Fall/Reduced Till	Rice	1,800	4.5	9.0

Inc., Hemet, California). Crown elevation was measured every 100 ft with a Topcon® self-leveling slope matching rotary laser level (Topcon Positioning Systems Inc., Livermore, CA), while furrow and distance along the irrigation pipeline were determined from aerial imagery. Furrow spacing was determined as the width between planted rows. Computerized hole selection was calculated with the Pipe Hole And Universal Crown Evaluation Tool (PHAUCET) version 8.2.20 (USDA-NRCS, Washington, DC). Surge flow irrigation was applied with a P&R STAR surge valve (P&R Surge Systems, Inc., Lubbock, TX). Four advance phases were utilized, and soak cycles were eliminated. This was done due to the soil being a 2:1 cracking clay soil and the desired irrigation application amount was achieved by the completion of the advance cycles.

Irrigation Scheduling

Irrigation was applied when the average soil water potential in the 0- to- 24-inch rooting depth was between –75 and –100 cbar as measured by Watermark Model 200SS soil water potential sensors (Irrometer Company Inc., Riverside, CA), installed at 6, 12, and 24-inch depths. Irrigation events were considered complete when water reached the end of 90% of the furrows. Irrigation was terminated at the R6.5 growth stage as recommended by the Mississippi State University Extension Service. Treatments were mechanically harvested at physiological maturity and yields determined with a calibrated yield monitor (Ag Leader Technology, Ames, IA). Irrigation water use efficiency was calculated as described by Vories et al. (2005):

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

where IWUE is irrigation water use efficiency (bu/acre-inch), Y is soybean grain yield (bu/acre), and IWA is irrigation water applied (acre-inch).

Economic Analysis

The model used to estimate irrigation costs in this research incorporates irrigation enterprise budgets developed utilizing the Mississippi State University Budget Generator for CONV and SURGE technologies at four different well depths: a stationary relift system for surface water with 18 ft maximum vertical pipe, "standard" well of 140 ft, "deep" well of 200 ft, and "SPARTA" well of 400 ft. As reported by Bryant et al. (2001) and Vories et al. (2005), the standard and deep wells refer to the alluvial aquifer found throughout the Mid-South while the 400-ft well is representative of wells in the Sparta aquifer, which underlies the MRVAA. The model develops estimates of total receipts, total direct expenses, total fixed expenses, total specified expenses, and net returns above total specified expenses on a per acre basis. The cost estimates are adjusted on an annual basis for the 2013, 2014, and 2015 crop years for changes in variable input costs other than diesel prices. Diesel costs are estimated for each observation based on the amount of water pumped at a baseline diesel cost of $2.83/gal, the average price used in developing Mississippi State University budgets for the 2013, 2014, and 2015 crop years (Mississippi State University, 2012, 2013, 2014). Soybean prices are held constant across all scenarios at $11.11 per bushel, the average price reported by USDA at Greenville, MS for the August, September, and October harvest time period for the 2013, 2014, and 2015 crop years (Mississippi Department of Agriculture-USDA Market News, 2017). To test the sensitivity of both technologies to differences in the major variable costs associated with pumping, a high diesel price and a low diesel price were evaluated. Prices for the scenarios were taken from the USDA Prices Paid Survey for the 2006–2015 timeframe for the Delta States region. The maximum annual average reported diesel price for the 2006–2015 timeframe of $3.70/gal is used in the high diesel price scenario, and the lowest price of $1.6/gal is used in the low diesel price scenario.

Assumptions related to equipment utilized in each enterprise budget are reported in Table 2. 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 alternative utilizes a 75 hp tractor as a power unit, with all other alternatives using a 100 hp stationary diesel engine for power. Irrigation water is assumed to be supplied at 2600 gal/min (gpm) for the RELIFT alternatives, 2000 gpm for the 140-ft standard depth well alternative, 1800 gpm for the 200-ft well alternative, and 1250 gpm for the 400-ft well alternative.

Table 2. Estimated purchase price, annual use, useful life, and fuel consumption rate for fixed items used in irrigation cost calculations.

Item name	Unit of measure	Purchase price (Dollars)	Useful life (Years)	Fuel use (gal/h)
Land Forming	Acre	450	25	N/A
Surge Valve–10″	Each	3,483	10	N/A
Pipe Elbows	Each	127	20	N/A
Soil Moisture Sensors	Each	39	3	N/A
Irrometer Datalogger (Package)	Each	450	10	N/A
RELIFT Tractor-75 Hp	Each	21,113	10	3.86
Engine-100 Hp	Each	20,000	20	3.6
RELIFT Pump	Each	6,670	25	N/A
Well and Pump-140 ft	Each	20,250	25	N/A
Well and Pump-200 ft	Each	25,150	25	N/A
Well and Pump-400 ft	Each	43,150	25	N/A

Table 3. Irrigation water applied per event, total irrigation water applied in season, soybean grain yield, and irrigation water use efficiency results from research comparing surge flow irrigation (SURGE) with conventional flow irrigation (CONV) of soybean on clay-textured soils at Stoneville, MS during the 2013 through 2015 growing seasons.

Parameter	Least square mean value		P value
	Irrigation method		
	CONV	SURGE	
Irrigation Water Applied per event (acre-inch)	3.98 (0.21)†	3.11 (0.16)	0.0285
Irrigation Water Applied in Season (acre-inch)	6.25 (1.36)	4.75 (1.14)	0.0349
Soybean Grain Yield (bu/acre)	66.3 (1.02)	66.2 (1.16)	0.7711
Irrigation Water Use Efficiency (bu/acre-inch)	14.0 (3.31)	18.0 (3.85)	0.0076

†Standard deviation

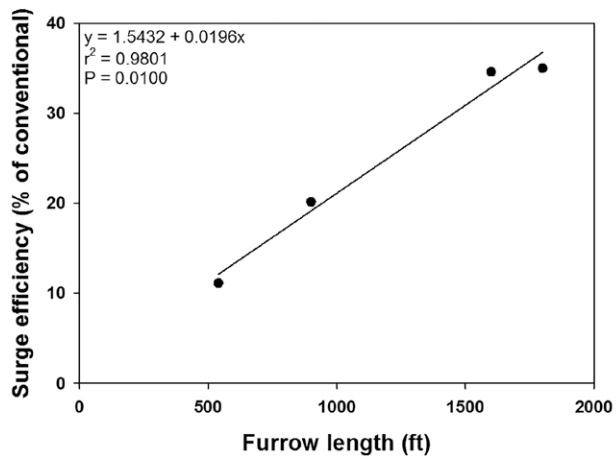

Fig. 1. Surge flow irrigation efficiency on clay-textured soils as a function of furrow length.

Statistical Analysis

Using a general linear mixed model (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, North Carolina), a preliminary analysis was performed to evaluate the year and field interactions with treatment as an error term. Year, field(year), and year×irrigation method were random effects with residual measuring field×irrigation method within year. Based on 95% confidence interval about year×irrigation method covariance estimate, this affect was combined with residual error for final analysis of variance. For total irrigation water applied, soybean grain yield, IWUE, and net return above irrigation costs, year and field(year) served as random effects. For irrigation water applied per event, there were up to three events for each irrigation method. Analysis of variance was conducted for irrigation water applied per event as repeated measures with field×year×irrigation method as a subunit. Degrees of freedom were estimated using the Kenward-Roger method. Means were separated using the LSMEANS statement. Differences were considered significant for $\alpha = 0.05$.

Irrigation Water Applied

Surge flow irrigation had a significant effect on irrigation water applied per event and total irrigation applied in season ($P \leq 0.0349$). Water applied per SURGE event and total water applied with SURGE in season was reduced by 22 and 24%, respectively, as compared with CONV (Table 3). Others reported that SURGE on clay-textured soils reduced total irrigation water use 31 to 80% (Izuno et al., 1985; Testezlaf et al., 1987; Musick et al., 1987; Rodriguez et al., 2004). Additionally, linear regression analysis indicated that 98% of the variability in the percent reduction in irrigation water applied by SURGE was a function of furrow length (Fig. 1). Water savings with SURGE compared with CONV increased by 2% per 100 ft as row length increased from 540 to 1800 ft. Advantages of SURGE extend beyond reduced irrigation water use in soybean on clay-textured soils. At the farm scale, improved irrigation application efficiency provided by SURGE on clay-textured soils reduces the time required for a well to be committed to an irrigation set. Surge irrigation improves on-farm irrigation capacity, thereby allowing additional acres to be irrigated by a single well in a more timely manner. Improved timeliness of irrigation reduces the potential for yield loss associated with drought stress. Additionally, water savings attributed to SURGE are scalable and have regional implications. The overdraft on the MRVAA in the Delta region of Mississippi is 300,000 acre-ft/yr (Wax et al., 2009). These data suggest that 25% of the agricultural overdraft in the Delta of Mississippi will be eliminated if SURGE is implemented on CONV soybean grown on clay-textured soils.

Soybean Grain Yield and Irrigation Water Use Efficiency

The principal hypothesis of this research was that SURGE will have no adverse effect on soybean grain yield, but that the technique will improve irrigation application efficiency,

Table 4. Estimated irrigation costs per acre by system for conventional continuous flow irrigation (CONV) and surge flow irrigation (SURGE) at average quantities of water pumped and baseline diesel prices.

Estimated costs per acre for CONV technology for 6.25 acre-inches water and $2.83/gal diesel price.					
Water lift depth	Diesel	Other direct	Total direct	Total fixed	Total specified
18 ft	13.65	21.55	35.20	54.98	90.18
140 ft	16.24	21.76	38.00	59.22	97.22
200 ft	17.75	22.52	40.27	61.41	101.68
400 ft	24.76	25.39	50.15	69.46	119.61
Estimated costs per acre for SURGE technology for 4.75 acre-inches water and $2.83/gal diesel price.					
Water lift depth	Diesel	Other direct	Total direct	Total fixed	Total specified
18 ft	10.81	24.30	35.11	59.86	94.97
140 ft	12.78	24.51	37.29	64.10	101.39
200 ft	13.92	25.27	39.19	66.29	105.48
400 ft	19.25	28.14	47.39	74.34	121.73

and subsequently, IWUE. Pooled over site years, soybean grain yield averaged 66 bu/acre and was not different between SURGE and CONV (P = 0.7711, Table 3). As theorized, SURGE improved IWUE 29% relative to CONV (P = 0.0076; Table 3). Others noted that on clay-textured soils, grain yields were either not affected by SURGE or were reduced up to 12% (Onder, 1994; Kanber et al., 2001; Goldhamer et al., 1987; Musick et al., 1987). Many researchers, however, report that SURGE on clay-textured soils increased IWUE up to 19% relative to the control (Izuno and Podmore, 1986; Unlu et al., 2007; Okasha et al., 2013). These data indicate that SURGE will improve IWUE on clay-textured soils throughout the Mid-South while maintaining soybean grain yield equivalent to that of CONV.

Economic Return

The estimated irrigation costs per acre calculated at the average acre inches of water pumped at the baseline diesel price of $2.83/gal for the CONV (6.25 acre-inches) and SURGE (4.75 acre-inches) technologies are reported in Table 4. The higher values for the “other direct” under SURGE are attributed to the extra cost associated with transfer pipe and surge valve batteries. The higher values for the “total fixed” values for SURGE are attributed to the capital recovery cost for the surge valves and elbows. As would be expected, the advantage of CONV in lower total specified cost declines as the depth that water is being lifted increases. A premise of this research was that water savings afforded by SURGE would compensate for the additional costs required to implement the technology, regardless of fuel price or pumping depth. Estimated least square means for net returns above total specified irrigation costs for CONV and SURGE at the baseline soybean price of $11.11/bu and baseline diesel price of $2.83/gal, high diesel price of $3.70/gal, and low diesel price of $1.60/gal are reported in Tables 5, 6, and 7, respectively. As theorized, regardless of diesel fuel cost or pumping depth, net returns above irrigation costs were not different between CONV and SURGE ($P \geq 0.1149$). These data confirm that the additional costs associated with the purchase of surge valves, elbows, transfer pipe, and batteries are offset by reduced water use, regardless of the pumping depth or diesel cost. These results indicate that producers may profitably adopt SURGE irrigation of soybean grown on Sharkey clay soil, a dominant soil in the Mississippi Delta.

Table 5. Estimated least square means for net returns above irrigation costs at baseline soybean price of $11.11/bu and baseline diesel price of $2.83/gal for continuous flow irrigation (CONV) and surge flow irrigation (SURGE) when water is lifted from four well depths: 18 ft, 140 ft, 200 ft, and 400 ft.

Water lift depth	CONV	SURGE	P value
	———— $/acre ————		
18 ft	649.34 (17.93)†	644.89 (17.17)	0.2063
140 ft	642.33 (17.21)	638.54 (18.03)	0.2810
200 ft	638.13 (18.11)	634.82 (17.87)	0.3481
400 ft	621.15 (18.04)	619.98 (18.56)	0.7544

†Standard deviation

Table 6. Estimated least square means for net returns above irrigation costs at baseline soybean price of $11.11 per bushel and high diesel price of $3.70/gal for continuous flow irrigation (CONV) and surge flow irrigation (SURGE) when water is lifted from four well depths: 18 ft, 140 ft, ft, and 400 ft.

Water lift depth	CONV	SURGE	P value
	———— $/acre ————		
18 ft	645.15 (18.05)†	641.57 (18.91)	0.3091
140 ft	637.39 (17.86)	634.66 (18.21)	0.4421
200 ft	632.69 (18.32)	630.56 (18.87)	0.5549
400 ft	613.52 (17.89)	614.05 (18.97)	0.8985

†Standard deviation

Table 7. Estimated least square means for net returns above irrigation costs at baseline soybean price of $11.11/bu and low diesel price of $1.60/gal for continuous flow irrigation (CONV) and surge flow irrigation (SURGE) when water is lifted from four well depths: 18 ft, 140 ft, 200 ft, and 400 ft.

Water lift depth	CONV	SURGE	P value
	—————— $/acre ——————		
18 ft	655.26 (17.81)†	649.58 (17.23)	0.1149
140 ft	649.44 (18.19)	644.13 (17.85)	0.1370
200 ft	645.87 (17.89)	640.89 (17.03)	0.1605
400 ft	631.88 (18.12)	628.32 (18.96)	0.3117

† Standard deviation

Conclusion

The objective of this research was to determine the effect of SURGE on the amount of irrigation water applied, soybean grain yield, IWUE, and net return above irrigation cost on clay-textured soils. Surge flow irrigation on clay-textured soils will have no adverse effect on soybean grain yield, but this technique will reduce irrigation water applied and the time required to irrigate a given site. Moreover, these data confirm that the water savings recouped by SURGE will compensate for the increased capital investment required for this irrigation strategy. In essence, SURGE on clay-textured soils can be adopted by Mid-South producers without adversely affecting yield or on-farm profitability while concurrently easing the region's groundwater shortage problems.

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