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Efficacy of tailwater recovery systems as an approach to water resource conservation

By

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Efficacy of tailwater recovery systems as an approach to water resource conservation

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Water conservation practices are being widely implemented to alleviate sediment and nutrient losses from agricultural land and unsustainable groundwater use for irrigation. Tailwater recovery (TWR) systems are conservation practices being implemented to collect and store runoff to reduce nutrient losses and provide a source of irrigation water. This collection of research is focused on evaluating TWR systems through the following actions: 1) investigate ability to reduce solids and nutrients delivery to downstream systems, 2) compare differences in solid and nutrient concentrations in surface water samples from TWR systems to irrigation water from a TWR systems; 3) determine the potential to irrigate water containing solids and nutrients; 4) quantify a water budget for TWR systems; 5) conduct cost and benefit analyses of TWR systems; and 6) analyze economic cost to reduce solids and nutrients and to retain water. Tailwater recovery systems did not significantly reduce concentrations of solids and nutrients; however, loads of solids, P, and N were significantly reduced by 43%, 32% and 44%, respectively. Mean nutrient loads per hectare available to be recycled onto the landscape were 0.20 kg ha^{-1} P and 0.86 kg ha^{-1} N. Water budget analyses show these systems save water for irrigation but were inefficient. Net present value (NPV) and benefit cost ratios were positive and >1 for producers who owned the land, but remained <1 if land was rented. However, beyond improvements to irrigation infrastructure, farms with a TWR system installed lost NPV of $51 to $328 per ha. Mean total cost to reduce solids using TWR systems ranged from $0 to $0.77 per kg, P was $0.61 to $3,315.72 per kg, and N was $0.13 to $396.44 per kg. The mean total cost to save water using TWR systems ranged from $189.73 to $628.23 per ML, compared to a mean cost of groundwater of $13.99 to $36.17 per ML. Mechanistically, TWR systems retain runoff on the agricultural landscape, thereby reducing the amount of sediment and nutrients entering downstream waterbodies and provide an additional source of water for irrigation; however, more cost-effective practices exist for nutrient reduction and providing water for irrigation.

DEDICATION

This work is dedicated to my parents, Rick and Donna, for their lifelong guidance and financial support through my endeavors. Without your discipline and lifelong commitment to my wellbeing and education, this would not have been possible. I have been truly blessed with many family and friends and I thank you for your support and understanding.

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INTRODUCTION

1.1 Agriculture and the environment

Agriculture has been attributed with degrading the quality of water, soil, and air. The irony is that agriculture relies on healthy ecosystems and services provided by water, soil, and air to maintain production. This is evident in the strong reliance of agriculture on water and the water cycle, coinciding with the pollution of surface waters and the depletion of groundwater. Humans have always been reliant on the water cycle to provide life. We often forget as Jacques Cousteau said, “the water cycle and the life cycle are one” (Glennon 2004). The switch from hunter-gatherer societies to agricultural-based societies has amplified this reliance on the water cycle (Postel 1999; Fagan 2011). The 1955 Yearbook of Agriculture was a prelude to the present-day water issues related to agriculture; titled “Water”, the book focused on water issues in agriculture, many of which still persist today (Stevens 1955). Within the 1955 yearbook, Karl Kohler explains that five developments since 1940 have produced a realization that humans involved in agriculture must take immediate steps to increase conservation (Stevens 1955). The five developments include: World War II, increases in population, shifts in industry, droughts, and pollution of lakes and streams. The last two of these come as a direct threat to agriculture and the growing human population and are also directly based on water.

1.2 Agriculture water quality issues

Pollution of lakes, streams, and oceans (i.e. surface waters) have continued from 1955 to present day through runoff and leaching losses of chemicals including: pesticides, herbicides, and fertilizers (i.e. nutrients) (USEPA 2016). This has led many to call for protection of water resources, such as, Maude Barlow's Third Law of Nature for water conservation (Barlow 2009). This law explains that we must stop polluting our surface and groundwater sources and must regulate the common sources (Barlow 2009). The importance of human impact on nutrient cycles including nitrogen fixation from the atmosphere and phosphorus pollution to the oceans has been identified as crucial for maintaining Earth's Holocene state (Rockström et al. 2009).

During the Green Revolution (1930 to late 1960s), use of synthetic agricultural fertilizer applications became widespread in order to increase maximum yields of crops and feed a growing global population. Within the United States (US), the increase in fertilizer application has led to an increase in nonpoint source nutrient pollution of surface waters (Carpenter et al. 1998; Turner and Rabalais 2003). Presently, agricultural nutrient loadings to surface waters are particularly problematic in the Great Lakes (USEPA 2011), Florida Everglades (McCormick et al 2001; McCormick and Lang 2003), and the Mississippi River Basin (MRB) regions, where they have resulted in water quality impairments (USEPA 2016).

Runoff of nutrients has led to large changes in the frequency and scale of eutrophication of surface waters leading to hypoxic zones (Bennett et al. 2001). Eutrophication begins with excessive primary production of macrophytes and algal growth which is caused by the increased presence of a limiting constituent, such as carbon, sunlight, or nutrients (Schindler 2006). Next the algae die and bacteria begin to breakdown the biomass utilizing dissolved oxygen to a point of hypoxia. Increased primary production in aquatic systems has been shown to cause distasteful drinking water, decrease aesthetics of surface waters, and hypoxia threating aquatic species (Carpenter et al. 1998). Eutrophication has occurred worldwide and has been attributed to increased levels of nitrogen (N) and phosphorus (P) in surface waters, which are highly correlated with algal biomass (Dodds et al. 2002).

High spring loadings of N and P from agricultural landscapes may impair downstream receiving waters by increasing primary production. In the MRB, this nutrient related eutrophication causes periodic hypoxia and may decrease local biota (Killgore et al. 2008). In addition to eutrophication in lakes and streams, nutrients from agricultural runoff in the MRB contribute to increased size of the Gulf of Mexico hypoxic zone (Turner and Rabalais 2003). In 2015, the Gulf of Mexico Hypoxic Zone measured 16,760 km^2, and averaged 14,024 km^2 from 2011 to 2015 (Louisiana Universities Marine Consortium 2015). Alexander et al. (2008) estimated agricultural sources contributed 70% of N and P inputs to the Gulf of Mexico via the Mississippi and Atchafalaya rivers. Gulf hypoxia has caused substantial declines in biodiversity and poses a serious threat to a $2.8 billion Gulf fisheries industry (Rabotyagov et al. 2012).

1.3 Water use for agriculture

In addition to the impact of agricultural pollution on surface waters, agriculture is becoming more susceptible to severe droughts. To combat drought and maintain maximum yields, agricultural has turned to irrigation, which has become unsustainable due to advances in pump technology rapidly expanding irrigated land area and depleting ground water supplies. The Green Revolution led to a 2.4-fold increase in world grain productivity between 1950 and 1995; however, it was matched by a 2.2-fold rise in irrigation water use (Postel 1999). Maude Barlow's Second Law of Nature for water conservation states humans cannot mine groundwater supplies at a rate greater than recharge (Barlow 2009). Fresh water harvesting of groundwater for agriculture is now one of the biggest threats to irrigated agriculture (Postel 1999) and is one of three large scale activities risking potentially irreversible harm to fresh water sustainability (Feldman 2012). This will only amplify as the impacts of agricultural water use become more critical for four reasons: 1) increased population means increased land consigned to grow food; 2) increased modernization and increased standard of living in developing countries is increasing demands for energy and ethanol which rely on water for refining; 3) mass migration to urban areas in regions with decreasing water supplies; and 4) unbalanced virtual water use and trade (Feldman 2012).

Water use for agriculture is often in conflict with municipal uses for direct human use. Runoff is the renewable aspect of the water cycle, totaling 34,000 km^3 a year on Earth, of which humans use half, 35% for irrigation and 19% for instream needs (Villiers 2001). In fact, of the 34,000 km^3, there are 8,000 m^3 of water available for every human on earth (i.e. enough for every person on Earth), however water availability varies due to both spatial and temporal inequities (Villiers 2001). The 2007 International Water Management Institute projected global water needs for agriculture from 2007 to 2050 and they concluded that: 1) globally, there is enough land and water to produce food for the growing population; 2) if continued, today's food production and environmental trends will lead to crises in many parts of the world; and 3) only if we improve agricultural water use will we meet the acute fresh water challenge facing humankind (Rogers and Leal 2010). They also concluded that, without climate change, a 10% improvement in efficiency would be sufficient for the next 50 years and that 10% improvement would free up more water than is currently used by all the cities and industries across the globe (Rogers and Leal 2010). This may need to be reassessed with consideration for climate change.

In the southeast US, New England, and Mid-Atlantic states climate change will result in more frequent and higher intensity rainfall (Montgomery 2012). Six major impacts on water resources are expected from climate change: 1) increased precipitation in northern hemisphere and decreased precipitation in southern hemisphere; 2) huge economic losses to regionally important activities dependent on water; 3) increased temperature of water and increased pollutants in surface water, resulting in decreased dissolved oxygen and increased flows of polluted runoff; 4) increased flooding due to increases in urban runoff; 5) continued decline in groundwater levels; and 6) increased use of water for energy production (Feldman 2012).

Within the US, withdrawals for irrigation peaked in the 1980s. The US produces 60% more agricultural products than in 1980, and US farmers use 15% less water, meaning the water productivity of today’s farmers has increased by 90% (Fishman 2012). However, in the US, groundwater use for irrigation exceeds recharge levels on at least 20% of all irrigated land (Frederick 2006). Evidence is increasing that use of many aquifers is not sustainable, converting these resources into what Sophocleous and Merriam (2012) referred to as “functionally nonrenewable.” One such aquifer is the Mississippi Alluvial Aquifer (MAA), which is the third most used aquifer in the US and totals 12% of the US water use (Maupin and Barber 2005). Since the 1970s, groundwater levels in the MAA have decreased at a rate of approximately 12,335 ha-m per year due to an increase in irrigated acres (Thornton 2012). Falling aquifer levels are the result of increased use (Czarnecki 2010) combined with a low rate of aquifer recharge from infiltration (Arthur 2001). The alluvial aquifer is recharged by 1) water from the Mississippi River, local lakes and streams, aquifers underlying the eastern Bluff Hills region, 2) precipitation, and 3) the underlying Cockfield and Sparta aquifers (Arthur 2001). Of these, it has been proposed that precipitation infiltration is the main source of recharge (Boswell et al. 1968); however, due to a near impermeable top stratum of sand, silt and clay (Arthur 2001), only around 6.6 cm of the annual 142 cm of precipitation recharges the alluvial aquifer (Krinitzsky and Wire 1964). Water is discharged from the alluvial aquifer into underlying aquifers, the Mississippi River, lakes, and streams, as well as being withdrawn for municipal, industrial and agricultural uses (Arthur 2001).

Mississippi is second largest user of the MAA (Maupin and Barber 2005) and it is the most heavily used aquifer in the state (Arthur 2001). Use is almost exclusively (98%) for irrigation of agricultural fields (Arthur 2001). It is estimated that 64% of production land in the area of northwest Mississippi overlying the MAA (hereafter the “Delta”), requires 3,401,316 ha-m of water per growing season. Within the Delta, groundwater pumping continues to increase at unsustainable rates, the outcome of which is a cone of depression located primarily under the central Delta region (Arthur 2001; Barlow and Clark 2011; Clark et al. 2011). This unsustainable trend is expected to continue into the future (Clark et al. 2011). This situation is also present in neighboring Arkansas

(Czarnecki 2010), another user of the MAA, and in other regions and underlying aquifers in the US (e.g., California's Central Valley) (Maupin and Barber 2005).

1.4 Tailwater recovery systems

Agricultural water use is consumptive, meaning water is not immediately returned to the source, but rather is used up or transported elsewhere (Feldman 2012), unless surface water is captured and reused. Catching rainwater and surface runoff for storage has taken place for centuries. In India, capturing rainfall into reservoirs called "tanks" is an age-old practice and is even a central feature in ancient temple complexes (Postel 1999). This has also taken place in other parts of Asia and Africa (Richter 2014). Based on this model, a relatively new best management practice (BMP), surface water capture-and-irrigation reuse systems, also known as tailwater recovery (TWR) systems, has been given increased attention. Arkansas has had collection basins for runoff and surface water irrigation for 20-40 years. Although some of these systems have been present in Mississippi for many years, they did not become a widespread practice until 2012 due to the increasing awareness of decreasing aquifer levels and increasing amount of available financial assistance. Currently, over 700 TWR systems have been installed in the mid-South region (P. Rodrigue and C. Bowie, NRCS, personal communication, 2015). In Mississippi, 180 of these systems are primarily within the area overlying the cone of depression of the MAA (P. Rodrigue, NRCS, personal communication, 2015). The US Department of Agriculture Natural Resource Conservation Service (NRCS) has financially assisted with installation of over 180 TWR systems in the Delta under Practice 436 in Mississippi (USDA NRCS 2016) (447 in other states; USDA NRCS 2014). Within the cone of depression, 123 TWR systems have been implemented in

Sunflower and Bolivar counties to alleviate the need for groundwater withdrawal (P. Rodrigue, NRCS, personal communication, 2015). The cost of TWR systems can range between $400,000-900,000, with 60 to 80% of total costs covered by financial assistance from NRCS (chapter 6).

Tailwater recovery systems are designed to store surface water by combining a ditch (which captures surface water) with an optional on-farm storage (OFS) reservoir to increase capacity for surface water storage and pumps to re-lift surface water into the OFS reservoir or onto fields as irrigation. The shape and size of TWR systems varies, although minimum standards are used as guidelines for TWR system design. Ditches are designed to hold a minimum of 14.8 ML of water, collect runoff water from an area 3-4 times the size of the area to be irrigated by the TWR system, store 9 cm-ha of water to cover the irrigated area, and store 1/6-1/8 the capacity of the OFS reservoir (P. Rodrigue, NRCS, personal communication, 2015). The OFS reservoirs are designed to be a minimum of 1/13 of the area to be irrigated, have an area running off into the TWR ditch associated with the OFS reservoir as that is equal to the area to be irrigated by the OFS reservoir, and store 15 cm ha $^{-1}$ of irrigation water (P. Rodrigue, NRCS, personal communication, 2015). Tailwater recovery systems are usually installed along with other NRCS conservation practices aimed at directing water into the TWR ditch, which may include land leveling, water control structures (e.g. slotted riser-board pipes) and grade stabilization (e.g. field perimeter pads). Although, TWR systems were originally designed as irrigation reservoirs to provide an alternative source of irrigation water, they have been described to have an additional benefit of reducing losses of solids and nutrients to downstream waters (USDA NRCS 2011).

Previous research has led to publications describing nutrient concentrations within TWR systems and the seasonal fluctuations in nutrient concentrations. Kirmeyer et al. (2012) collected grab samples of water every three weeks during the growing season (April to June) from two TWR systems in the Delta. Mean concentrations of total phosphorus (TP), ammonium (NH_4^+), total Kjeldahl nitrogen (TKN), total suspended solids (TSS), and turbidity were greater within the TWR ditch and OFS reservoir than at the outlet sampling locations, with nitrate (NO_3^-) concentrations highest in the spring (April and May). They also monitored water levels from April to June in TWR systems which increased through the middle of May, then decreased dramatically due to water use and lack of precipitation. Smukler et al. (2012) investigated a TWR system on an organic farm in California for two years and found a 40% increase in NO_3^- concentrations and a decrease in TSS concentration between TWR system influent and effluent. They attributed the NO_3^- increase to the small size of the TWR system, thereby decreasing the hydraulic residence time (HRT) within the system. Carruth et al. (2014) extended the previous study by Kirmeyer et al. (2012) by collecting grab samples of water from the same two TWR systems from March to December. Total phosphorus observed by Carruth et al. (2014) showed relatively steady concentrations, with the exception of a few samples being higher due to winter precipitation events. Numeric observations by Carruth et al. (2014) showed the greatest concentrations of NH_4^+, NO_3^-, and TSS in the spring to early summer (March to June). Karki et al. (2015) sampled a TWR system located in east Mississippi and observed the highest TP concentrations in winter and spring (January to March). They also observed that during storm events, concentrations of TP, NO_3^-, and total nitrogen (TN) were greater in samples collected at the inflow locations than samples taken from within the TWR system. Moore et al. (2015), collected samples from one TWR system in the eastern Arkansas region and numerically showed summer and fall NO_3^-/NO_2^- and TP nutrient concentrations to be greater than spring concentrations. They also found a difference in NO_3^- concentrations in water samples taken at the surface and samples taken from the bottom of OFS reservoirs.

An additional study assessing the water savings of TWR systems described the quantity of water saved, lost and irrigated by TWR systems. Prince Czarnecki et al. (2017) observed that although a large amount of surface water was stored, this amount was only enough water to offset at best 10 days of irrigation in the Delta region. They also compared TWR system performance to NRCS design guidelines and found in TWR systems with an OFS reservoir, the ditches were 90% sufficient, while the OFS reservoirs were only 37% sufficient. In TWR systems without an OFS reservoir, sufficiency was limited to 35%.

Previous economic analyses of TWR systems (Bouldin et al. 2004; Young et al. 2004; Falconer et al. 2015) have focused on hypothetical scenarios which may not represent reality. Bouldin et al. (2004) modeled the cost and benefits of TWR systems using present values and benefit-cost ratios (BCR) to show that TWR systems are a positive investment, however they included large monetary values for the external benefits of ecological services of wetlands. The capability of TWR systems to provide those services was an assumption due to the lack of research. In addition, they included a monetary value for groundwater use and currently there is no monetary value in Mississippi for reducing groundwater use. In an adequate groundwater scenario in Arkansas, Young et al. (2004) used differences in net present values (NPV) to show that

TWR systems are not economical. Yet these results have not influenced the implementation of TWR systems in Mississippi where groundwater is adequate but decreasing. Last, Falconer et al. (2015) concluded from NPV on a hypothetical farm that TWR systems in Mississippi may not be economical due to the lost income from land taken out of production for TWR ditch and OFS reservoir. They warned that each system is a specific case and should be considered that way. Research into implemented TWR systems would allow the NPV and BCR to be calculated for scenarios of actual external benefits and lost production land.

As a result of environmental degradation, federal and state legislation targeted research aimed at implementing and evaluating conservation or BMP on agricultural landscapes, particularly within the Lower Mississippi Alluvial Valley (LMAV) of the MRB has been called for (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008; MDEQ 2011). In addition, the 2014 Farm Bill increased funding for working lands programs while decreasing funding for land retirement programs (US Congress 2014). Unfortunately, this is opposed to Maude Barlow's First Law of Nature which is that water must remain in the local watershed and natural spaces must restore (i.e. land retirement) so that the water can fall and flow (Barlow 2009). The expansion in funding toward working lands programs will result inevitably in amplified conservation practice implementation. Through the USDA Regional Conservation Partnership Program, which matches federal funds with private funds to help shoulder the cost of conservation, more interest in determining monetary values for the benefits of conservation may arise. In addition, it has been shown that adoption rates of conservation practices increase when information programs include details about impacts on farm profitability and when practices are economically appealing (Feather and Amacher 1994; Feather and Cooper 1995; Cestti et al. 2003). However, little is done especially with an economic component, and even less is done in a comprehensive study where results are comparable between the conservation efficacy research and the economic research. Research of BMPs should consist of comprehensive studies or similar research designs, methodologies and equipment to improve the comparability of results.

Shiva (2002) explains that we must understand how conservation practices and water technologies interact with the natural patterns so that they don't violate water rhythms and further degrade and deplete water resources. To identify practices which do not create these violations, research is needed on real world implementations of BMPs. These investigations should provide analyses of anthropogenic benefits and costs so that decision makers can evaluate practices based on merits and likelihood of achieving the desired outcomes within economic reason. This work aims to quantify environmental benefits, direct benefits, and cost of TWR systems, as well as compare them for future decision support. This is called for in the 1955 Yearbook of Agriculture by Robert Saltwater and Omer Kelley (Stevens 1955), and the Gulf Hypoxia Action Plan 2008. The Gulf of Mexico Action Plan calls for reducing, mitigating, and controlling hypoxia in the Northern Gulf of Mexico and improving water quality in the Mississippi River Basin (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008). However, few studies comprehensively analyze conservation practices from the evaluation of performance to the economic comparison of benefits and costs (Kröger et al. 2012). Of the studies that have assessed BMP effectiveness at the farm scale using edge-of-field practices in the LMAV region, none have reported the effectiveness of TWR systems.

Specifically, TWR systems have had little published evaluations of their performance and economic analyses. This may be due to the increased need for collaboration across fields or due to lack of funding for exhaustive data collection and analyses. Analyzing larger scale studies, including multiple aspects of benefits and costs, provides cohesion in results, compared to multiple investigations with varying experimental designs, unaligned objectives, and differing in-field and analytical equipment. The continued expenditure of federal, state, and private funds toward these practices necessitates an economic analysis comparing benefits and costs of implemented TWR systems. With this impetus, this research is organized and investigated through the following objectives and sub-objectives.

1.5 Objectives

1. The first research chapter of this dissertation (Chapter 2) addresses effectiveness of TWR systems at reducing losses of solids and nutrients (i.e., TWR performance) from the agricultural landscape, through the following sub-objectives:
    a. Determine if there was a difference between inputs into TWR systems and the outflow from the TWR systems in solids and nutrient concentrations and loads (TWR system performance).
    b. Investigate seasonal TWR system performance.
    c. Evaluate the influence of TWR design on TWR system performance.
2. The third chapter investigates the representation of grab samples from the surface of TWR ditches and OFS reservoirs to the water being applied to agricultural fields. This objective supports the methods used in Chapter 4, and is as follows: determine if solid and nutrient concentrations in grab samples collected from surface water in TWR systems are representative of solid and nutrient concentrations in water that is being irrigated from TWR systems.

3. While considering the findings of Chapter 3, Chapter 4 quantifies the nutrient concentrations and loads in TWR systems, with consideration of seasonal differences by describing the potential to recycle solids and nutrients captured by TWR systems back onto productions fields through irrigation applications, while also investigating the seasonal differences of concentrations of solids and nutrient analytes.

4. The second of the dual purposes of TWR systems is to hold water onto the landscape for irrigation. Chapter 5 develops and quantifies a water budget through the following sub-objectives:

    a. Summarize gains and losses of water into and out of TWR systems.

    b. Design a water budget for TWR systems.

    c. Develop coefficients for parameters of the water budget.

    d. Quantify the total water budget for all 180 TWR systems in the Delta.

    e. Assess the efficacy of TWR ditches to save water and OFS reservoirs to irrigate water.

5. Chapter 6 of this dissertation provides an economic analysis of TWR systems for decision makers to consider against other options for mitigation of sediment and nutrient losses from the agricultural landscape. This was accomplished by comparing the costs and benefits of TWR systems through the following sub-objectives:

    a. Compare NPV and BCR of operation scenarios with and without TWR systems, as well as, with and without solids reduction benefits.

    b. Evaluate the impact of the level of USDA NRCS financial assistance on NPV.

6. Chapter 7 quantifies the costs to reduce solid and nutrient losses from the agriculture landscape and retain water on the agricultural landscape through the following sub-objectives:

    a. Obtain a dollar value for costs incurred to reduce solids and nutrient loss using TWR systems.

    b. Calculate the cost of surface water saved in TWR systems compared to the cost of pumping groundwater.

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CHAPTER II

REDUCTION OF SUSPENDED SOLID AND NUTRIENT LOSS FROM AGRICULTURAL LANDS BY TAILWATER RECOVERY SYSTEMS

2.1 Abstract

Best management practices are being implemented throughout the Lower Mississippi River Alluvial Valley with the aim of alleviating pressures placed on downstream aquatic systems by sediment and nutrient losses from agricultural land; however, research evaluating the performance of one practice, tailwater recovery (TWR) systems, is limited. This study evaluated the ability of six TWR systems to retain sediment and nutrient draining from agricultural landscapes. Composite flow-based samples were collected during flow events (precipitation or irrigation) over a two-year period. Performance of TWR systems was evaluated by comparing concentrations and loads in water leaving agricultural fields and entering TWR systems (i.e. runoff or influent) to water overflow exiting TWR systems (effluent). In addition, performance was analyzed seasonally for adaptive management and insights into the impacts of landscape changes. Potential parameters influencing TWR system performance (i.e. effluent volume, system fullness, sampling method, season, time since the previous event, and system volume) were analyzed using factor and regression analyses. Tailwater recovery systems did not reduce solids and nutrient concentrations; however, loads of solids, P, and N were reduced by 43%, 32% and 44%, respectively. Influent and effluent of TWR systems showed no seasonal differences for analyte concentrations and loads. Performance of TWR systems was influenced by effluent volume, system fullness, time since the previous event, and capacity of the system. Mechanistically, TWR systems retain runoff on the agricultural landscape, thereby reducing the amount of sediment and nutrients entering downstream waterbodies. System performance can be improved through manipulation of influential parameters.

Keywords: tailwater recovery system, best management practice, water reuse, irrigation, water quality

2.2 Introduction

During the Green Revolution of the 1930s to late 1960s, synthetic agricultural fertilizer applications became widespread to increase maximum yields of crops and feed a growing global population. Within the United States (US), the increase in fertilizer application led to an increase in nonpoint source nutrient pollution to surface waters (Turner and Rabalais 2003). Presently, within the US, agricultural nutrient loadings to surface waters are particularly problematic in the Great Lakes (USEPA 2011), Florida Everglades (McCormick et al 2001; McCormick and Lang 2003), and the Mississippi River Basin (MRB) regions, where they have resulted in water quality impairments (USEPA 2016). Within the MRB, nutrient loadings usually peak during spring, decrease in fall, and then begin to increase throughout the winter (Antweiler et al. 1996).

High nutrient loadings of nitrogen (N) and phosphorus (P) from agricultural landscapes may impair downstream receiving waters by increasing primary production. In the MRB, this nutrient-related eutrophication causes periodic hypoxia and may decrease local biota (Killgore et al. 2008). In addition to eutrophication in lakes and streams, nutrients from agricultural runoff in the MRB contribute to Gulf of Mexico hypoxia (Turner and Rabalais 2003). In 2015, the Gulf of Mexico Hypoxic Zone measured 16,760 km^2 and averaged 14,024 km^2 from 2011 to 2015 (Louisiana Universities Marine Consortium 2015). Alexander et al. (2008) estimated agricultural sources contributed 70% of N and P inputs to the Gulf of Mexico via the Mississippi and Atchafalaya rivers. Gulf hypoxia has caused substantial declines in biodiversity and poses a serious threat to a $2.8 billion Gulf fisheries industry (Rabotyagov et al. 2012).

As a result of environmental degradation, federal and state legislation targeted research aimed at implementing and evaluating best management practices (BMP) on agricultural landscapes, particularly within the Lower Mississippi Alluvial Valley (LMAV) of the MRB (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008; MDEQ 2011). However, of the studies that have assessed BMP effectiveness at the farm scale using edge-of-field practices in this region (Kröger et al. 2012) none have reported the effectiveness of surface water capture-and-irrigation reuse systems, also known as tailwater recovery (TWR) systems. The US Department of Agriculture Natural Resource Conservation Service (USDA NRCS) has financially assisted with installation of over 180 TWR systems in Mississippi's region of the LMAV (locally known as the Delta) under Practice 436 in Mississippi (USDA NRCS 2016). Within the aquifer cone of depression underlying Sunflower and Bolivar counties, 123 TWR systems have been implemented to alleviate groundwater withdrawal (P. Rodrigue, NRCS, personal communication, 2015). Tailwater recovery systems were originally designed as irrigation reservoirs to provide an alternative source of water other than groundwater. These systems have been described to have an additional benefit of reducing solids and nutrient loss to downstream waters (USDA NRCS 2011), although, this capability has not been well documented.

Seasonal differences in solids and nutrient concentrations are typical in agricultural systems, and the efficiency of TWR systems needs to be understood at this level. Solids and nutrient concentrations are highest during the spring when increased occurrence of precipitation events coincides with reduced ground cover and agricultural fertilizer applications. During the summer, eutrophication and downstream hypoxia are due to high primary productivity (Rabalais et al. 2002; Jarvie et al. 2013). In the fall and winter, reduced ground cover and tillage practices increase concentrations of solids in agricultural runoff.

The capability of TWR systems to reduce solids and nutrients in agricultural runoff may be influenced by seasonal differences in runoff, capacity of the TWR system, the amount of water leaving the system, and the temporal aspect of events. A further understanding of these variables is critical for informing TWR system design and using adaptive management to optimize performance. Therefore, the purpose of this study was to investigate the ability of TWR systems to reduce solids and nutrient loss from the agricultural landscape. Objectives were to (1) assess if there was a difference between inflows and outflows from TWR systems in solids and nutrient concentrations and loads (TWR system performance); (2) investigate seasonal TWR system performance; and (3) evaluate the influence of TWR system design on TWR system performance.

2.3 Materials and Methods

2.3.1 Description of tailwater recovery systems

Tailwater recovery systems are designed to store surface water by combining a ditch which captures surface water, an optional on-farm storage (OFS) reservoir to increase capacity for surface water storage, and pumps to re-lift surface water into the OFS reservoir or onto fields as irrigation. The shape and size of TWR systems varies. Ditches are designed to hold a minimum of 14.8 ML of water, collect runoff water from an area 3-4 times the size of the area irrigated by the TWR system, store 9 cm ha^{-1} of water to cover the irrigated area, and store 1/6-1/8 the capacity of the OFS reservoir (P. Rodrigue, NRCS, personal communication, 2015). The OFS reservoirs are designed to be a minimum of 1/13 of the area to be irrigated, have an area running off into the TWR ditch associated with the OFS reservoir that is equal to the area to be irrigated by the OFS reservoir, and store 15 cm ha^{-1} of irrigation water (P. Rodrigue, NRCS, personal communication, 2015). Tailwater recovery systems are usually installed along with other NRCS conservation practices aimed at directing water into the TWR ditch, which may include land leveling, water control structures (e.g. slotted riser-board pipes), and grade stabilization (e.g. field perimeter pads).

2.3.2 Study design

Six TWR systems were investigated on four farms in the Delta (figure 2.1). Nutrient concentrations and discharge data were monitored at TWR system inflow points, field runoff points leading into a TWR system (influent), and outflow locations leaving a TWR system (effluent) (figure 2.2) on a flow (precipitation or irrigation) event basis from February 1, 2014, to January 31, 2016. Catchment areas draining into TWR systems ranged from 68.2 ha to 155.6 ha on farms growing crop rotations of continuous rice (*Oryza sativa*), rice-soybeans (*Glycine max*), and/or corn (*Zea mays*)-soybeans (table 2.1).

2.3.3 Water sampling design

Water samples were collected using a Sigma SD 900 Portable Compact Sampler Package (HACH, Loveland, CO). Samplers were powered by a 12-V rechargeable battery connected to a 12-V 30-W Solar Module with regulator (HACH) via an OTT 1205 12-V/5-A Solar Charger Controller (OTT Hydromet Ltd., United Kingdom). Sampler collection was triggered by 6526E Starflow Ultrasonic Doppler system (Unidata Pty Ltd., Perth, Australia) that measured depth, velocity and flow. Both the Sigma SD 900 sampler and Starflow 6526E Ultrasonic Doppler instrument were connected to an A753 addWAVE general packet radio service remote transmitting unit (ADCON Telemetry, Klosterneuburg, Austria), which was powered using a Solar Set 4, 3 W (ADCON Telemetry), and transmitted data wirelessly to a HACH server (HACH). Samples consisted of flow-triggered composites (Izuno et al. 1998; Stone et al. 2000) that took 200 mL sub-samples after a preset change in flow rate. Flow rate triggers were customized to each TWR system so that events were sub-sampled throughout the entire hydrograph. For each event, samples were collected into a single 10-L polyethylene bottle. Upon collection, samples were homogenized by agitating the bottle and transferred into two 500-mL sample containers.

At three locations (TWR-1A influent, TWR-2B effluent, and TWR-4F effluent; table 2.1), the use of automated samplers was not possible due to farm traffic and location of influent/effluent pipes. At these locations two passive samplers (Pierce et al. 2012b;

Baker et al. 2016) collected two 650-mL water samples (one from the bottom and one from the middle of the water column) from which two 500-mL samples were collected after agitating the passive samplers. Water depth was recorded at these locations using water level data loggers (HOBO, Onset, Bourne, MA). At sampling locations with passive samplers, flow was calculated using a modified Manning's equation for gradual varied flow utilizing the slope of the pipes (Chow 1959).

For all water samples collected, one of the two 500-mL samples was immediately acid-preserved with 2 mL of 49% sulfuric acid solution for subsequent nutrient analyses. Samples were collected, labeled, and placed on ice within 24 h of the event and transported within 48 h according to accepted QA/QC guidelines (USEPA 2002) to the Mississippi Department of Environmental Quality (MDEQ) laboratory for analyses.

2.3.4 Water sample analyses

Samples were analyzed for total suspended solids (TSS), total P (TP), total Kjeldahl N (TKN), nitrate-nitrite ($NO_3^-NO_2^-$), and ammonium (NH_4^+). Total suspended solids were determined using method 2540D described in Eaton et al. (1998). Prior to nutrient analyses, samples were vacuum filtered through a 0.45µm 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_4^{+}, and $NO_3^-NO_2^-$ according to standard methods of persulfate digestion, Berthelot reactions, and cadmium reduction, respectively (Eaton et al.1998). Total Kjeldahl N was analyzed using metal-catalyzed digestion, distillation, and automated colorimetry (Eaton et al. 1998). Total N (TN) was calculated as the sum of

TKN and $NO_3^-NO_2^-$, and organic nitrogen (ON) was calculated by subtracting NH_4^+ from TKN.

Water depth was monitored in TWR ditches and OFS reservoirs using OTT pressure level sensors (OTT Hydromet Ltd., United Kingdom). Sensors were connected to A755 addWAVE general packet radio service remote transmitting units (ADCON Telemetry, Klosterneuburg, Austria) that were powered using a Solar Set 4 (ADCON Telemetry). Surface water capture volumes were calculated based on depth of water and system dimensions (obtained from local NRCS personnel) following Prince Czarnecki et al. (2017).

All sample analyte concentrations below a detection or quantification limit were treated with the method described by Hornung and Reed (1990). With this method, one-half the quantification limit was assigned to levels below detection (i.e. 2, 0.01, 0.01, 0.05, and 0.02 mg L^{-1} for TSS, TP, $NO_3^-NO_2^-$, TKN, and NH_4^+, respectively). For events in which samples were not collected, linear interpolation of the concentration gaps was used as an estimate of analyte concentration (Moatar and Meybeck 2005; Jiang et al. 2014). Loads were calculated as the event's total volume of water multiplied by the event's solid and nutrient concentrations. To estimate loads of all field runoff flowing into the TWR systems, loads at unmonitored fields were estimated based on the loads of monitored fields. This was done by taking the load per hectare of the monitored fields multiplied by the additional field area flowing into the TWR system. The ratio of monitored to unmonitored fields ranged from 1:1 to 1:7. Data were paired to account for multiple influent events prior to an effluent event by averaging concentrations and summation of loads. Pairing was necessary to calculate the differences in concentrations and loads for events while accounting for the dependency of the concentrations and loads of an overflow event on the field runoff and inflow concentrations and loads leading up to the effluent event.

2.3.5 Statistical analyses

To address Objective 1, solid and nutrient (seven metrics including TSS, TP, TN, ON, TIN, $NO_3^-NO_2^-$, and NH_4^+) concentrations were compared between TWR influent and effluent using Hotelling's T-squared tests (glm procedure; SAS Institute 2015). The analysis was repeated for loadings. The Hotelling's T-squared test is the multivariate equivalent of a paired t-test and was used due to dependence of influent and effluent locations. If needed, univariate paired t-test were conducted to interpret results of the multivariate test.

To address Objective 2, paired differences in concentrations, and in loadings, between influent and effluent locations were compared over seasons using a multivariate analysis of variance (MANOVA; glm procedure; SAS Institute 2015). This analysis tested whether influent-effluent differences in the set of seven metrics depended on season. Months were grouped into seasons to represent distinctly different phases of agricultural management activity, biological activity, and climatic conditions. Seasons consisted of winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November). If significant differences among season were identified by the MANOVA, a Pillai's Trace *post hoc* test was used to evaluate how the seasons differed. Pillai's Trace statistic is robust for violations in MANOVA assumptions and was used as a precaution for any remaining deviations from assumption not addressed by the transformations (see below).

To address Objective 3, principal components analysis was used to reduce the paired differences in loadings for the seven metrics into one or two principal components (factor procedure; SAS Institute 2015). Principal components retained for further analyses were selected based on the Kaiser's criteria (eigenvalue > 1; Kaiser 1960). Principal components retained were examined relative to TWR system characteristics to distinguish characteristics linked to system performance. A stepwise regression procedure using the Akaike information criterion (AIC) was used to select the combination of TWR system covariates having the largest association with the principal components (Darlington 1968; Judge et al. 1985). Covariates considered included effluent volume (overflow out of TWR system during flood event), system fullness (fullness of TWR system prior to a flood event, represented as a percentage of the total capacity), event interval (days since previous overflow event), and system volume (total system capacity including OFS reservoir) (table 2.2). Season (four seasons defined earlier) and sampling method (automated or passive samplers) were also included as class variables to account for variability they may contribute.

All statistical tests were conducted at the strict $p < 0.05$ level of significance. The cost of TWR systems can range \$400,000-900,000 (Chapter 2). Thus, investing in such systems requires a rigorous test that reductions in loadings are attained. When multiple tests were conducted to interpret the results of global multivariate tests, the level of significance was adjusted for experiment-wise error using the false discovery rate technique (Benjamini and Hockberg 1995). Multiple testing was implemented only if multivariate significant differences were detected. For all analyses, the assumption of normality and homogeneity of variance were tested with Shapiro-Wilk test and Levene's test, respectively, and variables were log transformed as needed to meet assumptions.

2.4 Results and Discussion

In total, 280 samples were collected across all six TWR systems, 183 at TWR influent locations (field runoff and TWR inflow) and 97 at TWR effluent locations. Post interpolation, 149 paired events were included in analyses of performance, seasonal performance, and evaluation of the influence of tangential variables on performance.

2.4.1 Tailwater recovery system performance

The multivariate paired t-test indicated tailwater recovery systems altered overall solids and nutrients concentrations ($F_{7,140} = 4.38$, $p < 0.001$). Further univariate testing to interpret results of the multivariate test, adjusted for experiment-wise error, suggested the principal pairwise difference was a significant increase in TP concentration between influent and effluent that averaged 0.0627 mg L^{-1} per event ($F_{1,146} = 16.51$, $p < 0.0001$) (table 2.3). Pairwise differences in concentrations between each of the other six metrics varied in magnitude, but in a univariate manner, were not statistically different from zero. Observed differences in TP concentrations suggest TWR systems are a source of P due to loading (i.e. influent) during flow events, settling during and post-events, accumulation over multiple events, and resuspension during volatile storm events (Chapra 2008).

Although TWR systems did not produce strong reductions in concentrations, these systems do hold water on the landscape and thereby collect loads that would otherwise move downstream. The multivariate paired t-test indicated TWR systems did alter overall loads ($F_{7,140} = 10.09$, $p < 0.0001$). Univariate testing to interpret each of the seven metrics indicated load reductions for all metrics ($F_{1,146} > 10.46$, $p < 0.0001$), averaging 24 to 51% per event (table 2.3). Converted to annual loads, reductions in TSS averaged over 1,143 kg ha^{-1}, TP by 0.7 kg ha^{-1}, and TN by 3.8 kg ha^{-1} (table 2.4). Notably, load reductions are slightly lower than the targeted 45% reduction in TN and TP called for by the Gulf of Mexico Hypoxia Task Force (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008). While nutrient concentrations may not be reduced possibly due to insufficient residence time, low temperatures, or other environmental limitations, nutrient loads are likely decreased by retention and physical processes (i.e. settling) between flow events which may provide additional space for diffusion during the next event.

Observed trends in performance in this study differ from previous studies primarily due to TWR design and hydraulic residence time. Smukler et al. (2012) investigated a TWR system on an organic farm in California for two years and found a 40% increase in NO_3^- concentrations and a decrease in TSS concentration between TWR system influent and effluent. They attributed the NO_3^- increase to a smaller size of TWR system, thereby decreasing the hydraulic residence time within the system. Increases in residence time and decreases in depth have both resulted in increased nutrient removal (Durand et al. 2011). In our study, the average time water was flowing during an event was 3.6 days, which may have not been long enough for N removal. Nitrogen removal increases with increasing hydraulic residence time in treatment wetlands (Huang et al. 2000) and may require an 8-20 day hydraulic residence time depending on temperature (Akratos and Tsihrintzis 2007). Longer hydraulic residence times may be required for N removal in TWR systems compared to treatment wetlands due to the former containing less aquatic vegetation and a greater amount of water per unit of soil contact. A reduced residence time and decreases in activity of aquatic algae, macrophytes, and bacteria during cold months (Reay et al. 1999) presumably contribute to the poor performance of TWR systems in analyte concentration reductions through biogeochemical processes. An increase in TP concentrations and no change between influent and effluent concentrations of other analytes as observed in this study (table 2.3) suggest TWR systems do not completely treat the advection of solids and nutrients leaving agricultural land during flow events.

Effectiveness of BMPs to reduce solids and nutrient concentrations has been highly variable (table 2.5). Tailwater recovery systems have some of the greatest solid and nutrient reductions of all BMPs, although there is a wide range of efficiencies. Similarly, reduction efficiencies of the top TWR system performances are among the top performing BMPs; however, the lowest performing of TWR systems are less efficient than alternative BMPs (table 2.5). This wide range of efficiency suggests there is room for improvement in BMP performance.

The BMPs most comparable to TWR systems are edge-of-field applications (table 2.5). Beyond their similar locations on the landscape to TWR systems, edge-of-field BMPs create conditions similar to wetlands. Wetlands, weirs, and improved drainage ditches all attempt to create anoxic conditions favorable for denitrifying bacteria. Denitrification is the main process for N removal from the hydrosphere, although immobilization may tie up N in vegetation, curtailing its loss (Lee et al. 2009). Biota for immobilization was observed in TWR systems (e.g. green algae), however systems may lack aquatic macrophytes until sedimentation greatly reduces depth of the TWR system.

Tailwater recovery systems reduce nutrient loads making them an effective BMP; however, efficiency may be improved through operation, or alternatively, installing a different BMP.

2.4.2 Tailwater recovery system seasonal performance

Denitrification rates in wetlands increase and decrease with changes in temperature and hydrologic regime that follow seasonal patterns (Song et al. 2014). Temperature has direct effects on bacterial and enzyme activity limiting denitrification rates (Reay et al. 1999). However, performance of TWR systems did not show convincing seasonal differences in concentrations ($F_{21,417} = 1.54$, $p = 0.061$) nor loads ($F_{21,417} = 1.55$, $p = 0.057$) (figure 2.3). This lack of substantial seasonal differences further suggests that the observed decrease in analyte loads was principally through physical rather than biological processes controlled by temperature. Nevertheless, further investigation into the seasonal performance of TWR systems may be justified given both MANOVA tests were marginally non-significant ($p > 0.05$).

2.4.3 Predictors of tailwater recovery system performance

Principal components analysis indicated the first principal component accounted for 68% of the variability in the seven analytes, with an eigenvalue of 4.8. All remaining principal components had eigenvalues smaller than 1 and were therefore not interpreted. Individual analyte correlations with principal component 1 were all positive and included: 0.47 for TSS; 0.90 for TP; 0.96 for TN; 0.86 for ON; 0.92 for TIN; 0.82 for $NO_3^-NO_2^-$; and 0.76 for NH_4^+. These results suggest all analytes were directly correlated with each other and with the principal component, and that TN, TIN, and TP accounted for the most variability in analytes represented in the first principal component.

The stepwise multiple regression procedure selected system fullness, event interval, system volume, and effluent volume as predictors of the first principal component scores (table 2.6). Season and sampling method were not selected by the stepwise procedure, confirming earlier results that seasonal effects were weak and suggesting the two sampling methodologies provided similar results. The model had an R-square value of 0.47 and AIC value of 67.4. The model included interactions between event interval, system fullness, system volume, and effluent volume, suggesting the effect of one environmental descriptor depends on the level of another. Two 3-way interactions need to be interpreted and are described below.

The first 3-way interaction included event interval, system fullness, and system volume ($t = 4.72$, $p < 0.01$; table 2.6). First, this interaction indicated that if the TWR system was empty, event interval had no impact on performance (see flat slopes in figure 2.4, panels A, C, and E for 0 % fullness), although performance decreased with increasing system volume (see y-intercept decrease in panels A, C, and E for 0 % fullness). Second, when the system was not empty, performance increased with event interval and became progressively higher as system fullness and system volume increased (see slopes in figure 2.4, A, C, and E for 50 and 100 % fullness). The increased load reductions with longer event intervals when the system was full suggests either dilution or diffusion of loads when added to a full system undisturbed for longer, allowing for settling and nutrient assimilation. More water in a system prior to an event may also help buffer disturbance of bottom sediments and prevent resuspension.

The second 3-way interaction was between effluent volume, system fullness, and system volume ($t = 2.58$, $p = 0.01$; table 2.6). This interaction indicated load reductions were least when effluent volume was large and when the system volume was smaller (see y-intercept decrease in figure 2.4, panels B, D, and F for 0 % fullness). In addition, as system fullness and system volume increased, the load reductions increased (see y-intercept and slopes increase in figure 4, panels B, D, and F for 0 and 100 % fullness). While the pattern of load reductions relative to effluent volume and system fullness stayed similar with increasing system volume, system fullness became less influential, meaning the fuller and larger the system, the lower the effect of effluent volume on load reductions. The increased system performance when overflow was low and the system was emptier further suggests these systems reduce solid and nutrient losses through physical processes and increased hydraulic residence time.

Improvements in the management of TWR systems could be made by manipulating event interval, system fullness, system volume, and effluent volume. First, event interval, system fullness, and effluent volume may be controlled by using slotted boards in the riser pipes flowing into the TWR system. Only one producer utilized slotted board risers in the TWR systems investigated. By inserting or removing these boards, the influence of rain events on TWR systems may be controlled. When boards are in place, they keep water on the field thereby reducing effluent volume and increasing the residence time of water on the landscape and in the TWR system by slowing runoff velocity. In addition to utilizing boards, system fullness may be manipulated by pumping water into OFS reservoirs and removing water from the system later when runoff events are not occurring. Based on observations of the infrastructure of TWR systems in the

Delta, systems are not designed to allow control for the depth of the water in the TWR ditch without pumping into the OFS reservoir. Therefore, once the OFS reservoir is full, the fullness of the TWR ditch and effluent volume are dependent on precipitation.

2.5 Summary and Conclusions

Tailwater recovery systems did not reduce concentrations of the majority of solids and nutrients. However, loads of solids and nutrients were reduced through retention of surface water. Tailwater recovery system performance was similar across all seasons. Nevertheless, seasonal and variable influences on performance were equivocal and need further consideration in any future studies. Intuitively, there are variables known to affect system performance but have yet to be quantified (e.g. presence, amount, type of aquatic vegetation). Variables in this study that influenced TWR system performance were: how full the system was prior to an event; time since the previous event; and amount of overflow in the event. Based on current design of TWR systems, how full the systems are prior to an event, and the time since the previous event are precipitation driven and cannot be managed. The amount of overflow in an event can be addressed by using existing riser board pipes to store additional water. The dual purpose (i.e. water savings for irrigation and reducing sediment and nutrient losses) of these systems requires additional information including a water savings budget. A water savings budget analysis would be helpful prior to altering TWR design and management (i.e. water savings schedules).

Tailwater recovery systems are implemented as an alternative source of water available for irrigation, thereby alleviating the unsustainable pressure placed on groundwater resources throughout the LMAV. This study examined solids and nutrient reductions, one proposed benefit of TWR systems. Additional work needs to quantify the potential for these systems to save water and through an economic analysis of the cost and benefits.

2.6 Acknowledgments

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Table 2.1 Characteristics of six tailwater recovery (TWR) systems and TWR system catchments at four farms

TWR System^{+}	TWR Layout	TWR Volume (ML)	TWR Crop Rotation (2014/2015)	TWR Catchment Area (ha)*	Other BMPs Included in TWR System†
1A	ditch only	115.9	Rice-Rice	74.3	irrigation land leveling (zero grade rice) (342), water control structure (410) and grade stabilization (587)
2B	ditch	7.7	Corn-Soybeans, Rice-Soybeans	155.6	irrigation land leveling (342), water control structure (410) and grade stabilization (587)
	reservoir	86.3			
3C	ditch only	37.0	Corn-Soybeans	123.8	irrigation land leveling (342), water control structure (410) and grade stabilization (587)
3D	ditch	17.8	Corn-Soybeans	68.2	
	reservoir	139.4			
4E	ditch	50.6	Rice-Soybeans	80.4	irrigation land leveling (342), water control structure (410) and grade stabilization (587)
	reservoir	197.4			
4F	ditch	18.5	Rice-Soybeans	57.2	
	reservoir	80.2			

Notes:“$^{+}$” in this column number represents farm and letter represents TWR system; “*” is total area of the tailwater recovery ditch and the land draining into the tail water recovery ditch; Crops in crop rotation include rice (*Oryza sativa*), soybeans (*Glycine max*) and corn (*Zea mays*); “†” number in parentheses shows the NRCS conservation practice number.

Table 2.2 Tailwater recovery system variable descriptors

Covariates	Brief Description	Minimum	Maximum	Mean	SD
Effluent volume	Mega liters overflowing out of TWR system during event.	0.002	306.7	11.2	33.5
System fullness	How full the TWR system is prior to the event, represented as a percentage of the total capacity.	9.72	142.0	81.9	26.8
Sampling method	Represents the method of sampling at that location, the primary method or secondary method.	NA	NA	NA	NA
Season	Months were split into seasons: winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November).	NA	NA	NA	NA
Event interval	Days past since the previous overflow event.	1.0	245.0	24.7	38.6
System volume	Volume (mega liters) of the TWR system when full.	37.0	248.0	110.9	61.2

Notes: SD is standard deviation, NA not applicable due to variable being nominal; system fullness > 100 means the system was overflowing from a previous event when the next event occurred.

Table 2.3 Performance of tailwater recovery (TWR) systems per event

Analyte	Influent - effluent (mg/L)[a]	Change (%)[b]	Influent - effluent (kg)[a]	Change (%)[b]
TSS	0.0705 ± 0.0305	21	0.1943 ± 0.0343†	43
TP	-0.0627 ± 0.0154†	-36	0.2082 ± 0.0332†	32
TN	-0.0238 ± 0.0237	-13	0.2350 ± 0.0384†	44
ON	-0.0045 ± 0.0250	-10	0.2469 ± 0.0377†	42
TIN	-0.0021 ± 0.0218	-13	0.2134 ± 0.0393†	47
$NO_3^-NO_2^-$	0.0221 ± 0.0189	27	0.2372 ± 0.0379†	51
NH_4^+	-0.0199 ± 0.0160	-245	0.0954 ± 0.0295†	24

Notes: "[a]" columns are the difference of influent and effluent locations mean ± standard error; "†" the difference between influent and effluent locations is significantly different than 0 (Hotelling's T-squared; n = 149, false discovery rate *p* value adjustment = 0.007 (mg/L) and 0.007 (kg); SAS Institute 2015); "[b]" column of percent change calculated as the mean difference divided by the mean of the field runoff and multiplied by 100, a negative number represents an increase between influent and effluent.

Table 2.4 Tailwater recovery (TWR) system annual solids and nutrient load (kg) reductions per hectare

Site	TSS	TP	TN	ON	TIN	$NO_3^-NO_2^-$	NH_4^+
1	2,057.30	1.97	10.26	6.59	3.44	2.88	0.55
2	347.01	0.40	1.81	1.13	0.64	0.68	(0.04)
3	748.24	0.14	1.16	0.40	0.76	0.69	0.07
4	1,772.97	0.82	4.00	1.78	2.23	1.99	0.24
5	789.19	0.35	1.71	1.19	0.53	0.49	0.04
6	739.21	0.10	1.45	0.87	0.74	0.86	(0.11)
Mean	1,142.9	0.7	3.8	2.2	1.5	1.3	0.2
SD	732.7	0.7	3.8	2.5	1.3	1.0	0.2

Notes: values are the total loads at TWR overflow locations subtracted from field runoff and inflow locations (n = 147). SD is standard deviation, and values in parenthesis indicate an increase in loads.

Table 2.5 Range of best management practices' reduction efficiencies

	BMP	% Reduction											References (location, design, scale)
		TSS	TP	TIP	PP	DP	SRP	TN	ON	TIN	$NO_3^-NO_2^-$	NH_4^+	
In field	No-till/ conservation tillage		35-84	-230		96		66-75			76	44	McDowell and McGregor (1980) (Mississippi, paired, plots); McDowell and Gregor (1984) (Mississippi, paired, plots); Devlin et al. (2003) (Kansas, paired, field); Anders et al. (2004) (Arkansas, paired, field); Dinnes (2004) (Iowa, paried, field); Rebich (2004) (Mississippi, paired, field)*
	Fallow rice field management						0				100	26	Manley et al. (2009) (Mississippi, inflow-outflow, field)
	Contour planting and terracing		30-75										Devlin et al. (2003) (Kansas, paired, field)
	Contour buffer strips	19	26					20			39	32	Udawatta et al. (2002) (Missouri, paired, field)*
	Cover crops	92	7-63			7-63					37-77	35-41	Zhu et al. (1989) (Missouri, paired, plots)*; Dinnes (2004) (Iowa, paired, field); Strock et al. (2004) (Minnesota, paired, plots)*; Kaspar et al. (2007) (Iowa, paired, plots)*; Qi et al. (2011) (Iowa, paired, plots)*; Kaspar et al. (2012) (Iowa, paired, plots)*
Edge of field	Current study TWR systems[1]	20-94	23-92	.	.	.	.	34-97	30-96	29-98	27-98	-108-97	Current study (Mississippi, inflow-outflow, farm)
	Tailwater recovery system	71-97	.	.	.	.	.	.	.	.	-40	.	Smulker et al. 2012 (California US, inflow-outflow, farm)*[C]

Notes: table adjusted from Kröger et al. (2012), Pierce et al. (2012a), Sharpley et al. (2009), and additional more current sources. Grey shaded row are the results from this study, TSS = total suspended solids, TP = total phosphorus, TIP = total inorganic phosphorus, PP = particulate phosphorus, DP = dissolved inorganic phosphorus, SRP = soluble reactive phosphorus, TN = total nitrogen, ON = organic nitrogen, TIN = total inorganic nitrogen, $NO_3NO_2^-$ = nitrate-nitrite nitrogen, NH_4^+ = ammonium, "[1]" Range across all sites in the current study, "[C]" concentrations used in manuscript, "*" NO_3^- reported in the manuscript, "$^+$" TKN reported in manuscript not ON.

Table 2.5 (continued)

	BMP	% Reduction											References (location, design, scale)
		TSS	TP	TIP	PP	DP	SRP	TN	ON	TIN	$NO_3^-NO_2^-$	NH_4^+	
Edge of field (continued)	Riser board pipes		24-42	-105-88				26-45			41-79	44	Evans et al. (1991) (North Carolina, paired, field); Evans et al. (1995) (North Carolina, paired, field); Rebich (2004) (Mississippi, paired, field)*; Kröger et al. (2012) (Arkansas, inflow-outflow, plots)*; Kröger et al. (2013) (Arkansas, inflow-outflow, plots)*
	Vegetated buffer/filter strip	91	4-67		68	62		77			51	58	Devlin et al. (2003) (Kansas, paired, field); Blanco-Canqui et al. (2004) (Missouri, continuous monitoring, plots)*; Dinnes (2004) (Iowa, paired, field)
	Riparian buffers		40-93										Smith et al. (1992) (Oklahoma, multiple, watershed); Dinnes (2004) (Iowa, paired, field)
	System: Buffer strips/slotted board risers	70	41										Locke et al. (2008) (Mississippi, paired, watershed)
	System: Buffer strips/ riparian zones/slotted board risers	53	31								-4	-13	Cullum et al. (2006) (Mississippi, before/after, watershed)*^{c}
	Subsurface drainage	31	31					17					Bengston et al. (1995) (Louisiana, paired, plots)
	Subsurface controlled drainage		20-95					44			46-96		Gilliam et al. (1979) (North Carolina, paired, plots)*; Evans et al. (1991) (North Carolina, paired, field)*; Evans et al. (1995) (North Carolina, paired, field)*; Wesstrom et al. (2001) (Sweden, paired, plots)*; Wesstrom and Messing (2007) (Sweden, paired, plots)*

Notes: table adjusted from Kröger et al. (2012), Pierce et al. (2012a), Sharpley et al. (2009), and additional more current sources. Grey shaded row are the results from this study, TSS = total suspended solids, TP = total phosphorus, TIP = total inorganic phosphorus, PP = particulate phosphorus, DP = dissolved inorganic phosphorus, SRP = soluble reactive phosphorus, TN = total nitrogen, ON = organic nitrogen, TIN = total inorganic nitrogen, $NO_3^-NO_2^-$ = nitrate-nitrite nitrogen, NH_4^+ = ammonium, "^{1}" Range across all sites in the current study, "^{C}" concentrations used in manuscript, "*" NO_3^- reported in the manuscript, "$^+$" TKN reported in manuscript not ON.

Table 2.5 (continued)

	BMP	% Reduction											References (location, design, scale)
		TSS	TP	TIP	PP	DP	SRP	TN	ON	TIN	$NO_3^-NO_2^-$	NH_4^+	
Edge of field (continued)	Subsurface controlled drainage (riser)										14-96		Lalonde et al. (1996) (Ontario, paired, field)*; Tan et al. (1998) (Ontario, paired, plots)*; Borin et al. (2001) (Italy, paired, plots)*; Ng et al. (2002) (Ontario, paired, plots)*; Fausey (2005) (Ohio, paired, plots)*; Bastiené et al. (2009) (Lithuania, paired, plots)*; Drury et al. (2009) (Ontario, paired, plots)*
	Wetlands (natural)	3	5-10								38-85		Davis (1981) (Iowa, inflow-outflow, field)*; Mitsch (1992) (Illinois, inflow-outflow, field); DeLaune et al. (2005) (Louisiana, inflow-outflow, watershed)^{C}*; Mitsch et al. (2005) (Louisiana, inflow-outflow, field)
	Wetlands (constructed)	63-96	0-98				-15-86	15-44	39-85		1-93	-77-20	Mitsch (1992) (Illinois, inflow-outflow, field); Smith et al. (1992) (Oklahoma, multiple, watershed); Phillips and Crumpton (1994) (Illinois, inflow-outflow, field)*; Phillips (1997) (Illinois, inflow-outflow, field)*; Hunt et al. (1999) (North Carolina, inflow-outflow, watershed)*$^{+}$; Xue et al. (1999) (Illinois, inflow-outflow, field); Kovacic et al. (2000) (Illinois, inflow-outflow, field); Zhang and Mitsch (2000, 2001, 2002, 2004) (Ohio, inflow-outflow, field)*; Braskerud (2002) (Norway, inflow-outflow, field); Koskiaho et al. (2003) (Finland, inflow-outflow, field); Dinnes (2004) (Iowa, paired, field); Fink and Mitsch (2004) (Ohio, inflow-outflow, field); Tanner et al. (2005) (New Zealand, inflow-outflow, field)*; Crumpton et al. (2006) (Iowa, inflow-outflow, field)*; Kovacic et al. (2006) (Illinois, inflow-outflow, field)*; O'Geen et al. (2007) (California, inflow-outflow, field)C; Sukias and Tanner (2011) (New Zealand, inflow-outflow, field)*

Notes: table adjusted from Kröger et al. (2012), Pierce et al. (2012a), Sharpley et al. (2009), and additional more current sources. Grey shaded row are the results from this study, TSS = total suspended solids, TP = total phosphorus, TIP = total inorganic phosphorus, PP = particulate phosphorus, DP = dissolved inorganic phosphorus, SRP = soluble reactive phosphorus, TN = total nitrogen, ON = organic nitrogen, TIN = total inorganic nitrogen, $NO_3^-NO_2^-$ = nitrate-nitrite nitrogen, NH_4^+ = ammonium, "[1]" Range across all sites in the current study, "^{C}" concentrations used in manuscript, "*" NO_3^- reported in the manuscript, "$^{+}$" TKN reported in manuscript not ON.

Table 2.5 (continued)

	BMP	% Reduction											References (location, design, scale)
		TSS	TP	TIP	PP	DP	SRP	TN	ON	TIN	$NO_3^-NO_2^-$	NH_4^+	
Edge of field (continued)	Drainage ditches		44-91		44	44		31	85	57	42-76	59-66	Kröger et al. (2007) (Mississippi, inflow-outflow, field)*; Kröger et al. (2008) (Mississippi, inflow-outflow, field)*; Moore et al. (2010) (Mississippi, inflow-outflow, field)*+
	Two-stage drainage ditches										1-11		Roley et al. (2012) (Indiana, before-after-control-impact, field); Mahl et al (2015) (Indiana, Michigan, Ohio, paired, field/stream)
	In-ditch weirs			-2-97							-885-96		Kröger et al. (2011) (Arkansas, inflow-outflow, plots); Littlejohn et al. (2014) (Mississippi, inflow-outflow, field)*; Baker et al. (2016) (Mississippi, inflow-outflow, field)
Retirement	Conservation reserve program	36-85	52			36		60	54		71-83	35	Cullum et al. (2010) (Mississippi, before/after paired, field)*+

Notes: table adjusted from Kröger et al. (2012), Pierce et al. (2012a), Sharpley et al. (2009), and additional more current sources. Grey shaded row are the results from this study, TSS = total suspended solids, TP = total phosphorus, TIP = total inorganic phosphorus, PP = particulate phosphorus, DP = dissolved inorganic phosphorus, SRP = soluble reactive phosphorus, TN = total nitrogen, ON = organic nitrogen, TIN = total inorganic nitrogen, $NO_3^-NO_2^-$ = nitrate-nitrite nitrogen, NH_4^+ = ammonium, "[1]" Range across all sites in the current study, "[C]" concentrations used in manuscript, "*" NO_3^- reported in the manuscript, "[+]" TKN reported in manuscript not ON.

Table 2.6 TWR system descriptors selected by a stepwise multiple regression selection procedure to predict the scores of principal component 1

Variable	Estimate	t	*p* > t
Intercept	3.72915	7.06	< 0.0001
System fullness	-0.03405	-7.17	< 0.0001
Event interval*System fullness*System volume	0.00003	4.72	< 0.0001
Effluent volume	-1.19177	-4.86	< 0.0001
Effluent volume*System fullness	0.00496	1.56	0.1205
System volume	-0.00817	-4.00	0.0001
Effluent volume*System fullness*System volume	0.00005	2.58	0.0109

Notes: The principal component included the six analytes (loads) listed in table 2.3. Variables of the stepwise multiple regression are listed in table 2.2. “*” represents an interaction between variables.

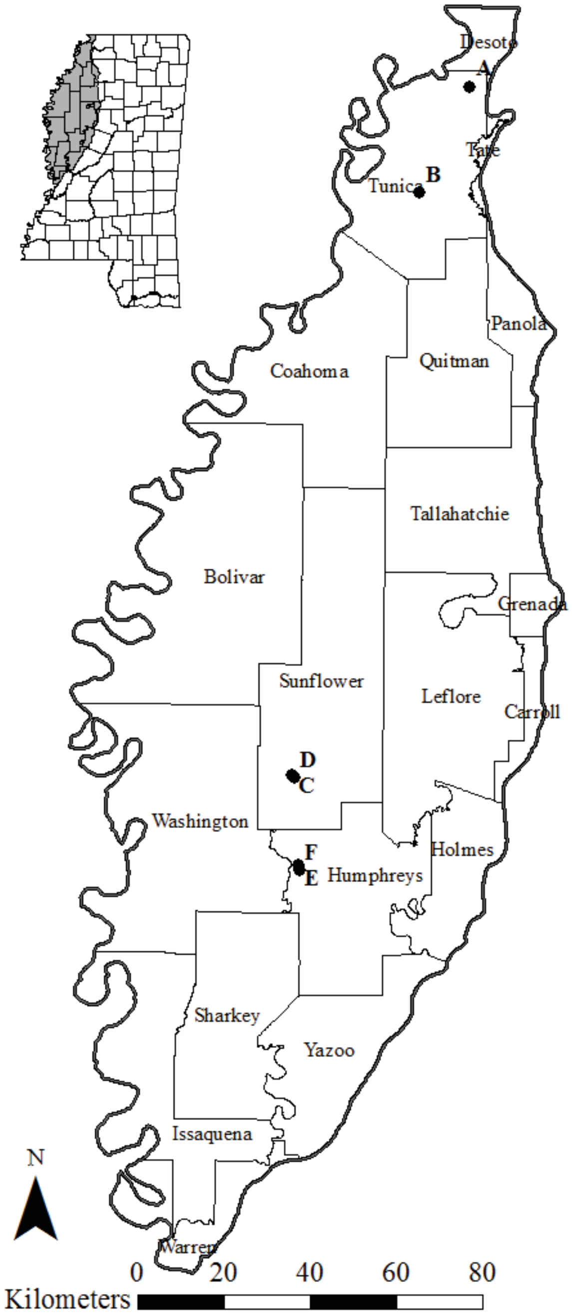

Figure 2.1 Map of the Delta region of Mississippi and location of the tailwater recovery systems included in this study

Notes: Map insert top left is the state of Mississippi showing the Delta region shaded in dark grey. Map bottom right depicts TWR systems represented as dots and labeled with letters corresponding to table 2.1, and counties outlined and labeled in black. Coordinate system Mississippi Transverse Mercator (mstm), projection is transverse Mercator and datum is North American 1983.

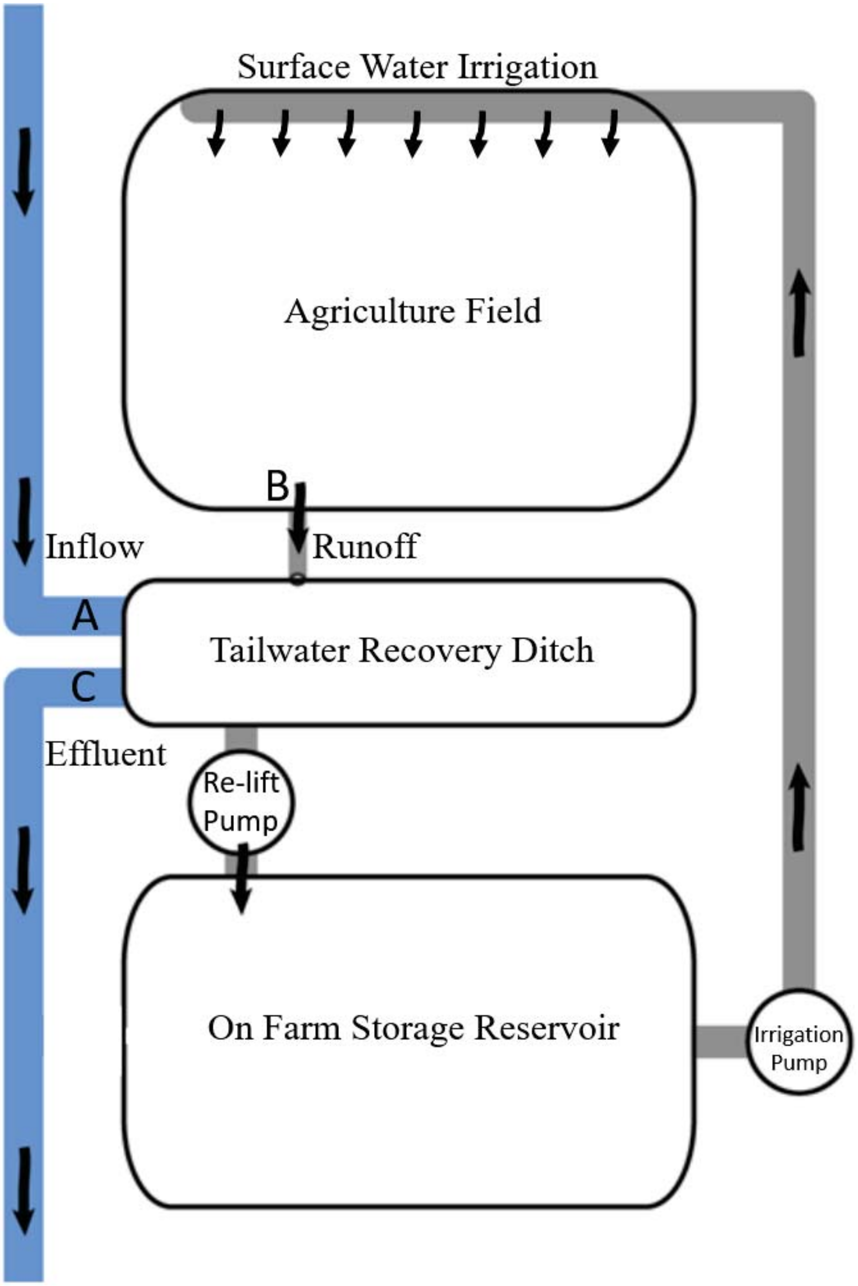

Figure 2.2 Schematic of generic tailwater recovery (TWR) system and sampling locations

Notes: Diagram is a visualization tool, and is not inclusive of all TWR systems. Tailwater recovery systems may differ by only containing a large TWR ditch and no on-farm storage reservoir, off-farm inflow location (i.e. inflow), and different pumps and service pipes. A, B, and C represent sampling locations. Samples were collected at A the off-farm inflow to the TWR system (only system A (table 2.1) contained an inflow location), B represents field runoff locations at each system (both A and B are considered influent), and C locations were the effluent to each TWR system.

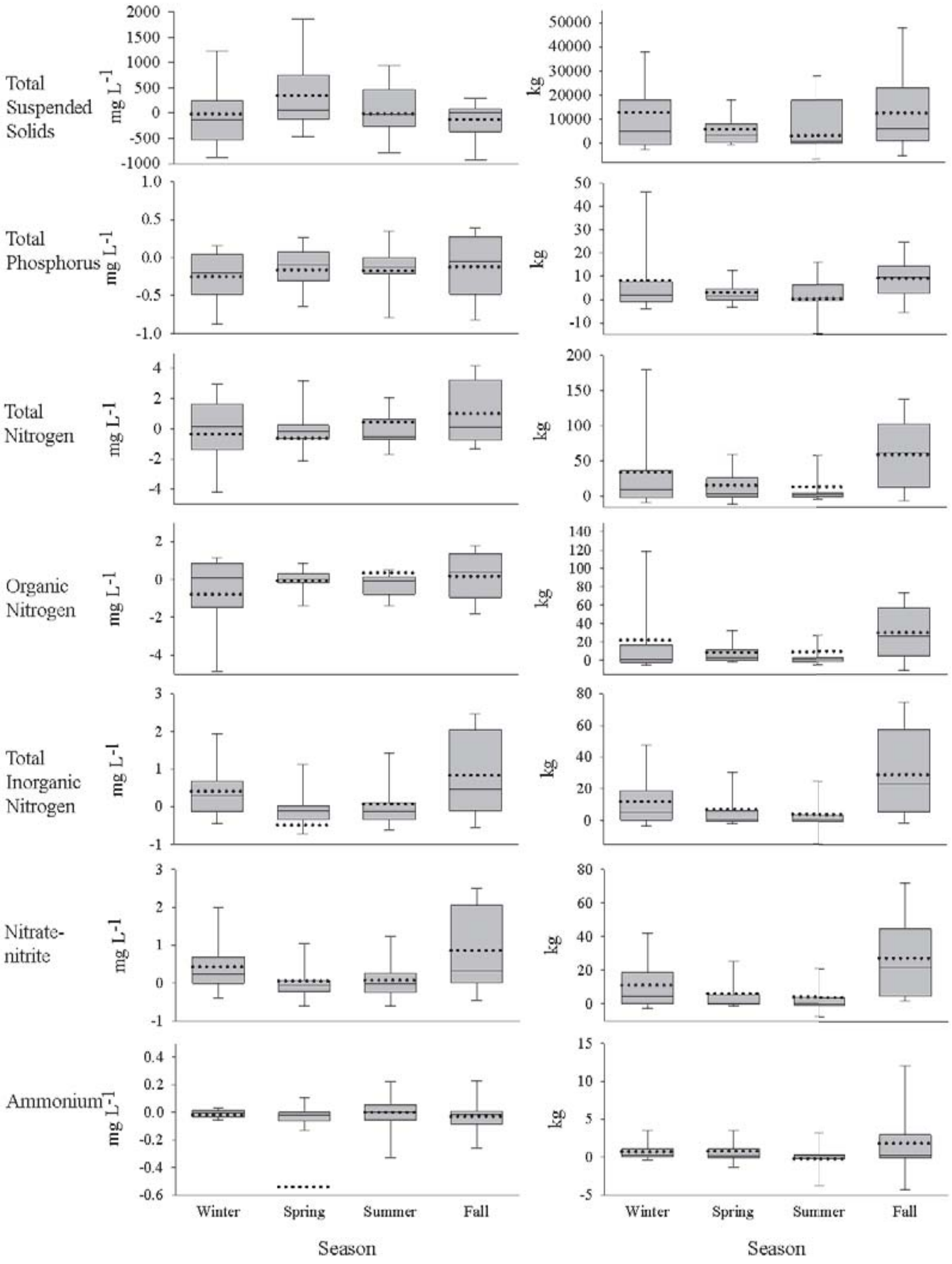

Figure 2.3 Seasonal differences in tailwater recovery (TWR) system performance (influent-effluent)

Notes: Whiskers represent standard error, dotted lines represent means, solid lines represent medians, (MANOVA, n = 147, false discovery rate p value adjustment $p < 0.014$; concentrations $F_{146} = 1.54$ $p > 0.05$, loads $F_{146} = 1.55$ $p > 0.05$, SAS Institute 2015).

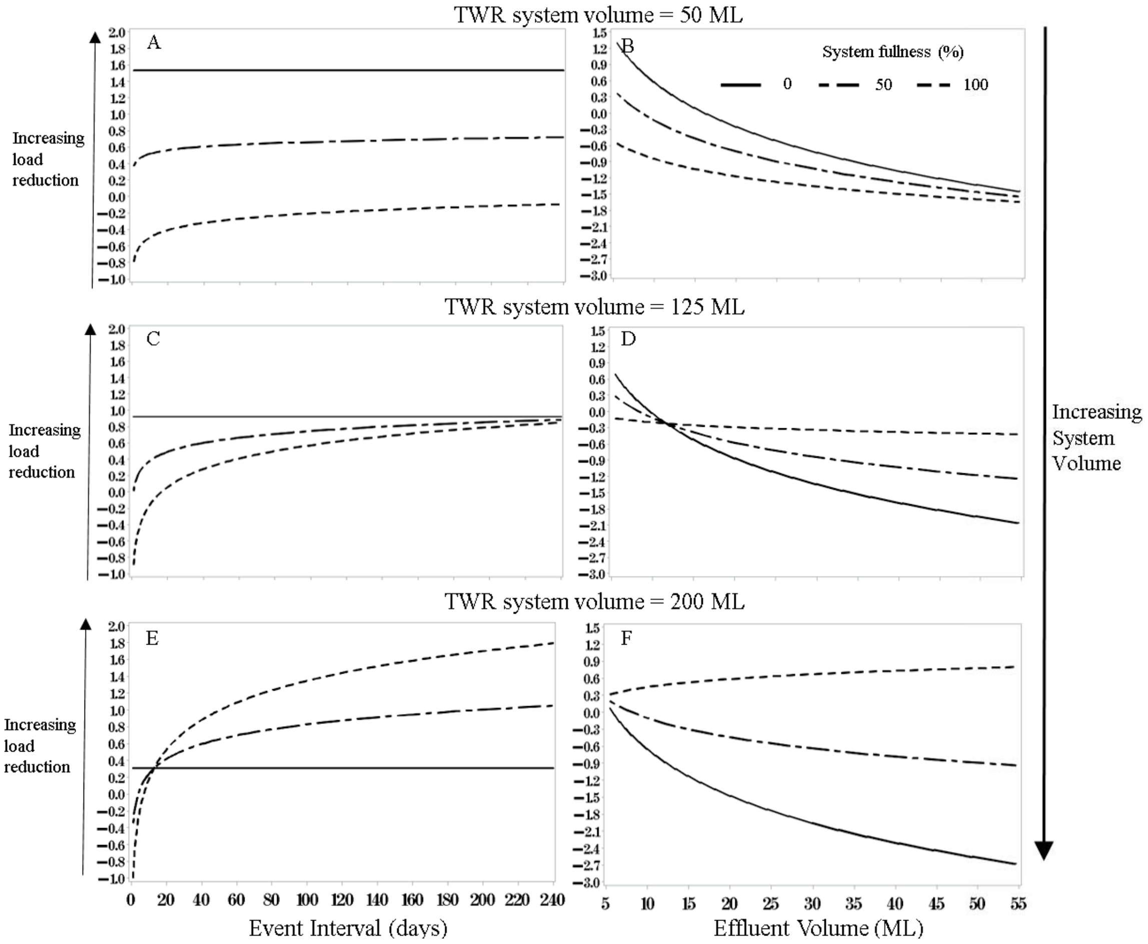

Figure 2.4 Relationships of tailwater recovery (TWR) system predictors to principal component scores

Note: Y-axis represent principal component scores which represent load reductions.

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CHAPTER III

REPRESENTATION OF SOLID AND NUTRIENT CONCENTRATIONS IN IRRIGATION WATER FROM TAILWATER RECOVERY SYSTEMS BY SURFACE WATER GRAB SAMPLES

3.1 Abstract

Tailwater recovery (TWR) systems are being implemented on agricultural landscapes to create an additional source of irrigation water. Existing studies have sampled TWR systems using grab samples; however, the applicability of solids and nutrient concentrations in these samples to water being irrigated from TWR systems has yet to be investigated. This is important if research using grab samples is used to quantify the application of solids and nutrients back onto the agricultural landscape. In order to test whether grab samples are representative of water pumped from TWR systems for irrigation use, this study compared concentrations of total suspended solids (TSS), total P (TP), total N (TN), total Kjeldahl N (TKN), nitrate-nitrite ($NO_3^-NO_2^-$) and ammonium (NH_4^+). Grab samples were collected simultaneously from the surface water and from their respective outflow of irrigation infrastructure in six TWR systems in the Lower Mississippi Alluvial Valley. Comparison of 14 irrigation events showed TSS, TP, TN, TKN, $NO_3^-NO_2^-$ and NH_4^+ did not differ between surface water grab samples and irrigation water samples. No differences were found for TN, TP, NH_4^+, and TKN across sites, however, differences between sites did exist for TSS and $NO_3^-NO_2^-$. This research suggests surface water grab samples from TWR systems represent the solid and nutrient concentrations being irrigated at that moment of time.

Key words: tailwater recovery system-best management practices-water reuse-irrigation-water quantity-water quality

3.2 Introduction

Throughout the US, aquifers are being utilized at unsustainable rates for agricultural irrigation (Frederick 2006; Thornton 2012). This has led to lower groundwater levels or even groundwater depletion, jeopardizing agricultural security and leading to an increased implementation of infrastructure to use surface water for irrigation. One conservation practice providing surface water for irrigation is surface water capture-and-irrigation reuse systems, also known as tailwater recovery (TWR) systems. Tailwater recovery systems are a combination of a ditch which captures surface water runoff, an on-farm storage (OFS) reservoir to store additional captured surface water, and pumps to re-lift captured water into the OFS reservoir or for irrigation back onto fields. The United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) provides financial assistance for TWR systems under practice code 436 (USDA NRCS 2016).

To date, studies on TWR systems (Kirmeyer et al. 2012; Carruth et al. 2014; Karki et al. 2015; Moore et al. 2015) have utilized non-isokinetic open-mouth bottle samples (i.e. grab samples) (Ward and Harr 1990; Wilde et al. 1999). These samples consist of taking a water sample at one moment in time ("snapshot") and may be collected by hand using a bottle or automatically using a pump. This sampling method has been used extensively in water quality research in both lotic (Pierce et al. 2012; Jarvie et al. 2002) and lentic (Baldwin et al. 2008; Glińska-Lewczuk 2009) systems, and is an approved method of sampling by the Environmental Protection Agency (EPA) (USEPA 1982) and US Geological Survey (USGS) (Wilde et al. 1999) for documenting water quality.

In TWR systems, the use of grab samples has not been verified to provide representative samples from irrigated water. Previous studies in TWR systems utilized grab sampling to describe the nutrient dynamics within the systems (Kirmeyer et al. 2012; Carruth et al. 2014; Karki et al. 2015; Moore et al. 2015). Studies were not designed to test whether surface grab samples were representative of irrigated water, although one study noted stratification may occur within OFS reservoirs (Moore et al. 2015). Moore et al. (2015) showed a difference in nitrate, nitrite and phosphate concentrations between grab samples taken at the surface and bottom of a shallow (mean depth of 1 m) OFS reservoir which was attributed to stratification. Research in TWR systems during irrigation is warranted to investigate if the solid and nutrient concentrations in grab samples of TWR systems represent surface water being irrigated. This is necessary if existing and future studies are to be used to quantify the additional value of reducing fertilizer inputs by using surface water for irrigation which contains nutrients.

In TWR systems, if routine grab samples represent irrigation samples, sampling regimes may be simplified thereby reducing resources required to quantify the quality of irrigation water. Researchers would not be required to be present at every irrigation event. In addition, grab sample data collected for existing and future studies may be used to quantify the quality of irrigated water during the irrigation season. Studies using grab samples to document nutrients within TWR systems may be applicable to economic analyses if the water sampled during the irrigation season is representative of the water being irrigated. Tailwater recovery systems have been hypothesized to allow for the irrigation reuse of nutrients, thereby allowing producers to reduce fertilizer inputs (Carruth et al. 2014). If fertilizer consumption is reduced, documentation of this benefit is important for economic analyses of TWR systems. Investigation into the benefits of TWR systems is imperative to justify federal and producer costs. Therefore, the objective of this study was to determine if solid and nutrient concentrations in grab samples collected from surface water in TWR systems are representative of solid and nutrient concentrations in water being used for irrigation from TWR systems.

3.3 Materials and Methods

3.3.1 Sampling sites and sample collection

Samples were collected from six TWR ditches and five OFS reservoirs on five separate farms in the Mississippi Delta (figure 3.1). Catchment areas draining into TWR systems ranged from 68.2 ha to 639.8 ha on farms growing different crop rotations of continuous rice (*Oryza sativa*), rice-soybeans (*Glycine max*), and corn (*Zea mays*)-soybeans (table 3.1). One TWR system consisted of only a TWR ditch. Samples were collected during the 2015 irrigation season (May-September) at intervals corresponding to irrigation events using TWR water. Sampling was coordinated between researchers to facilitate simultaneous water collection from the TWR ditch or OFS reservoir (depending on the irrigation source) and the outflow of the irrigation infrastructure (figure 3.2). Tailwater recovery system surface water samples were collected at a consistent location 3.7-m from shoreline to bypass aquatic vegetation. All samples were comprised of two, 1

L grab samples. For all water samples, one of the two 1-L samples was immediately acid preserved with 2 ml of 49% sulfuric acid solution for nutrient analyses, and the other was used for solids analyses. Samples were collected, labeled, placed on ice and transported within 24 h according to US-EPA QA/QC guidelines (USEPA 2002) to the Mississippi Department of Environmental Quality (MDEQ) laboratory for analyses.

3.3.2 Sample analyses

Samples were analyzed for total suspended solids (TSS) and nutrient concentrations including total phosphorus (TP), total Kjeldahl nitrogen (TKN), nitrate-nitrite ($NO_3^-NO_2^-$), and ammonium (NH_4^+). Total suspended solids were determined using method 2540D described in Eaton et al. (1998). Prior to nutrient analyses, samples were filtered using vacuum filtration through a 0.45µm 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_4^+ and $NO_3^-NO_2^-$ according to the standard methods of persulfate digestion, Berthelot reactions, and cadmium reduction, respectively (Eaton et al. 1998). Total Kjeldahl nitrogen 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 $NO_3^-NO_2^-$, and organic nitrogen (ON) was deduced from TKN and NH_4^+.

3.3.3 Statistical analysis of water samples

Statistical analysis consisted of a multivariate analysis of variance (MANOVA) with analytical data from irrigation sampling locations (TWR ditch or OFS reservoir) and irrigation infrastructure. Independent variables included site and location, with site being the farm from which samples were collected from and location being either TWR surface water or the irrigation infrastructure. Dependent variable data for all analytes were found using Shapiro-Wilks test to be non-normally distributed and were $\log_{10}$ transformed to meet MANOVA assumptions. In addition, homogeneity of variances was checked using Levene's test and found to be not significant (alpha = 0.05). Numbers of samples collected were unbalanced between farms due to more sampling opportunities at farms that irrigated more frequently with surface water. Type II sum of squares were used to perform MANOVA in package "Car" in R version 3.2.2 Statistical Software (R Development Core Team 2015). An alpha level of 0.05 was used for multivariate significance tests.

3.4 Results and Discussion

3.4.1 Results of sampling location analyses

Comparison of 14 events of irrigation pumping samples across six systems showed no significant difference (Pillai's trace $_{5,\,1} = 0.307$, $p > 0.5$) in analytes between surface water sources (i.e. TWR ditches or OFS reservoir) and the irrigation output (figure 3.3). These results suggest grab samples from TWR ditches or OFS reservoirs are representative of irrigation water in that moment of time.

Data from this experiment indicates grab samples from TWR systems represent irrigated water. Although stratification may occur in TWR systems, mixing of the water column at intake pumps provides comparable samples between irrigated water and surface grab samples. Stratification in N species has been documented in lakes, where an increase in depth corresponds to increasing NH_4^+ and decreasing NO_3^- (Wetzel 2001). In addition, this stratification intensifies in the warmer months of the year (Wetzel 2001).

Moore et al. (2015) showed a difference in NO_3^- concentrations between grab samples taken at the surface and samples taken at the bottom of OFS reservoirs, suggesting stratification may lead to a difference in surface water samples taken from OFS reservoirs and irrigated water during pumping events. Unlike the previous study by Moore et al. (2015), this study sampled TWR systems while irrigation water was being pumped. Although bottom samples were not collected, discrepancies between surface and bottom water samples potentially caused by stratification may be alleviated if mixing occurs during irrigation. Pumps in OFS reservoirs and TWR ditches were observed to mix the water column based on visual observation of vortex-type intake (i.e. whirlpool) in OFS reservoirs and TWR ditches (figure 3.4). This mixing could result in water being drawn from the surface and entire water column to the bottom where the sump pipe is located. This is, however, likely dependent on the size of the irrigation pump and depth of TWR system. Depth in systems included in this study (1.5-3 m) differed from those sampled by Moore et al. (2015) (mean depth: 1 m). Although the greater depth of this study's systems would more likely lead to stratification, this was not observed in comparisons between grab samples and irrigated water. Although grab sampling may be limited in spatial and temporal representation of the entire water body, the ease of sampling and representability of samples are clearly beneficial.

3.4.2 Results of samples across farms

Significant differences across locations (Pillai's trace $_{5,1} = 2.13$, $p < 0.05$) were found for analyte concentrations. Individual concentrations of TN, TP, NH_4^+, and TKN did not differ ($p > 0.05$) between locations. However, TSS ($F_{5,16} = 6.80$, $p < 0.007$) and $NO_3^-NO_2^-$ ($F_{5,16} = 8.90$, $p < 0.0001$) were different between locations. Moore et al.

(2015) found no difference among TWR systems within the same farm, suggesting TWR ditches and OFS reservoirs within the same spatial area receiving the same runoff from fields with similar management contain similar nutrient concentrations. In addition, during the irrigation season, Carruth et al. (2014) and Kirmeyer et al. (2012) showed little variability between TWR system sites (different farms) for solids and P with more variation in N species concentrations. Variability in N species across sites (i.e. farms) is expected due to individual tillage practices, fertilizer application and rates, crop rotations and TWR systems differences (i.e. depth).

3.5 Summary and Conclusions

Systematic grab sampling methods from six TWR systems, were representative of solid and nutrient concentrations being applied through surface water irrigation. Although stratification may occur in TWR systems, the mixing caused by irrigation pumps results in similar solid and nutrient concentrations to surface water grab samples. This research provides evidence toward sampling accuracy and methodology for determining sound measurements of irrigation water quality in surface water irrigation systems.

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Table 3.1 Characteristics of tailwater recovery systems

Farm	TWR	Layout	Volume (ML)	Crop Rotation	Catchment Area (ha)*	Other Best Management Practices†
1	A	TWRD	115.9	Rice-Rice	74.3	irrigation land leveling (zero grade rice) (342), water control structure (riserboard pipes) (410) and grade stabilization (field perimeter pads) (587)
2	B	TWRD	7.7	Rice-Soybeans, Corn-Soybeans	155.6	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
		OFS	86.3			
3	C	TWRD	25.5	Corn-Soybeans	639.8	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
		OFS	185.0			
4	D	TWRD	37.0	Corn-Soybeans	123.8	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
	E	TWRD	17.8	Corn-Soybeans	68.2	
		OFS	139.4			
5	F	TWRD	50.6	Rice-Soybeans	80.4	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
		OFS	197.4			
	G	OFS	80.2	Rice-Soybeans	57.2	

Notes: TWR is tailwater recovery system, ML is mega liters, ha is hectares, TWRD is the tailwater recovery ditch, OFS is on farm storage reservoir, “*” is the area of the catchment draining into the TWRD. Crops in crop rotation include: rice (*Oryza sativa*), soybeans (*Glycine max*) and corn (*Zea mays*). “†” Number in parentheses shows the USDA NRCS conservation practice number.

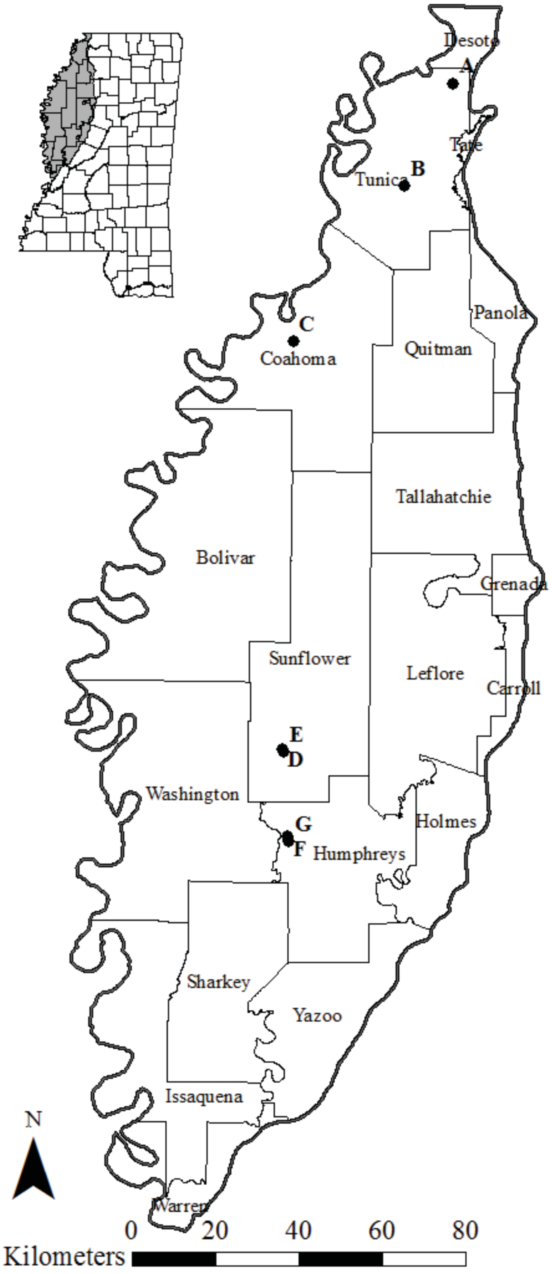

Figure 3.1 Map of the Delta region of Mississippi and locations of tailwater recovery systems

Notes: Map insert top left is the state of Mississippi the Delta region shaded in dark grey. Map bottom right depicts farms represented as dots and Delta counties outlined and labeled in black. Individual TWR systems noted by black letters corresponding to table 3.1. Coordinate system used is Mississippi Transverse Mercator (mstm), projection is transverse Mercator and datum is North American 1983.

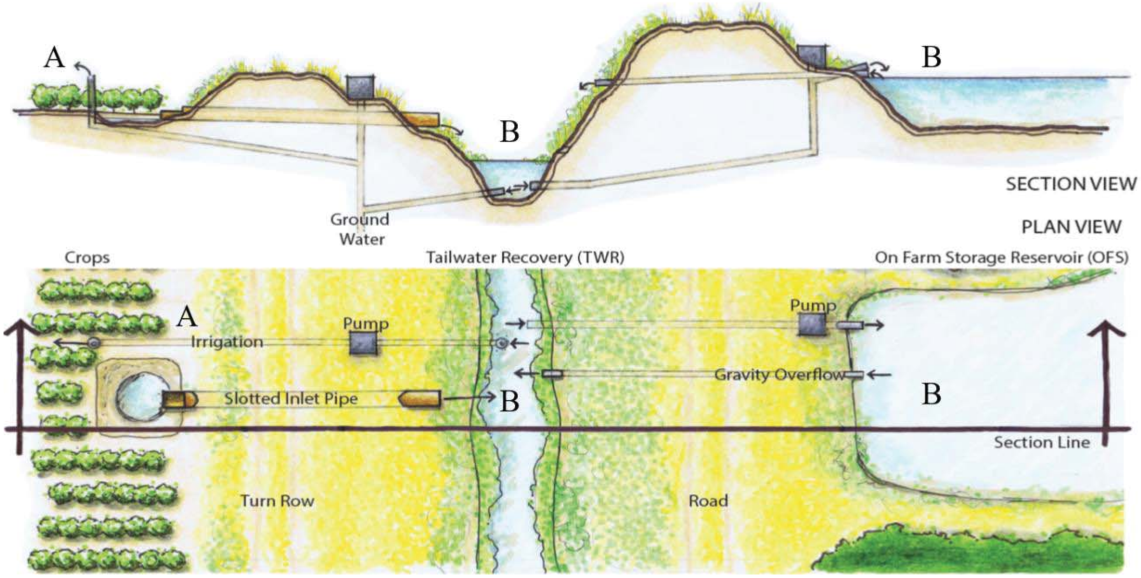

Figure 3.2 Tailwater recovery diagram

Notes: This diagram is meant as a visualization tool, as not all TWR are designed this way. Most TWR have differences including only containing a large TWR and no OFS and different pumps and service pipes. "A" and "B" represent sampling locations. Samples were collected from A and B locations depending on where surface water was being irrigated from. This diagram was provided courtesy of Mississippi State University's Research and Education to Advance Conservation and Habitat program.

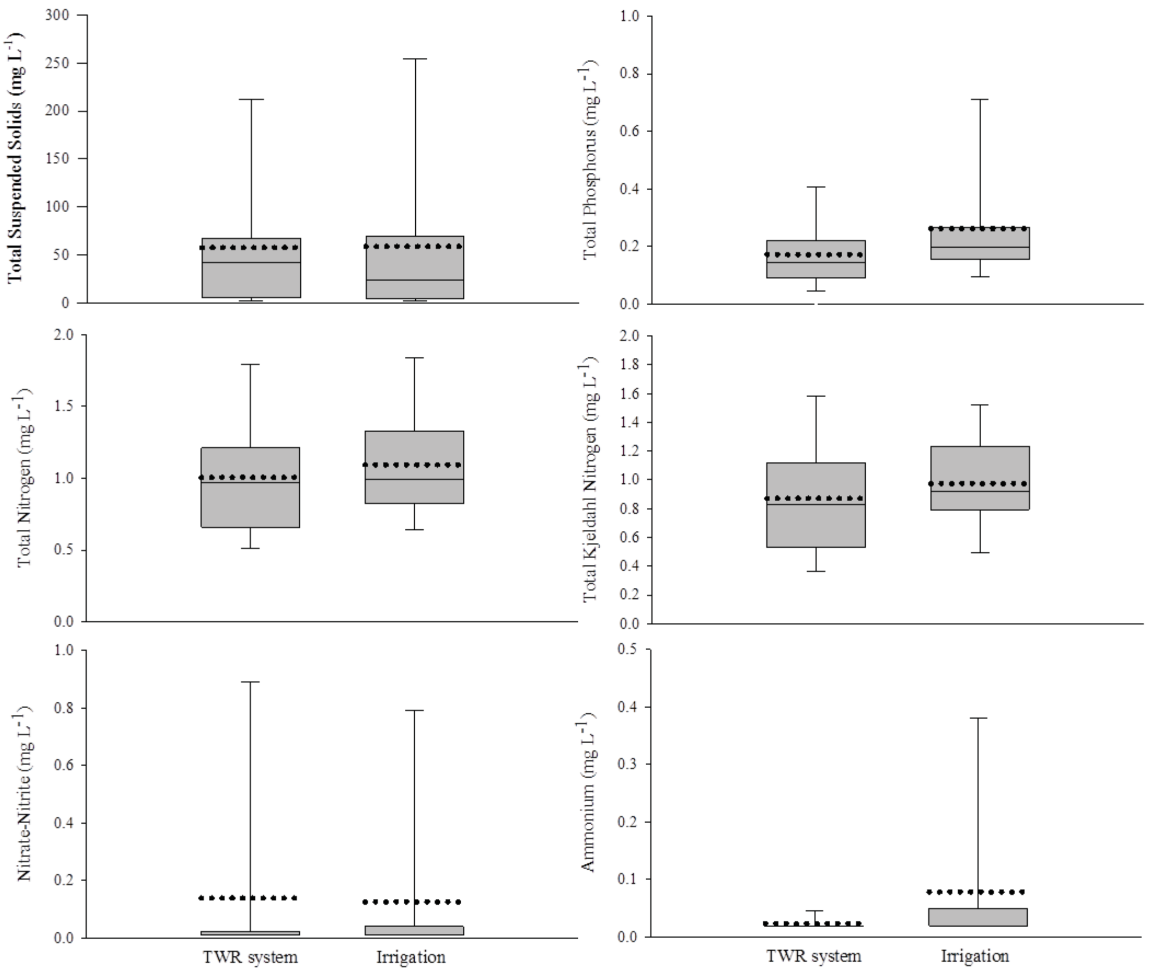

Figure 3.3 Comparison of analyte concentrations in TWR system samples and irrigation samples

Notes: Error bars represent standard error, dotted lines represent means, solid lines represent medians, no significant differences found (MANOVA, Pillai's trace *post hoc*; $p > 0.1$, n = 14).

Figure 3.4 Photographs of vortex-type activity created by tailwater recovery (TWR) system pumps

Notes: Above left was taken at TWR system A and above right was taken at TWR system C. Black arrows point to the disturbance area directly above pump intake pipes.

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CHAPTER IV

IRRIGATION POTENTIAL OF SUSPENDED SOLIDS AND NUTRIENTS FROM TAILWATER RECOVERY SYSTEMS

4.1 Abstract

Within the Lower Mississippi Alluvial Valley (Mississippi Delta), best management practices (BMP) are being utilized to mitigate nutrient loading from agricultural landscapes to downstream waters. Tailwater recovery (TWR) systems are an important BMP currently utilized to increase nutrient retention and hypothesized to supplement fertilization practices, however, their effectiveness has not been thoroughly evaluated. This study was conducted to determine the potential to use solids, P and N captured by tailwater recovery (TWR) systems for reuse onto production fields through irrigation applications. Seven TWR systems located in the Mississippi Delta were assessed for seasonal changes in water nutrient concentrations and total nutrient loads. Samples were collected every three weeks from 2013 to 2015 for seasonal analyses and weekly during the 2014 and 2015 growing seasons (May-September) for nutrient load analyses. Nutrient loads per hectare recycled back onto the landscape were estimated from the TWR system’s water volume, the concentrations in irrigation samples, and the tillable acreage being irrigated. Spring water samples had greater concentrations of solids than in winter and summer, as well as P than in summer. In addition, spring had greater concentrations of nitrate-nitrite than in all seasons, and ammonium than in summer and fall. Organic N concentrations in water samples collected from TWR systems were greater in the fall (post-growing season) than in the winter or spring. Mean nutrient loads per hectare recycled onto the landscape were 0.30 kg ha^{-1} solids, 0.20 kg ha^{-1} P, and 0.86 kg ha^{-1} N, with the N being irrigated as 77% organic. The greatest concentrations in TWR system solids and nutrients occurred during the spring instead of the summer irrigation season, thereby reducing the potential solids and nutrients to be irrigated. Tailwater recovery systems can be used to recycle solids, P and N onto the agricultural landscapes through irrigation events; however, nutrient loads will not be sufficient to alter agronomic fertilizer recommendations.

Keywords: tailwater recovery system, best management practices, water reuse, irrigation, water quantity, water quality

4.2 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 and Rabalais 2003). The second issue is the unsustainable water withdrawal from the Lower Mississippi River Valley Alluvial Aquifer for irrigation during the growing season when precipitation is minimal (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 and Clark 2011). This unsustainable use of groundwater has raised awareness about water conservation and the need to conserve existing 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. Tailwater recovery 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 into the OFS reservoir or onto fields as irrigation. Although the shape and size of TWR systems vary, ditches are designed to hold a minimum of 14.8 ML of water (3-4 times the hectares of runoff collection as the area irrigated from the TWR system); store 8.89 cm of water to cover the irrigated area, and if an OFS reservoir is present then the TWR ditch should have the capacity to store 1/6-1/8 the capacity of the OFS reservoir (P. Rodrigue, NRCS, personal communication, 2015). On-farm storage reservoirs are designed to be a minimum range of 1-13 of the hectares to be irrigated, with an equal number of hectares running off into the TWR ditch associated with the OFS reservoir as the hectares to be irrigated by the OFS reservoir, and it should store 15.24 cm of irrigation water for the irrigated area (P. Rodrigue, NRCS, personal communication, 2015). 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 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 have 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 irrigation of nutrients, 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 solids, P and N captured by TWR systems back on to production fields through irrigation applications.

4.3 Materials and Methods

4.3.1 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 (figure 4.1). One TWR system consisted of only a ditch and in another TWR system only the

OFS was sampled (table 4.1). Water samples were collected from 2013 to 2015 from both TWR ditches and OFS reservoirs every three weeks throughout the year to assess seasonal changes in water nutrient concentrations (hereafter described as “seasonal” samples) (figure 4.2). Additionally, to assess nutrient loads onto irrigated fields, water samples were collected from 2014-2015 on a weekly basis during the growing season (May-September) from source TWR locations used for irrigation (either TWR ditches or OFS reservoirs) (hereafter described as “irrigation” samples). All samples were collected at consistent locations and were comprised of two, 1 L grab samples collected 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.

4.3.2 Sample analyses

Samples were analyzed for total suspended solids (TSS) and nutrient concentrations including total phosphorus (TP), total Kjeldahl nitrogen (TKN), nitrate-nitrite ($NO_3^-NO_2^-$), and ammonium (NH_4^+). Total suspended solids were determined using method 2540D described in Eaton et al. (1998). Prior to nutrient analyses, samples were filtered using vacuum filtration through a 0.45μm 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_4^+ and $NO_3^-NO_2^-$ (i.e. NO_x) according to the standard methods of persulfate digestion, Berthelot reactions, and cadmium reduction, respectively (Eaton et al. 1998).

Total Kjeldahl nitrogen 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 $NO_3^-NO_2^-$, and organic nitrogen (ON) was determined as the difference between TKN and NH_4^+.

4.3.3 Water quantity monitoring

Water depth was also monitored in TWR ditches and OFS 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, four triangular prisms and a cuboid. Volume of water used for irrigation was monitored at each location using flow meters installed in the surface water irrigation pipelines (McCrometer, Hemet, California).

4.3.4 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 and Reed (1990) where one half the quantitation limit was equal to 2, 0.01, 0.01, 0.05, and 0.02 mg L^{-1} and substituted for TSS, TP, $NO_3^-NO_2^-$, TKN, and NH_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 Shaprio-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 body (TWR ditch or OFS). 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 technique (Benjamini and Hockberg 1995).

4.3.5 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 irrigation season (before May 1st) in both TWR ditch and OFS reservoir, multiplied by the average irrigation season nutrient concentrations from the respective TWR ditch or OFS irrigation samples by:

$$Available\ Loads\ Recycled = \sum_{i=1}^{n}(water\ saved)_i * \frac{1}{n}\sum_{i=1}^{n}\begin{matrix} irrigation\ sample \\ concentration \end{matrix}_{\ i} \tag{4.1}$$

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 by:

$$Estimated\ Loads\ Irrigated = \sum_{i=1}^{n}(water\ irrigated)_i * \frac{1}{n}\sum_{i=1}^{n}\begin{matrix} Irrigation\ sample \\ concentration \end{matrix}_{\ i} \tag{4.2}$$

Water irrigated is multiplied by the average irrigation season concentrations (equation 4.2). Available loads recycled and ELI were calculated for the 2014 and 2015 growing seasons.

4.4 Results and Discussion

4.4.1 Seasonality of analytes in tailwater recovery systems

There were differences ($F_{3,18} = 2.095$, $p < 0.005$) in analyte concentrations among years (2013-2015); however, pairwise comparisons with FDR adjustment showed no differences ($p < 0.05$). Differences ($F_{3,18} = 12.583$, $p < 0.0001$) in concentrations over seasons were observed across all analytes (figure 4.3). 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 ($F_1 = 12.583$, $p < 0.0001$) which increased with the growing season and was greater in summer than in spring (figure 4.3). Inorganic nitrogen is assimilated by biota for growth thereby increasing the amount of ON throughout the growing season. This suggests the seasonality of nutrients in TWR controls the nutrients available to irrigate onto the landscape.

Total suspended solids concentrations were greater in spring than in summer ($F_1 = 20.554$, $p < 0.0001$) and fall than in summer ($F_1 = 8.516$, $p < 0.01$), 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 numeric 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).

Total P concentrations were greater in spring compared to summer ($F_1 = 18.870$, $p < 0.0001$), with mean differences of 0.16 mg L^{-1}. Total phosphorus 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 occurred in winter and spring are similar to 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 ($F_3 = 1.186$, $p > 0.1$) in seasonal TN concentrations in TWR systems were observed. Tailwater recovery systems are lentic and are stabile (i.e. reduced fluvial nature) where flow is not occurring except following a precipitation event producing enough runoff to cause overflow. The lentic nature of TWR systems may result in TWR systems 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 ($F_1 = 16.705$, $p < 0.0001$), spring ($F_1 = 36.805$, $p < 0.0001$), and summer ($F_1 = 8.459$, $p < 0.01$) with fall being 0.24 mg L^{-1}, 0.19 mg L^{-1}, and 0.02 mg L^{-1} greater in fall than winter, spring, and summer, respectively. Summer concentrations of ON were also greater than in the spring by 0.17 mg L^{-1} ($F_1 = 15.632$, $p < 0.0001$). Organic N was greatest in the fall, most likely due to spring and summer assimilation, consumption and excretion of NH_4^+ and NO_3^- NO_2^- by phytoplankton and consumers (Wetzel 2001).

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). Ammonium concentrations were greater in the spring than summer by 0.24 mg L^{-1} ($F_1 = 17.294$, $p < 0.0001$) and fall by 0.20 mg L^{-1} ($F_1 = 7.596$, $p < 0.01$). Ammonium concentrations were also greater in the winter than summer by 0.25 mg L^{-1} ($F_1 = 20.149$, $p < 0.0001$) and fall by 0.21 mg L^{-1} ($F_1 = 12.394$, $p < 0.001$). In addition to NH_4^+, $NO_3^-NO_2^-$ was greater in the spring by 0.35 mg L^{-1} than in the winter ($F_1 = 13.043$, $p < 0.001$), 0.73 mg L^{-1} than in the summer ($F_1 = 68.441$, $p < 0.0001$) and 0.91 mg L^{-1} than in the fall ($F_1 = 114.416$, $p < 0.0001$). Numeric 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 ($F_1 = 36.079$, $p < 0.001$) by 0.56 mg L^{-1}

and summer ($F_1 = 10.270$, $p < 0.01$) 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 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 which contained all rice.

Analyses between TWR ditches and OFS reservoirs routine samples found greater concentrations in TWR ditch than in OFS reservoirs ($F_{1,6} = 31.433$, $p < 0.0001$), with pairwise comparisons of TSS ($F_1 = 69.185$, $p < 0.0001$), TP ($F_1 = 114.023$, $p < 0.0001$), TN ($F_1 = 4.987$, $p < 0.05$), $NO_3^-NO_2^-$ ($F_1 = 19.298$, $p < 0.0001$), and NH_4^+ ($F_1 = 28.022$, $p < 0.0001$) with differences to of 0.37 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 reservoir is 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 ($F_1 = 0.024$, $p > 0.05$), showed no differences between TWR ditches and OFS reservoirs.

4.4.2 Nutrient loads within tailwater recovery 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 4.2. Four sites show mixed results due to special circumstances. The first site, System B, during the 2014 and 2015 irrigation seasons necessitated maintenance and therefore did not irrigate any surface water. Other sites included systems E, F, and G which were still being built in the spring of 2014 and were unable to save their capacity of surface water prior to irrigation season on May 1st. However, TWR systems irrigated TSS (0.30 kg ha^{-1}), TP (0.2 kg ha^{-1}) and TN

(0.86 kg ha^{-1}) onto the landscape, thereby reducing potential detrimental impacts to receiving waters (table 4.2). Mean amounts of available TN (0.57 kg ha^{-1}) and TP (0.97 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 and 2015). For TWR system water, only 4.4% and 0.34% of the required P and N are available to irrigate the average hectare of crops in the Delta.

When considering the value of nutrients applied to agricultural crops, the form (i.e. species) of N is important to consider. The mean percent of total N for ON (77%), $NO_3^-NO_2^-$ (19%) and NH_4^+ (4%) during the 2014 and 2015 irrigation seasons (figure 4.4) demonstrate the majority of N available to be put back onto the tillable landscape was not readily available for uptake by crops, but was instead tied up in the organic form (Foth and Ellis 1997). This means that of the 0.86 kg ha^{-1} N available to be put back onto tillable land, only 0.20 kg ha^{-1} is immediately available for plant assimilation. Based on the average nutrient requirement to grow a hectare of the four dominant crop species in the Delta, only 0.91% P and 0.12% plant available N are available to be irrigated using TWR system water.

4.5 Summary and Conclusions

Tailwater recovery 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. Temporal differences by season indicate it is more advantageous to irrigate surface water associated with the greatest amount of nutrients to the landscape 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 0.97 kg ha^{-1} P and 0.57 kg ha^{-1} N, with the majority (77%) of N organic in form. However, these application rates are most likely too low to justify lowering synthetic fertilizer applications. This study investigated a single benefit of these systems. Further investigation is needed to quantify the additional benefits of TWR which include, but are not limited to, nutrient loss mitigation, water quantity conservation. In addition, an economic analysis comparing cost to benefits of TWR would be beneficial.

4.6 Acknowledgments

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Table 4.1 Characteristics of tailwater recovery systems

Farm	TWR	Layout	Volume (ML)	Crop Rotation	Catchment Area (ha)*	Other Best Management Practices†
1	A	TWRD	115.9	Rice	74.3	irrigation land leveling (zero grade rice) (342), water control structure (riserboard pipes) (410) and grade stabilization (field perimeter pads) (587)
2	B	TWRD	7.7	Rice-Soybeans, Corn-Soybeans	155.6	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
		OFS	86.3			
3	C	TWRD	25.5	Corn-Soybeans	639.8	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
		OFS	185.0			
4	D	TWRD	37.0	Corn-Soybeans	123.8	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
	E	TWRD	17.8	Corn-Soybeans	68.2	
		OFS	139.4			
5	F	TWRD	50.6	Rice-Soybeans	80.4	irrigation land leveling (342), water control structure (riser board pipes) (410) and grade stabilization (field perimeter pads) (587)
		OFS	197.4			
	G	OFS	80.2	Rice-Soybeans	57.2	

Notes: TWR is tailwater recovery system, ML is mega liters, ha is hectares, TWRD is the tailwater recovery ditch, OFS is on farm storage reservoir, "*" is the area of the catchment draining into the TWRD. Crops in crop rotation include: rice (*Oryza sativa*), soybeans (*Glycine max*) and corn (*Zea mays*). "†" Number in parentheses shows the USDA NRCS conservation practice number.

Table 4.2 Mean nitrogen, phosphorus and suspended sediments available to be applied with surface water

TWR	Description	Year	Water Available (ML)	Water Irrigated (ML)	Land Irrigated (ha)*	Total Suspended Solids (kg ha^{-1})		Total Phosphorus (kg ha^{-1})		Total Nitrogen (kg ha^{-1})	
						Available	Irrigated	Available	Irrigated	Available	Irrigated
A	TWR	2014	75.85	153.21	27.42	0.14	0.29	0.86	0.18	0.64	1.29
		2015	83.45	226.02	30.17	0.27	0.73	0.33	0.24	0.73	1.97
B[†]	TWR & OFS	2014	74.29	0.00	26.86	0.08	0.00	0.04	0.10	0.22	0.00
		2015	75.27	0.00	27.21	0.06	0.00	0.03	0.05	0.26	0.00
C	TWR & OFS	2014	170.18	114.94	61.53	0.14	0.10	0.08	0.10	0.23	0.15
		2015	171.89	198.45	62.14	0.18	0.21	0.43	0.07	0.47	0.54
D	TWR	2014	36.70	55.89	13.27	0.15	0.23	1.18	0.42	0.73	1.11
		2015	34.06	63.91	12.31	0.23	0.43	3.88	0.45	0.60	1.12
E	TWR & OFS	2014	35.04	52.31	12.67	0.21	0.31	4.82	0.47	0.35	0.52
		2015	165.54	99.89	59.85	0.08	0.05	1.16	0.02	1.47	0.89
F	TWR & OFS	2014	31.95	48.49	11.55	0.13	0.20	0.33	0.19	0.64	0.98
		2015	70.35	52.81	25.44	0.10	0.07	0.03	0.09	0.57	0.43
G	OFS	2014	30.93	160.88	11.18	0.29	1.52	0.46	0.31	0.51	2.66
		2015	136.51	89.92	49.35	0.07	0.05	0.02	0.05	0.61	0.40
Mean (SD)			85.14 (53.79)	94.05 (69.25)	30.78 (19.44)	0.15 (0.08)	0.30 (0.40)	0.97 (1.49)	0.20 (0.16)	0.57 (0.31)	0.86 (0.75)
Median			74.78	76.91	27.04	0.14	0.21	0.38	0.14	0.58	0.71

Notes: TWR is tailwater recovery system, ML is mega liters, OFS is on farm storage reservoir, SD is standard deviation, "†" producer did not irrigate surface water for 2014 and 2015 growing seasons, "*" 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 equaled 2.77 ML/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.

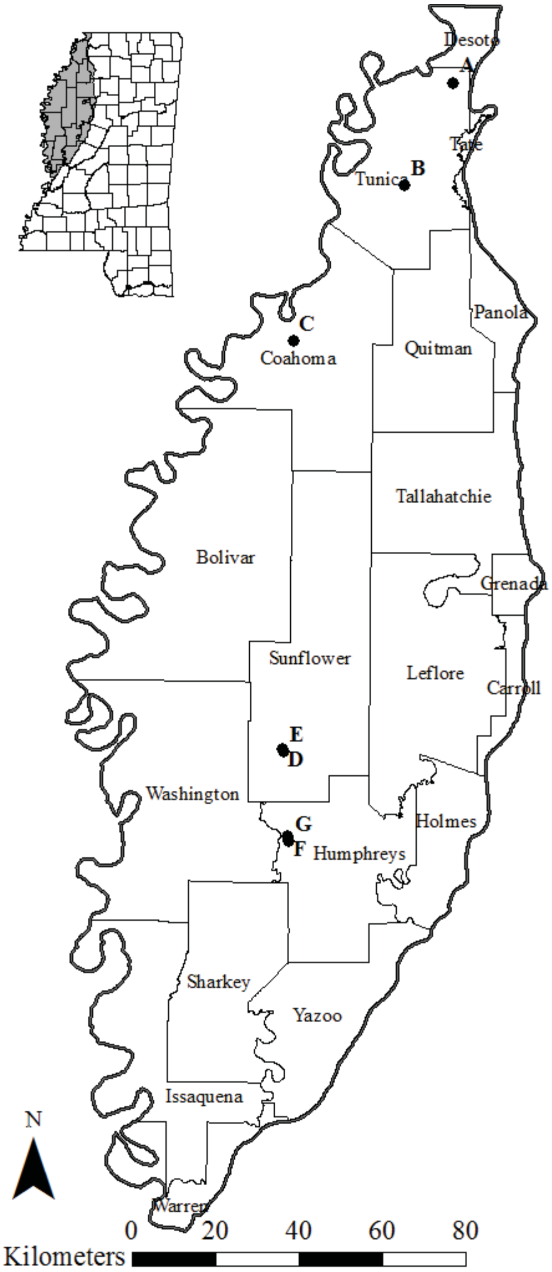

Figure 4.1 Map of the Delta region of Mississippi and this studies tailwater recovery systems locations

Notes: map insert top left is the state of Mississippi with counties outlined in black and the Mississippi Delta region shaded in dark grey. Map bottom right depicts tailwater recovery system locations represented as dots and labeled with letters corresponding to table 4.1, and Delta counties outlined and labeled in black. Coordinate system used is Mississippi Transverse Mercator (mstm), projection is transverse Mercator and datum is North American 1983.

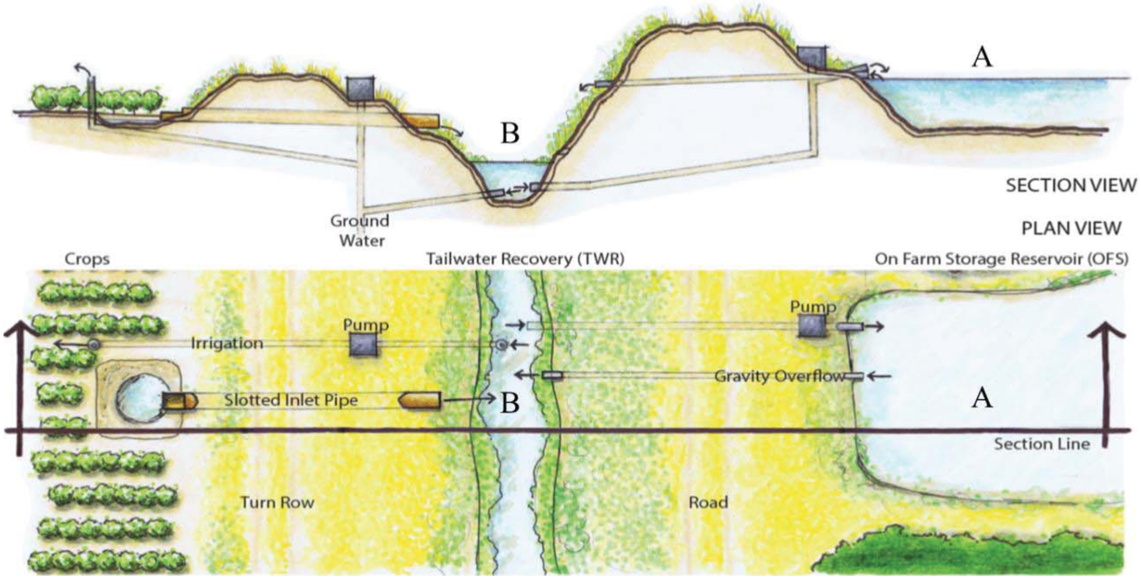

Figure 4.2 Tailwater recovery diagram

Notes: diagram is a visualization tool, and is not inclusive of all tailwater recovery (TWR) systems. Tailwater recovery systems may differ by only containing a large TWR ditch and no on-farm storage reservoir and different pumps and service pipes. A and B represent sampling locations. 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. Diagram provided courtesy by Mississippi State University's Research and Education to Advance Conservation and Habitat program.

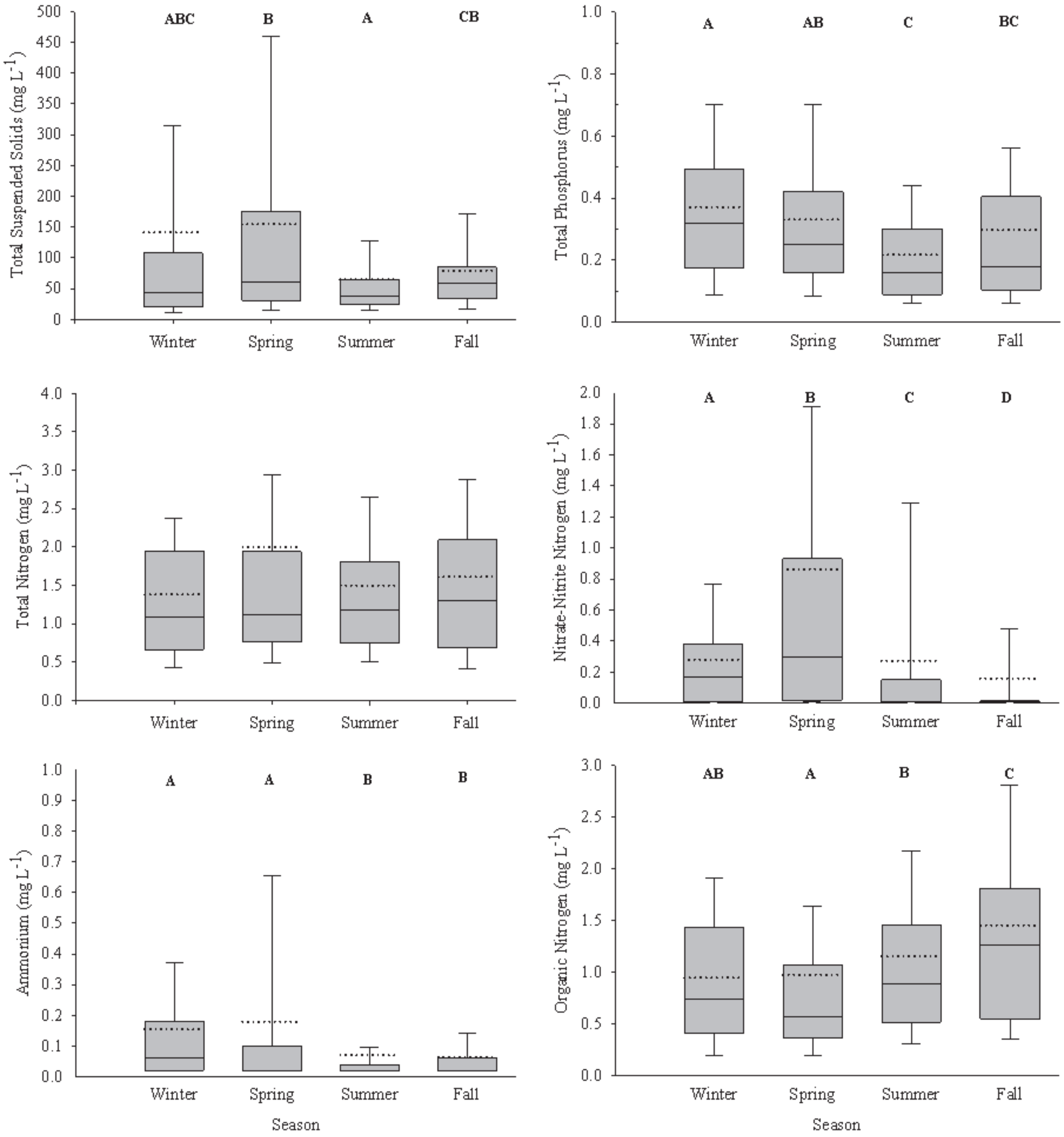

Figure 4.3 Mean seasonal analyte concentrations, 2014-2015

Notes: error bars represent standard error, dotted lines represent means, solid lines represent medians, different letters above boxes represent significant differences (Multivariate analysis of variance, alpha of 0.05 adjusted using false discovery rate technique; n = 324).

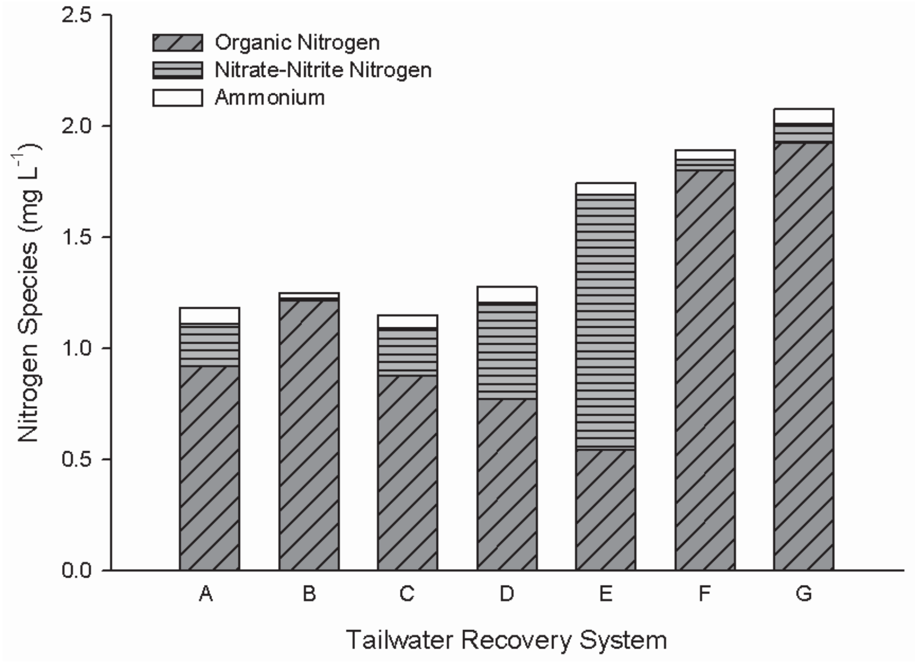

Figure 4.4 Nitrogen species concentrations in irrigation samples from tailwater recovery systems

Notes: samples for 2014 and 2015 irrigation seasons and n = 35-39 samples.

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CHAPTER V

DEVELOPMENT OF A WATER BUDGET FOR TAILWATER RECOVERY SYSTEMS

5.1 Abstract

Excessive groundwater use for agricultural irrigation has led to decreasing levels of aquifers across the US, necessitating implementation of water conservation practices. One conservation practice being implemented throughout the Lower Mississippi River Alluvial Valley (LMAV) is tailwater recovery (TWR) system which collects and stores surface water for irrigation. Water budgets allow for assessment of the efficiency of such conservation practices, however a water budget has yet to be quantified for a TWR system. Accordingly, the objectives of this research were to (1) summarize gains and losses of water into and out of TWR systems; (2) design a water budget for TWR systems; (3) develop coefficients for parameters of the water budget; (4) quantify the total water budget for all 180 TWR systems in Mississippi's section of the LMAV; and (5) assess the efficiency of TWR systems to retain and irrigate water. Eight TWR systems in Mississippi's LMAV region were monitored. Water flow was monitored into and out of the systems along with water depth within the systems. Precipitation and evaporation were calculated from US Department of Agriculture Soil Climate Analysis Network data. Infiltration was derived from stable periods of loss and evaporation estimates. Using these budgets, water balance for TWR systems was calculated and found to be gaining, except during months of irrigation (June to September). Extrapolating the water budget to 180 TWR systems shows a total gain of 28,714 ML annually with 15,507 ML of infiltration and 13,234 ML of irrigation which can be considered TWR systems' contribution toward offsetting unsustainable water withdrawals of the Mississippi Alluvial Aquifer. However, total water gained from TWR systems is 15% of the annual groundwater deficit. Tailwater recovery system efficiencies show that designs may be altered to improve the water savings and use of these systems.

Keywords: tailwater recovery system-best management practice- water reuse-irrigation-surface water

5.2 Introduction

In the United States (US), groundwater use for irrigation exceeds recharge levels on at least 20% of all irrigated land (Frederick 2006). The unsustainable use of many aquifers has converted these resources into what Sophocleous and Merriam (2012) referred to as "functionally nonrenewable." One such aquifer is the Mississippi Alluvial Aquifer (MAA), which is the third most used aquifer in the US and totals 12% of US water use (Maupin and Barber 2005). Since the 1970s, groundwater levels in the MAA have decreased at a rate of approximately 123,350 ML per year due to an increase in irrigated area (Thornton 2012). Falling aquifer levels are the result of increased use (Czarnecki 2010) combined with a low rate of aquifer recharge from infiltration (Arthur 2001). The MAA is recharged by water from the Mississippi River, local lakes and streams, aquifers underlying the eastern Bluff Hills region, precipitation, and by the underlying Cockfield and Sparta aquifers (Arthur 2001). It has been proposed that precipitation infiltration is the main source of recharge (Boswell et al. 1968), and due to a near impermeable top stratum of sand, silt and clay (Arthur 2001), only around 6.6 cm of the annual 142 cm of precipitation recharges the alluvial aquifer (Krinitzsky and Wire 1964). The majority of surface recharge from precipitation into the MAA is maximum along the Tallahatchie River basin and along the bluff boundary to the east (Dyer et al. 2015). Water is discharged from the alluvial aquifer into underlying aquifers, the Mississippi River, lakes, and streams, as well as withdrawn for municipal, industrial and agricultural uses (Arthur 2001).

Mississippi is the second largest user of the MAA (Maupin and Barber 2005), and it is the most heavily used aquifer in the state (Arthur 2001). Use of the MAA is almost exclusively (i.e., 98%) for irrigation of agricultural fields (Arthur 2001). It is estimated that 64% of production land in the area of northwest Mississippi overlying the MAA (hereafter the "Delta") requires 3,401,316 ha m of water per growing season (YMD 2010). Within the Delta, groundwater pumping continues to increase at unsustainable rates, the outcome of which is a cone of depression located primarily under the central Delta region (Arthur 2001; Barlow and Clark 2011; Clark et al. 2011). This unsustainable trend is expected to continue into the future (Clark et al. 2011) and is present in neighboring Arkansas (Czarnecki 2010), which also utilizes the MAA, as well as other regions throughout the US and world (e.g., California's Central Valley and Australia).

To alleviate dependency on groundwater resources, attention has been given to use of surface water and best management practices that capture surface water for later use as irrigation. Although practiced in many regions for centuries, the practice of capturing surface water for agricultural use is fairly new in the mid-South region of the US. This practice, which is referred to as a "tailwater recovery (TWR) system," allows producers to capture runoff and reuse this water for irrigation in lieu of pumping from groundwater. A TWR system consists of a primary ditch, which collects surface water runoff from agricultural fields, and may or may not include an additional on-farm storage reservoir (OFS) that increases the holding capacity of the TWR system. Within Mississippi, ditches are designed to hold a minimum of 14.8 ML of water; collect runoff water from 3-4 times the surface area as the area irrigated from the TWR system; store enough water to cover the irrigated area with 8.9 cm of water; and store 1/6-1/8 the capacity of the OFS reservoir (P. Rodrigue, USDA NRCS, personal communication, 2015). On-farm storage reservoirs are designed to be a minimum of 1/13 of the area to be irrigated; have an equal area running off into the TWR ditch associated with the OFS reservoir as the area to be irrigated by the OFS reservoir; and store enough water to cover the irrigated area with 15.24 cm of water (P. Rodrigue, USDA NRCS, personal communication, 2015). Water can be moved between ditch and OFS and pumped from either waterbody as a source for irrigation. Tailwater recovery systems are usually installed along with other US Department of Agriculture Natural Resources Conservation Service (USDA NRCS) conservation practices aimed at directing water into the TWR ditch, which may include irrigation land leveling, water control structures (e.g. slotted riser-board pipes) and grade stabilization (e.g. field perimeter pads).

The USDA NRCS covers TWR systems under practice code 436 or 447, depending on the state (USDA NRCS 2014). This federal agency provides financial assistance as cost-share for installation to qualifying producers, thus requiring both federal and private investment. Currently, over 700 TWR systems have been installed in the mid-South region, with almost 180 installed in the state of Mississippi, primarily within the area overlying the cone of depression in the Mississippi Delta (P. Rodrigue and C. Bowie, USDA NRCS, personal communication, 2015).

In order to calculate a return on investment for TWR systems, previous research by Prince Czarnecki et al. (2017) monitored water volumes gained, lost, and used within these systems over the course of a year to quantify the potential to provide a water conservation benefit. Much of the outcome from this case study relied on assumptions that were necessary because verifiable data did not exist for some parameters of interest. As a continuation of that research, the next step was to calculate coefficients for a water budget for TWR systems. A water budget will allow stakeholders to assess the efficiency of TWR systems as a water conserving practice. With this motivation, objectives of this research are to (1) summarize gains and losses of water into and out of TWR systems; (2) design a water budget for TWR systems; (3) develop coefficients for parameters of the water budget; (4) quantify the total water budget for all 180 TWR systems; and (5) assess the efficiency of TWR ditches and OFS reservoirs to provide water for irrigation.

5.3 Materials and Methods

5.3.1 Tailwater recovery systems

Eight TWR systems were monitored for this study (figure 5.1), including eight TWR ditches and six OFS reservoirs. Ditch and reservoir capacity ranged from 7.7-115.9 ML and 80.2-209.7 ML with catchment areas draining into TWR systems ranging from 57.2 ha to 63.98 ha (table 5.1). Catchment areas were in one of three production systems including continuous rice (*Oryza sativa*), a rice-soybean (*Glycine max*) rotation, or a corn (*Zea mays*)-soybean rotation (table 5.1). Two of the TWR ditches were not installed with an OFS reservoir, resulting in irrigation withdrawal directly from the ditch. In all other instances, withdrawal was from the OFS reservoir.

5.3.2 Water monitoring

Water depth was monitored using pressure level sensors (OTT Hydromet Ltd., Germany) in both the TWR ditches and OFS reservoirs (figure 5.2A). Sensors were connected to A755 addWAVE general packet radio service remote transmitting units (ADCON Telemetry, Klosterneuburg, Austria) powered using a Solar Set 4 (ADCON Telemetry, Klosterneuburg, Austria). Surface water capture volumes were calculated based on depth of water and system dimensions (obtained from local USDA NRCS personnel) following Prince Czarnecki et al. (2017). Volume of water used for irrigation was monitored at each location using flow meters (McCrometer, Hemet, California) installed in the surface water irrigation pipelines (figure 5.2B).

In addition to water depth and volume in the TWR systems, volume irrigated, depth, velocity and flow were monitored at inflow (figure 5.2C), field runoff (figure 5.2D) and overflow (figure 5.2E) locations using 6526E Starflow Ultrasonic Doppler systems (Unidata Pty Ltd., Perth, Australia). Starflow 6526E Ultrasonic Doppler instruments were connected to an A753 addWAVE general packet radio service remote transmitting unit (ADCON Telemetry, Klosterneuburg, Austria), powered using a Solar Set 4, 3 W (ADCON Telemetry, Klosterneuburg, Austria) and transmitted data wirelessly to a HACH server (HACH, Loveland, Co). At three locations (TWR ditch A inflow, TWR ditch B overflow, and TWR ditch M overflow; table 5.1), use of Starflow Ultrasonic Doppler systems was not logistically feasible due to farm traffic and the location of pipes for monitoring. Water depth was recorded at these locations using water level data loggers (Hobo, Onset, Bourne, MA) and flow was calculated using a modified Manning's equation for gradual varied flow utilizing the slope of the pipes (Chow 1959).

5.3.3 Water budgets

Water budgets were designed based on an adjusted water budget from Mitsch and Gosselink (2007) (figure 5.3). Three different budgets were generated for the TWR ditch,

$$\Delta V/_{\Delta t} = P + Si - So - E - \quad - REL \tag{5.1}$$

OFS reservoir,

$$\Delta V/_{\Delta t} = P + REL - E - \quad - R \tag{5.2}$$

or a single TWR ditch without an OFS reservoir,

$$\Delta V/_{\Delta t} = P + Si - So - E - \quad - R \tag{5.3}$$

where "ΔV/Δt" is the change in volume over time, "P" is precipitation, "Si" is surface water inflow, "So" is surface water overflow, "E" is evaporation, "I" is infiltration, "REL" is re-lift or pumping from the TWR ditch into the OFS reservoir and "IR" is pumping from the OFS reservoir onto fields as irrigation. Precipitation was estimated using hourly multi-sensor precipitation estimates based on Weather Surveillance Radar-1988 Doppler (WSR-88D), which have a nominal spatial resolution of 4x4-km (Fulton et al. 1998). This method has been used and verified against other data sources for precipitation estimates in the region of study (Dyer 2008, 2009). Surface water inflow and outflow was monitored using the equipment previously mentioned. Two types of surface water inflow were separated for analyses including precipitation driven runoff (PRO) and irrigation driven runoff (IRO). At two locations (TWR systems 3 and 4) water inflow and outflow was not monitored due to resource limitations. Volumes at unmonitored fields were estimated based on the volumes of monitored fields by taking the volume per hectare of the monitored fields multiplied by the additional field area flowing into the TWR system. Evaporation was calculated using a modified FAO-65 Penman-Monteith equation (Monteith 1965; Allen et al. 1998) for open bodies of water and parameters from the nearest USDA Soil Climate Analysis Network (SCAN) station (USDA NRCS 2016). The modified equation uses an albedo of 0.05 (Cogley 1979), surface resistance of 0.002 m, and surface height of 0 s m^{-1}. Additional adjustment to the albedo was used to reflect the relatively high water turbidity seen in this region within the TWR ditches and OFS reservoirs. The total loss from each TWR ditch or OFS reservoir was calculated as the slope of the change in water level over a stable period of time (i.e., when there hadn't been recent precipitation leading to runoff and therefore re-lift pumping or irrigation pumping; Prince Czarnecki et al. 2017). Infiltration was estimated as the remaining loss when evaporation was subtracted from the total loss. Soil types are provided in table 5.1, and the average depth of ground water across all five sites from January 2012 to May 2015 was 8.47 m (D. Kelly, Yazoo Mississippi Delta Joint Water Management District, personal communication, 2015). This led to the assumption that infiltration was a net loss from TWR systems. Re-lift and irrigation were calculated from the OFS reservoir (or TWR ditch if no OFS reservoir was present) as the change in volume over time during pumping periods, which were depicted on the hydrograph as a steep and steady rate of decline (Prince Czarnecki et al. 2017).

Coefficients for the parameters of the water budget were calculated in mm d^{-1} using the dynamic surface area for the respective TWR system component. A mean volume for each parameter was used to quantify the water budget for the 180 TWR systems. This was done with the assumption that the 180 systems were represented by the TWR systems in this study, where 25% of the TWR systems had no OFS reservoir (representative of the percentage from those monitored in this study).

5.3.4 Efficiencies of tailwater recovery systems and system components

Efficiency of TWR ditches to re-lift water and OFS reservoirs to irrigate water were calculated by manipulating water budgets used by Fairweather et al. (2003). Overall system efficiencies were calculated for TWR ditch or TWR ditch without OFS reservoir,

$$\%\ \text{Efficiency} = \left(1 - \frac{\mathrm{Si + P - I - E - So}}{\mathrm{Si + P}}\right) * 100 \qquad (5.4)$$

OFS reservoir,

$$\%\ \text{Efficiency} = \left(1 - \frac{\mathrm{REL + P - I - E}}{\mathrm{REL + P}}\right) * 100 \qquad (5.5)$$

and TWR system,

$$\%\ \text{Efficiency} = \left(1 - \frac{\mathrm{Si} + \mathrm{P}_{\mathrm{TWR}} + \mathrm{P}_{\mathrm{OFS}} - \mathrm{I}_{\mathrm{TWR}} + \mathrm{I}_{\mathrm{OFS}} - \mathrm{E}_{\mathrm{TWR}} + \mathrm{E}_{\mathrm{OFS}} - \mathrm{So}}{\mathrm{Si} + \mathrm{P}_{\mathrm{TWR}} + \mathrm{P}_{\mathrm{OFS}}}\right) * 100 \qquad (5.6)$$

where “P” is precipitation, “Si” is surface water inflow, “So” is surface water overflow, “E” is evaporation, “I” is infiltration, “REL” is re-lift or pumping from the TWR ditch into the OFS reservoir and “IR” is pumping from the OFS reservoir onto fields as irrigation.

5.4 Results and Discussion

5.4.1 Water budgets for tailwater recovery systems

Water budgets for TWR systems are driven by the climate in the Mississippi Delta region, which receives 130-140 cm of precipitation annually, with 62% occurring in winter and spring (December through May), 21% during the summer (June to August), and 17% during the Fall (September to November) (Arthur 2001). The water budget showed a clear gaining period driven by precipitation from January to April and a period of lower rate of gain from October to December (figure 5.4). Lack of precipitation and increased evaporation and irrigation create a losing period from June to September, with June and July dominated by irrigation and August and September by increased evaporation and decreased precipitation (figure 5.4). This is similar to trends in the balance between precipitation and evaporation described by data collected by Cooke et al. (2008), where a clear gaining period exists between January to July and a losing period from July to December. Evaporation rates double between January and May and maintain high rates through September, after which they decrease (table 5.2).

Within the Delta, a high percent of precipitation becomes runoff due to reduced ground cover during the agricultural fallow season and the presence of heavy clay soils (Fisk 1944; Arthur 2001). The majority of the total runoff was precipitation runoff with only August having greater irrigation runoff than precipitation runoff. Irrigation runoff is attributed to either the inefficiency in the irrigation system (which necessitates overflow to irrigate the entire field) or irrigator error due to neglect (failure to shut off the pump). The majority of farms investigated with TWR systems use poly pipe to direct water down furrows or into rice paddies (table 5.1). The water balance is dependent on precipitation runoff, which suggests that catchment area is the dominant variable in designing TWR systems. Overflow persisted throughout spring months suggesting one of three scenarios: 1) systems were not empty at the end of the previous irrigation season, 2) the TWR ditch cannot hold enough water to allow pumps to re-lift water during and after runoff events, or 3) or the pumps are not large enough.

Low rates of infiltration in the Delta are due to high clay content of surface soils, and were estimated at 66 mm annually from areal recharge, which is 5% of the annual precipitation in this region (Arthur 2001). Annual infiltration estimates calculated from stable losing periods ranged from 1.7 to 11.0 mm d^{-1} (table 5.2), similar to infiltration rates found by Prince Czarnecki et al. (2017) of 3.2 to 9.2 mm d^{-1}. In addition, infiltration estimates for catfish ponds in the Delta range from 0 to 2 mm d^{-1} (Pote and Wax 1993), which is on the lower end of the TWR system range. Estimates for TWR systems may be higher in the Delta region than for catfish ponds due to the younger age of TWR systems and the fact that the majority of catfish production occurs in regions of the Delta with higher clay content in the soil, therefore reducing infiltration. It is hypothesized that infiltration would decrease with increasing age due to settling of fine clay particles and pressure of overlying water eventually "sealing" up the wetted perimeter of TWR systems (Shao et al. 2013; Prince Czarnecki et al. 2017).

Producers were all able to fill their TWR systems prior to the May irrigation season in every year monitored. By manipulating the budget and using the amount of irrigation over the capacity of the systems a ratio of the amount of water irrigated compared to a volume of water stored can be calculated to assess how much of the water in each TWR system is being utilized. In 2014, this ratio ranged from 0.14-2.02 times the capacity of the system with a mean of 0.84. In 2015, the ratio ranged from 0.40-1.79 with a mean of 0.82. On average, producers in 2014 and 2015 used less water than the total capacity of their TWR systems, although each year at least one producer either used or was close to using two times the capacity of their TWR system. Use was dependent on the amount of precipitation during the irrigation season and the crop being irrigated. The

2014 irrigation season was considered a wet season with precipitation exceeding the 30-year average in every month from March to October (Prince Czarnecki et al. 2017); conversely, 2015 was a dry irrigation season with April through September having precipitation less than the 30-year average with August and September having a total of 14 mm of precipitation (USDA NRCS 2016). Even in the dry year, five of the six producers did not use the entire volume capacity of water from their TWR system, suggesting adjustments in size, catchment area, and irrigation infrastructure (to irrigate more acres with surface water) may be warranted. An additional observation is that producers who installed TWR systems on the landscape are progressively conservation minded and in many instances are using in-field conservation measures (i.e., zero-grade rice, surge valves, and pipe planner software) to conserve water in addition to collecting and irrigating surface water.

Tailwater recovery system re-lift can be evaluated by using a similar method to irrigation use ratio, only with the volume of the TWR system at the end of the prior irrigation season and the re-lift volume over the following fallow (i.e. non-irrigating) season divided by the capacity of the system (i.e., represents the full capacity at the beginning of irrigation season). Depth data revealed producers filled their systems to capacity prior to irrigation season (May 1) for both 2014 and 2015. This ratio provided the amount of water re-lift necessary to save a quantity of water prior to the beginning of irrigation season (May 1). The 2014 range equaled 0.34-1.37 with a mean of 0.57 and the 2015 range equaled 0.65-1.65 with a mean of 0.89. In other words, the average in 2014 of 0.57 indicates producers had to re-lift just over half a ML of water to save a ML of water.

Remaining water was either left over from the previous irrigation season or fell directly as precipitation into the OFS reservoir or TWR system without an OFS reservoir.

Extrapolating the water budget to 180 TWR systems in the Delta shows 15,507 ML of infiltration and 13,234 ML of irrigation (figure 5.5) annually. Assuming no exfiltration to a gaining stream (due to proximity of TWR systems to an incised stream), both infiltration and surface water irrigation can be considered as a positive practice for offsetting the unsustainable water withdrawals of the alluvial aquifer; however, the total annual 28,741 ML of water from TWR systems is 15% of the annual groundwater deficit of 185,947 ML (YMD 2010; Barlow and Clark 2011). Barlow and Clark (2011) modeled a 5% and 25% conservation of water resources in the Delta which resulted in an 11% and 60% increase in aquifer storage, respectively. They explained this was due to a larger area of unsaturated area and greater hydraulic gradient. This suggests an additive response in the Delta region, meaning TWR systems may make a greater impact than the estimated 15% annual volume initially suggests, especially since 123 of the 180 systems are centered around the aquifer’s cone of depression under the central Delta (figure 5.6) (P. Rodrigue, USDA NRCS, personal communication, 2015). The importance of targeting conservation efforts in the Delta above areas where groundwater is being depleted is highlighted by this outcome.

5.4.2 Tailwater recovery system efficiencies

Tailwater recovery system efficiencies were calculated such that efficiency values less than 100 denote a gaining system and values greater than 100 are considered a losing system. The ideal system would be at 0% efficiency in January - a gaining system - and increase in value until peaking in July, the middle of irrigation season. The TWR systems analyzed in this study were close to the 100% efficiency line but gained from January to April with a switch in April and May to a slightly losing system (figure 5.7). This is due to the systems being full prior to irrigation season (March and April) and therefore any additional inputs resulting in overflow. From June to November, systems have efficiencies over 100% due to irrigation, reduced precipitation, and an elevated evaporation rate. Tailwater recovery ditches remain gaining systems throughout the entire year except in September (figure 5.7), which is also the period of greatest irrigation. This draws the OFS reservoirs down, allowing additional re-lift during one of the months with the highest rates of evaporation (table 5.2). These results suggest TWR ditches could be reduced in size or catchment area increased while TWR systems could continue to maintain sufficient gains. January through July remain gaining periods for the OFS reservoirs with August through October being losing periods. Tailwater recovery systems without an OFS reservoir are gaining systems except during two periods of irrigation, June and August-September. Based on the previous results, TWR systems could increase efficiency through adjustments of size and catchment area; however, a tradeoff exists between increasing size to maximize gains and irrigation water potential, and the area of land removed from production.

5.5 Summary and Conclusion

The objective of this manuscript is to design, describe and use a water budget to investigate TWR system water savings and use. Tailwater recovery systems retain water on the landscape, therefore decreasing reliance of agricultural irrigation on groundwater and allowing recharge to decrease declines in the underlying alluvial aquifer. Notably, the amount of surface water irrigation and infiltrated water projected for all TWR systems in the Delta is 15% of the annual alluvial aquifer's deficit. Assuming that each of the 180 TWR systems was installed on a different farm of the 7,084 farms in the Delta (USDA NASS 2012), 2% of Delta farms reduced 15% of the entire deficit caused mainly by agriculture and also by industry, aquaculture, municipalities and recreational waterfowl hunting. This suggests TWR systems make a substantial contribution to groundwater infiltration, but additional TWR systems and/or conservation measures are needed. If additional TWR systems are implemented, an economic analysis is warranted to justify that these practices are the most economical way to sustainably supply water for irrigation. In addition to an economic analysis, efficiencies need to be increased through further research into the individual variables influencing the efficiencies and the optimum size of the TWR ditch, OFS reservoir, and pumps for a certain catchment area and irrigated area. Individual inputs (e.g., precipitation) into the TWR systems need to be investigated for their influence on performance of water savings and irrigation, which will allow for adaptive management of TWR design guidelines.

5.6 Acknowledgments

This study was supported by Delta Farmers Advocating Resource Management, Mississippi State's Research and Education to Advance Conservation and Habitat program, and Mississippi State Agricultural and Forestry Experimental Station. The author thanks the producers and landowners who allowed TWR system access. The author thanks Paul Rodrigue (USDA NRCS, Grenada, MS) and Trinity Long (USDA NRCS, Indianola, MS) for their help and sharing their extensive knowledge of TWR systems. The author thanks Leandro Miranda (U.S. Geological Survey, Starkville, MS), Matthew Moore (USDA ARS, Oxford, MS), Jason Krutz (Mississippi State University, Stoneville, MS), Joby Prince Czarnecki (Mississippi State University, Starkville, MS), Robert Kröger (Covington Civil and Environmental LLC, Gulfport, MS), Beth Baker (Mississippi State University, Starkville, MS), Peter Allen (Mississippi State University, Starkville, MS), James Henderson (Mississippi State University, Starkville, MS), and Derek Faust (Mississippi State University, Starkville, MS) for their support in preparing this chapter, as well as Tyler Lacefield, Jay Hogue, and Jonathon Rodgers for field support.

Table 5.1 Characteristics of tailwater recovery (TWR) system ditches and on-farm storage (OFS) reservoirs

System	Name	Component	Age (yr)*	Monitoring Period (Months)	Volume (ML)	Catchment Area (ha)^a	Crop Rotation	Irrigation Type	Soil Type
1	A	TWRD	<1	41	115.9	74.3	Rice-Rice	Zero-grade flood irrigation	100 % SC
2	B	TWRD	3	41	7.7	155.6	Corn-Soybeans, Rice-soybeans	Furrow (corn, soybeans), side-inlet (Rice)	73 % TN, 27 % SC
	C	OFS	3	41	123.3	4.5	Corn-Soybeans, Rice-soybeans	Furrow (corn, soybeans), side-inlet (Rice)	90 % TN, 10 % SC
3	D	TWRD	2	42	9.4	639.8	Corn-Soybeans	Furrow and center pivot	95% DC, 5% SC
	E	OFS	2	42	209.7	6.9	Corn-Soybeans	Furrow and center pivot	90% FD, 10 % DC
4	F	TWRD	<1	27	9.6	144.8	Rice-soybeans	Furrow (soybeans), side-inlet (Rice)	77 % FD, 21 % DC, 2 % AC
	G	OFS	<1	27	88.6	4.9	Rice-soybeans	Furrow (soybeans), side-inlet (Rice)	70 % FD, 19 % DC, 12 % AC
5	H	TWRD	<1	32	37.0	123.8	Corn-soybeans	Furrow	42 % DC, 26 % FD, 20 % DN, 12 % DB
6	I	TWRD	0	22	17.8	68.2	Corn-soybeans	Furrow	56 % DN, 18 % FD, 15 % DC, 11 % DB
	J	OFS	0	27	139.4	9.24	Corn-soybeans	Furrow	46 % DC, 31 % DB, 13 % DN, 11 % FD
7	K	TWRD	0	22	50.6	80.4	Rice-soybeans	Furrow (soybeans), side-inlet (Rice)	100 % AC
	L	OFS	0	30	197.4	10.7	Rice-soybeans	Furrow (soybeans), side-inlet (Rice)	100 % AC
8	M	TWRD	0	18	18.5	57.2	Rice-soybeans	Furrow (soybeans), side-inlet (Rice)	100 % AC
	N	OFS	0	32	80.2	5.4	Rice-soybeans	Furrow (soybeans), side-inlet (Rice)	99 % AC, 1 % FD

Notes: yr is years, ML is mega liters, ha is hactares, TWRD is the tailwater recovery ditch, OFS is on farm storage reservior, *age equal to 0 mointoring began immediately after the TWR system was built, ^{a} TWRD catchment areas are the land area which runs to the overflow pipe of the TWRD and OFS catchment area is the area which runs into the OFS including the banks and surface area of the OFS. Crops in crop rotation include: rice (*Oryza sativa*), soybeans (*Glycine max*) and corn (*Zea mays*). Soil types were obtained using USDA Web soil survey data (Soil Survey Staff, NRCS, USDA. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/. Accessed [8/11/2016].) 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.

Table 5.2 Tailwater recovery (TWR) system mean (2013-2016) water budget coefficients (mm d^{-1})

					TWR system					
Month	P	E	PRO	IRO	Si	So	SP	I	REL	IR
Jan.	3.24 (0.18)	1.97 (0.08)	20.11 (4.14)	0.00 (0.00)	20.11 (4.14)	1.98 (1.21)	5.26 (0.95)	3.77 (0.88)	114.35 (16.93)	0.00 (0.00)
Feb.	3.99 (0.50)	2.47 (0.25)	27.02 (10.12)	0.00 (0.00)	27.02 (10.12)	7.30 (9.21)	5.98 (3.47)	4.29 (2.91)	147.19 (37.45)	0.00 (0.00)
Mar.	5.62 (5.62)	2.78 (2.78)	14.63 (14.63)	0.00 (0.00)	13.92 (13.92)	6.85 (6.85)	8.54 (8.54)	5.76 (5.76)	97.05 (97.05)	0.00 (0.00)
Apr.	6.38 (7.40)	4.20 (4.13)	56.42 (0.00)	0.00 (0.00)	56.42 (0.00)	16.78 (0.00)	9.94 (7.69)	5.73 (3.55)	188.79 (192.83)	0.00 (0.00)
May	4.73 (4.45)	4.98 (4.29)	36.99 (35.09)	0.00 (0.00)	36.99 (35.09)	16.86 (8.37)	9.76 (5.87)	4.78 (1.58)	190.36 (226.61)	33.34 (0.00)
Jun.	3.77 (2.64)	4.27 (3.62)	44.75 (0.00)	4.75 (0.00)	49.50 (0.00)	25.74 (0.00)	12.49 (8.40)	8.22 (4.78)	195.06 (255.04)	189.27 (297.69)
Jul.	2.84 (2.54)	4.05 (3.68)	28.52 (24.27)	8.70 (6.20)	37.22 (30.46)	1.40 (0.00)	9.79 (6.16)	5.74 (2.48)	237.02 (142.25)	213.32 (0.00)
Aug.	1.98 (1.70)	4.06 (5.02)	1.60 (0.00)	10.65 (0.00)	12.25 (0.00)	2.84 (0.00)	9.49 (10.12)	5.43 (5.10)	79.05 (52.89)	97.30 (135.05)
Sep.	1.44 (1.50)	4.29 (5.55)	0.51 (0.00)	1.27 (0.00)	1.78 (0.00)	0.03 (0.00)	8.58 (15.35)	4.28 (9.80)	6.97 (4.88)	16.52 (0.00)
Oct.	4.05 (5.02)	3.63 (4.30)	22.94 (39.55)	0.00 (0.00)	22.94 (39.55)	1.58 (4.89)	6.19 (5.08)	2.62 (0.77)	77.43 (0.00)	3.18 (0.00)
Nov.	3.57 (5.36)	2.30 (2.36)	49.85 (0.00)	0.00 (0.00)	49.85 (0.00)	8.38 (0.00)	8.26 (3.17)	5.97 (0.82)	134.39 (52.38)	0.00 (0.00)
Dec.	3.77 (3.73)	1.59 (1.70)	34.13 (34.13)	0.00 (0.00)	34.13 (34.13)	5.15 (5.15)	5.35 (3.52)	3.99 (1.81)	232.42 (87.49)	0.00 (0.00)
					TWR ditch					
Month	P	E	PRO	IRO	Si	So	SP	I	REL	IR
Jan.	3.41 (0.33)	1.96 (0.19)	23.66 (3.65)	0.00 (0.00)	23.66 (3.65)	1.22 (0.58)	7.12 (1.86)	5.16 (1.81)	114.35 (25.11)	NA
Feb.	3.91 (0.26)	2.43 (0.07)	26.18 (4.06)	0.00 (0.00)	26.18 (4.06)	3.52 (1.24)	7.36 (1.73)	4.94 (1.72)	147.19 (16.03)	NA
Mar.	5.28 (0.43)	2.75 (0.08)	9.89 (2.82)	0.00 (0.00)	9.08 (2.76)	2.89 (1.28)	10.87 (2.49)	8.12 (2.55)	97.05 (31.76)	NA
Apr.	6.39 (0.52)	4.20 (0.28)	48.28 (13.08)	0.00 (0.00)	48.28 (13.08)	9.02 (2.74)	14.34 (4.65)	10.14 (4.86)	188.79 (47.40)	NA
May	4.39 (0.35)	5.04 (0.48)	36.84 (8.97)	0.00 (0.00)	36.84 (8.97)	13.39 (4.88)	10.03 (1.95)	4.99 (1.88)	190.36 (35.86)	NA
Jun.	3.85 (0.57)	4.28 (0.24)	42.97 (10.20)	5.92 (2.05)	48.89 (9.14)	19.09 (8.27)	15.27 (3.62)	10.99 (3.69)	195.06 (45.50)	NA
Jul.	2.68 (0.41)	4.11 (0.24)	33.15 (5.23)	10.18 (1.12)	43.33 (5.90)	0.77 (0.35)	9.09 (1.85)	4.98 (1.92)	237.02 (78.69)	NA
Aug.	2.18 (0.51)	3.97 (0.61)	2.13 (1.53)	14.20 (18.14)	16.34 (18.99)	3.78 (6.63)	10.74 (3.59)	6.77 (3.75)	79.05 (98.57)	NA
Sep.	1.34 (0.37)	4.20 (0.40)	0.41 (0.23)	1.69 (1.21)	2.10 (1.44)	0.04 (0.03)	10.07 (2.00)	5.87 (1.97)	6.97 (6.05)	NA
Oct.	3.91 (0.48)	3.57 (0.36)	21.81 (5.84)	0.00 (0.00)	21.81 (5.84)	1.29 (0.43)	7.19 (1.08)	3.75 (1.17)	77.43 (19.86)	NA
Nov.	3.09 (0.39)	2.30 (0.14)	56.59 (17.76)	0.00 (0.00)	56.59 (17.76)	7.83 (3.37)	12.59 (3.11)	10.29 (3.13)	134.39 (42.37)	NA
Dec.	3.84 (0.18)	1.49 (0.06)	40.38 (8.24)	0.00 (0.00)	40.38 (8.24)	3.52 (1.23)	5.82 (1.30)	4.33 (1.33)	232.42 (71.71)	NA

Notes: OFS is on-farm storage, P is precipitation, E is evaporation, PRO is precipitation driven runoff, IRO is irrigation driven runoff, Si is surface water runoff (i.e. PRO and IRO), So is overflow out of the TWR ditch, SP is total stable period losses (E and I), I is infiltration, REL is re-lift from the TWR ditch to the OFS reservoir, IR is irrigation, and NA is not applicable.

Table 5.2 (continued)

					OFS reservoir					
Month	P	E	PRO	IRO	SI	So	SP	I	REL	IR
Jan.	3.13 (0.28)	1.98 (0.08)	NA	NA	NA	NA	3.66 (0.80)	2.78 (0.73)	114.35 (25.11)	0.00 (0.00)
Feb.	4.02 (0.20)	2.48 (0.13)	NA	NA	NA	NA	4.38 (0.77)	3.25 (0.17)	147.19 (16.03)	0.00 (0.00)
Mar.	5.84 (0.76)	2.78 (0.13)	NA	NA	NA	NA	6.80 (1.25)	4.02 (1.14)	97.05 (31.76)	0.00 (0.00)
Apr.	6.48 (0.48)	4.16 (0.31)	NA	NA	NA	NA	6.59 (0.72)	2.43 (0.57)	188.79 (47.40)	0.00 (0.00)
May	4.83 (0.19)	4.86 (0.43)	NA	NA	NA	NA	8.67 (1.66)	3.82 (1.38)	190.36 (35.86)	36.46 (36.46)
Jun.	3.71 (0.59)	4.13 (0.30)	NA	NA	NA	NA	11.34 (2.71)	7.21 (2.72)	195.06 (45.50)	206.61 (71.58)
Jul.	3.04 (0.21)	3.98 (0.19)	NA	NA	NA	NA	8.72 (1.08)	4.74 (1.08)	237.02 (78.69)	219.23 (59.63)
Aug.	1.73 (0.60)	4.14 (0.74)	NA	NA	NA	NA	9.31 (3.08)	5.16 (3.58)	79.05 (98.57)	111.91 (108.16)
Sep.	1.27 (0.18)	4.33 (0.35)	NA	NA	NA	NA	7.69 (0.77)	3.36 (1.06)	6.97 (6.05)	8.24 (8.24)
Oct.	4.22 (0.36)	3.69 (0.31)	NA	NA	NA	NA	5.42 (0.55)	1.73 (0.36)	77.43 (19.86)	4.25 (2.75)
Nov.	4.01 (0.34)	2.30 (0.09)	NA	NA	NA	NA	4.34 (0.44)	2.04 (0.46)	134.39 (42.37)	0.00 (0.00)
Dec.	3.71 (0.10)	1.68 (0.06)	NA	NA	NA	NA	5.12 (1.54)	3.99 (1.27)	232.42 (71.71)	0.00 (0.00)
					TWR wo/OFS reservoir					
Month	P	E	PRO	IRO	SI	So	SP	I	REL	IR
Jan.	3.09 (0.27)	1.95 (0.17)	9.47 (3.19)	0.00 (0.00)	9.47 (3.19)	4.29 (4.29)	4.47 (1.41)	2.58 (1.51)	NA	0.00 (0.00)
Feb.	4.15 (0.06)	2.57 (0.20)	29.53 (10.13)	0.00 (0.00)	29.53 (10.13)	18.65 (10.10)	6.66 (3.25)	5.49 (2.06)	NA	0.00 (0.00)
Mar.	5.96 (1.21)	2.88 (0.11)	28.87 (26.69)	0.00 (0.00)	28.42 (27.08)	18.71 (5.87)	6.79 (1.81)	3.90 (1.92)	NA	0.00 (0.00)
Apr.	6.06 (1.12)	4.36 (0.45)	80.86 (45.52)	0.00 (0.00)	80.86 (45.52)	40.06 (13.84)	6.79 (1.81)	2.43 (2.27)	NA	0.00 (0.00)
May	5.46 (0.97)	5.18 (0.75)	37.42 (21.18)	0.00 (0.00)	37.42 (21.18)	27.30 (21.28)	12.19 (4.31)	7.02 (3.56)	NA	24.00 (24.00)
Jun.	3.75 (0.21)	4.65 (0.13)	50.07 (30.25)	1.25 (1.25)	51.32 (29.00)	45.68 (35.00)	7.57 (2.51)	2.92 (2.64)	NA	137.25 (46.85)
Jul.	2.74 (0.08)	4.11 (0.19)	14.64 (4.46)	4.26 (4.26)	18.91 (8.72)	3.30 (1.04)	15.12 (8.83)	11.01 (9.02)	NA	195.58 (37.25)
Aug.	2.12 (1.17)	4.07 (0.80)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	6.29 (0.44)	2.23 (0.37)	NA	53.46 (75.61)
Sep.	2.25 (0.33)	4.47 (1.00)	0.80 (0.80)	0.00 (0.00)	0.80 (0.80)	0.00 (0.00)	6.74 (0.75)	2.27 (0.25)	NA	41.35 (3.92)
Oct.	3.95 (3.95)	3.62 (3.62)	26.31 (26.31)	0.00 (0.00)	26.31 (26.31)	2.45 (2.45)	5.53 (5.53)	1.91 (1.91)	NA	0.00 (0.00)
Nov.	3.67 (0.36)	2.28 (0.30)	29.63 (7.66)	0.00 (0.00)	29.63 (7.66)	10.04 (5.38)	7.06 (1.74)	4.78 (1.44)	NA	0.00 (0.00)
Dec.	3.74 (0.38)	1.61 (0.15)	15.39 (6.11)	0.00 (0.00)	15.39 (6.11)	10.06 (6.81)	4.59 (1.38)	2.98 (1.52)	NA	0.00 (0.00)

Notes: OFS is on-farm storage, P is precipitation, E is evaporation, PRO is precipitation driven runoff, IRO is irrigation driven runoff, Si is surface water runoff (i.e. PRO and IRO), So is overflow out of the TWR ditch, SP is total stable period losses (E and I), I is infiltration, REL is re-lift from the TWR ditch to the OFS reservoir, IR is irrigation, and NA is not applicable.

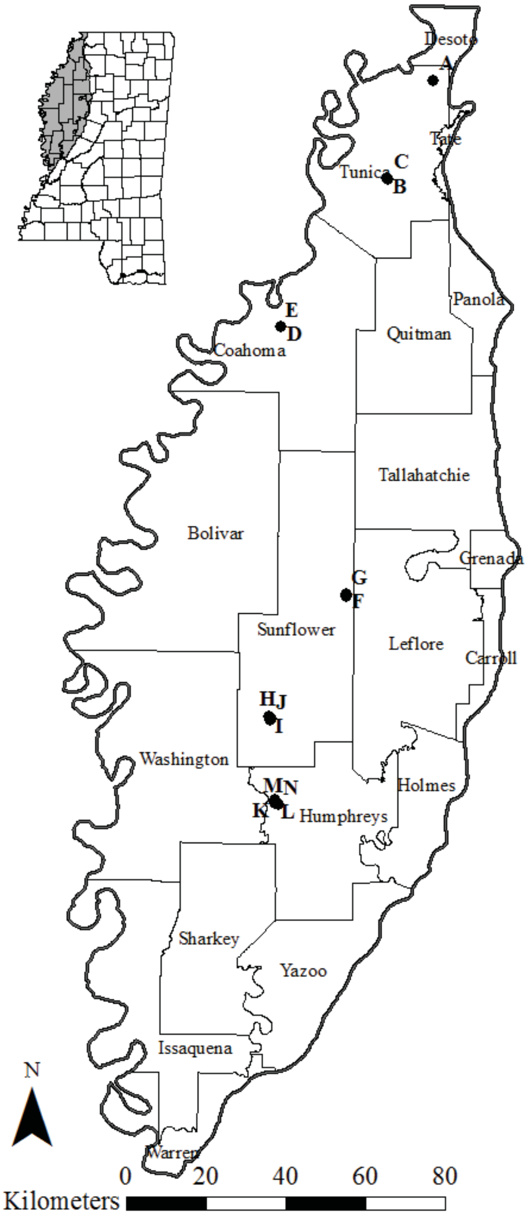


Figure 5.1 Map of the Mississippi Delta region, tailwater recovery (TWR) ditches, and on-farm storage (OFS) reservoirs farm locations

Notes: Map insert top left is the state of Mississippi with counties outlined in black and the Mississippi Delta region shaded in dark grey. Map bottom right depicts tailwater recovery ditches and on-farm storage reservoirs represented as dots and labeled with letters corresponding to table 5.1, and Delta counties outlined and labeled in black. Coordinate system Mississippi Transverse Mercator (mstm), projection is transverse Mercator and datum is North American 1983.

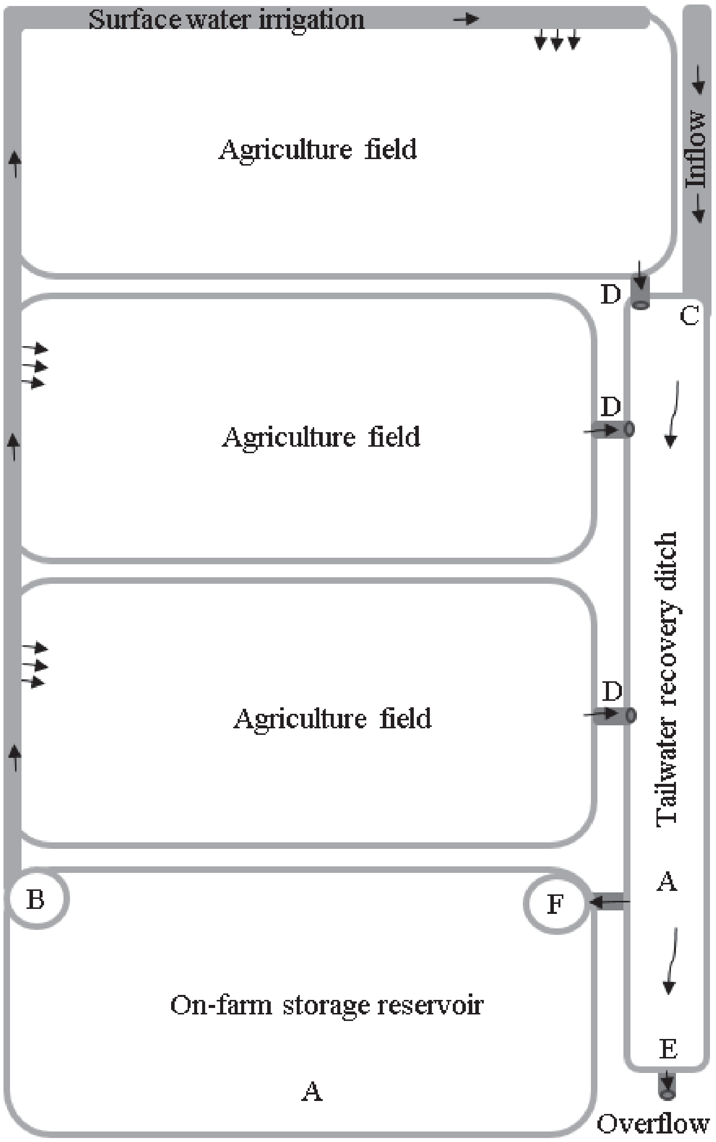
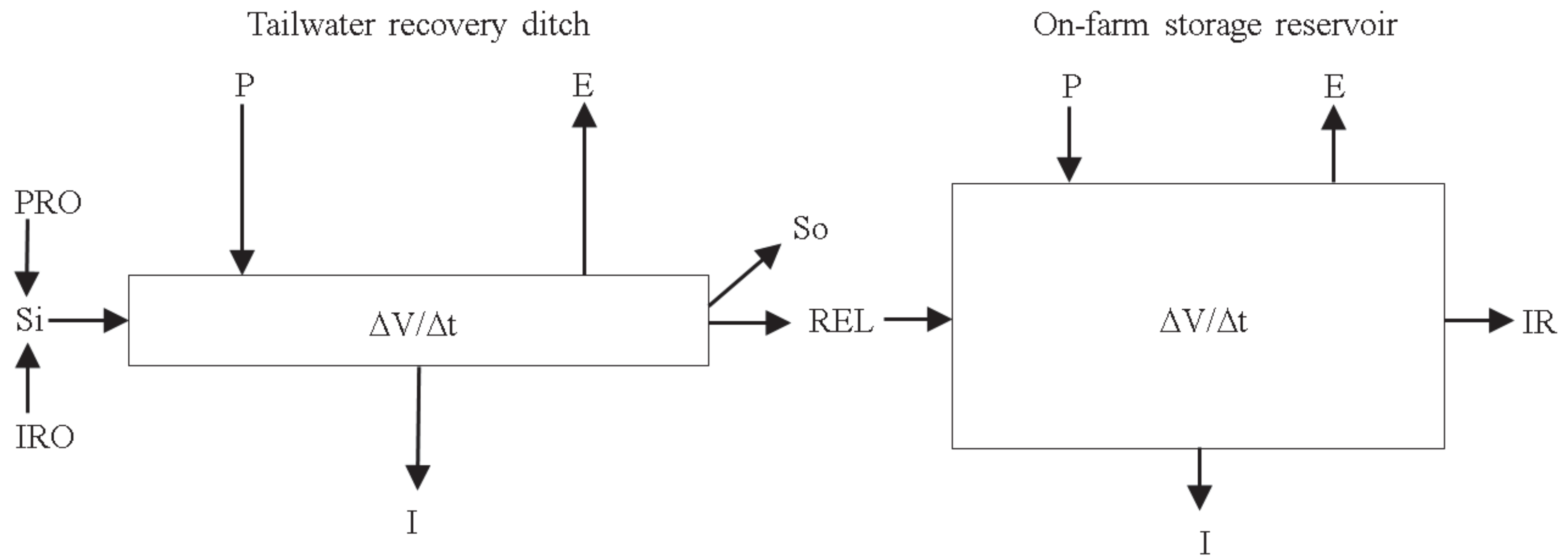


Figure 5.2 Schematic of the plan view of a generic tailwater recovery (TWR) system

Notes: This diagram is meant as a visualization tool, not all TWR systems are designed this way. Most TWR systems have differences including only containing a large TWR ditch and no OFS and different pumps and service pipes. In addition, not all TWR systems have off-farm inflow (i.e. inflow). “A” location represents depth monitoring locations; circles represent pumping locations, “B” represents monitoring location at surface water irrigation pumps, “C” represents the inflow monitoring location, “D” represents field runoff pipe locations into the TWR ditch; “E” represents the overflow pipe monitoring location and “F” denotes the surface water re-lift location, which pumps water from the TWR ditch into the on-farm storage reservoir.



$$\Delta V/\Delta t = P + Si - E - So - REL - I$$

$$\Delta V/\Delta t = P + REL - E - IR - I$$

Figure 5.3 Diagram and equations of tailwater recovery (TWR) systems' water budget

Notes: This is meant as a visualization tool this diagram is not drawn to scale, TWR ditches and OFS reservoirs may be larger or smaller to each other than what is pictured. Figure and budget adapted from Mitsch and Gosselink (2007); Δ delta is equivalent to change; V is volume of either TWR ditch or on-farm storage (OFS) reservoir; P is precipitation; PRO is precipitation driven runoff; IRO is irrigation driven runoff (i.e. irrigation tailwater); Si is surface water inflow (PRO+IRO); E is evaporation; So is surface water overflow; REL is surface water re-lift from TWR ditch into OFS reservoir; I is groundwater infiltration (assumed to be negative due to decreased levels in alluvial aquifer); IR is surface water irrigation from OFS reservoir.

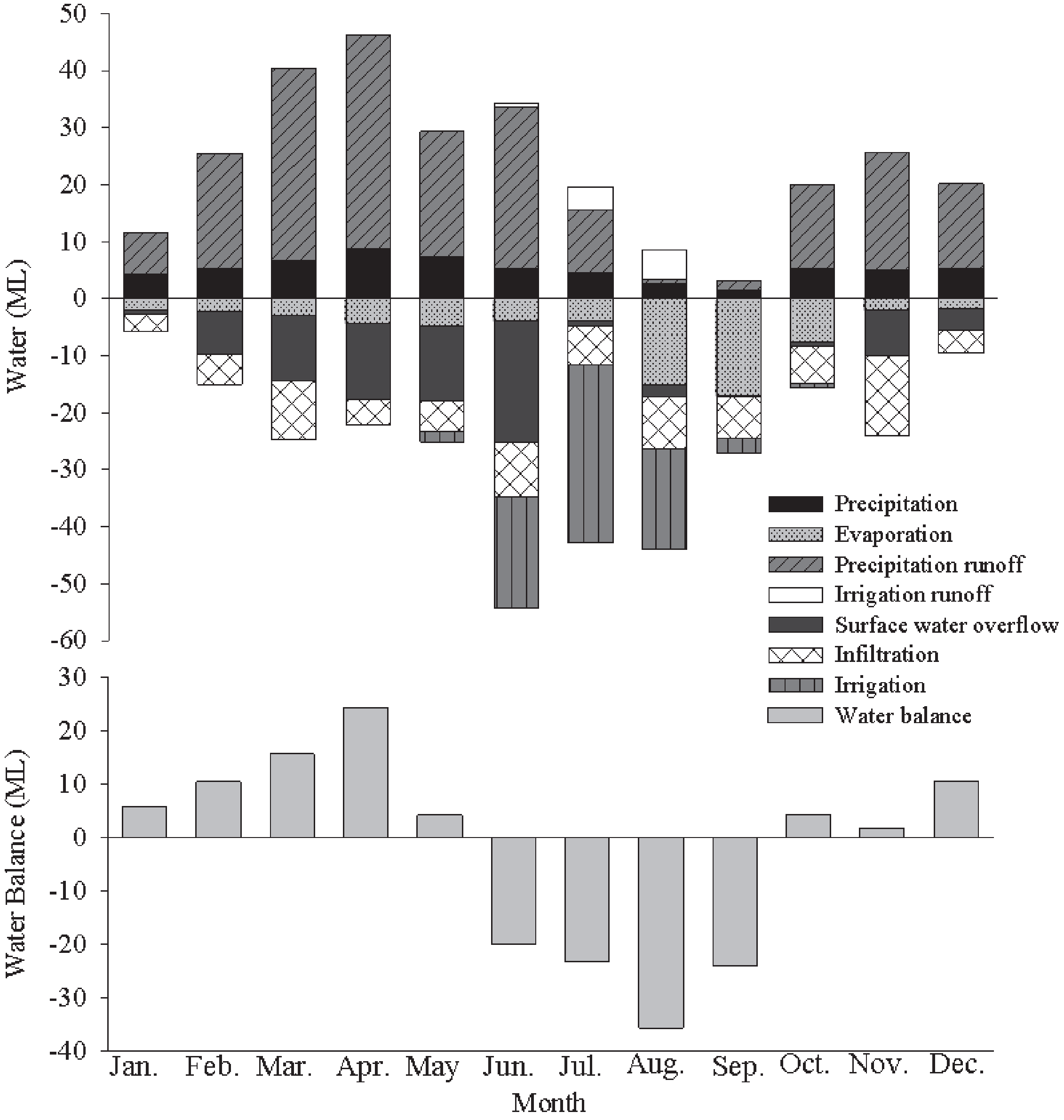


Figure 5.4 Mean (2013-2016) quantity of water for each budget variable and water balance

Notes: Water balance is the summation of precipitation, evaporation, precipitation runoff, irrigation runoff, surface water outflow, surface water overflow, infiltration, and irrigation (see figure 5.3).

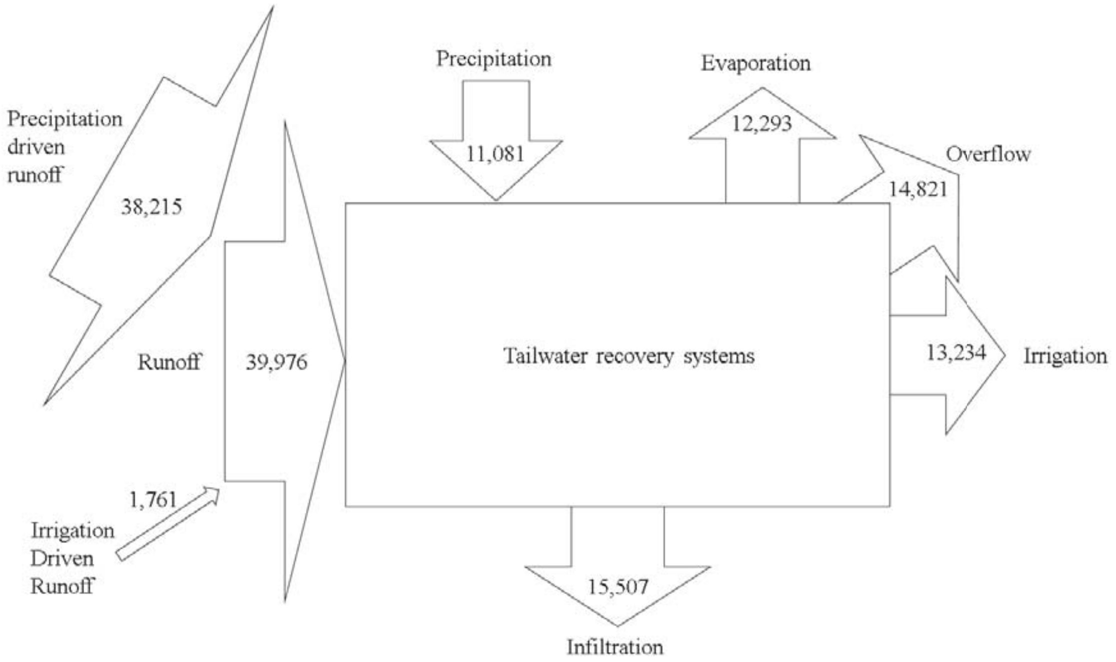


Figure 5.5 Hydrologic budget quantified to 180 tailwater recovery (TWR) systems in the Delta

Notes: numbers inside of the arrows represent the amount of water in ML moving into and out of the TWR system; width of the arrows are representative of the numbers. This quantification assumes 25% of the TWR systems are TWR ditches without OFS reservoirs.

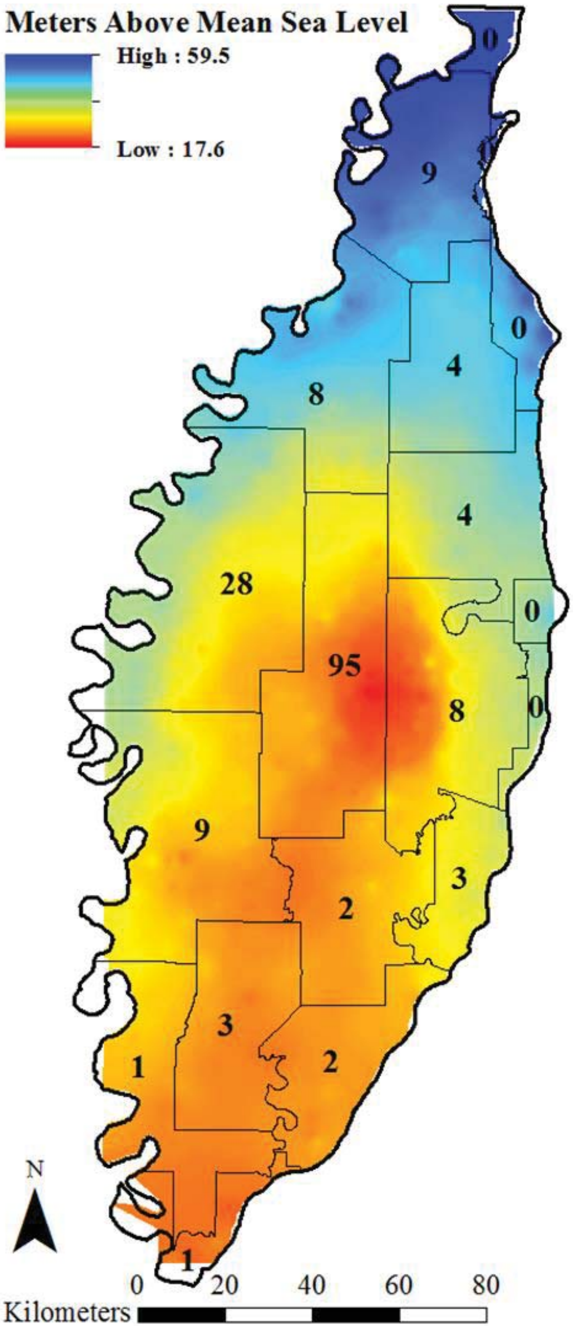


Figure 5.6 Map of ground water level in the Mississippi Delta and the population of tailwater recovery (TWR) systems by county.

Notes: Map depicts county outlined in black and the population of TWR systems labeled (P. Rodrigue, NRCS, personal communication, 2015). Coordinate system Mississippi Transverse Mercator (mstm), projection is transverse Mercator and datum is North American 1983. Groundwater data provide by Yazoo Mississippi Delta Joint Water Management District, Groundwater Level Data (Fall 2016), http://www.ymd.org.

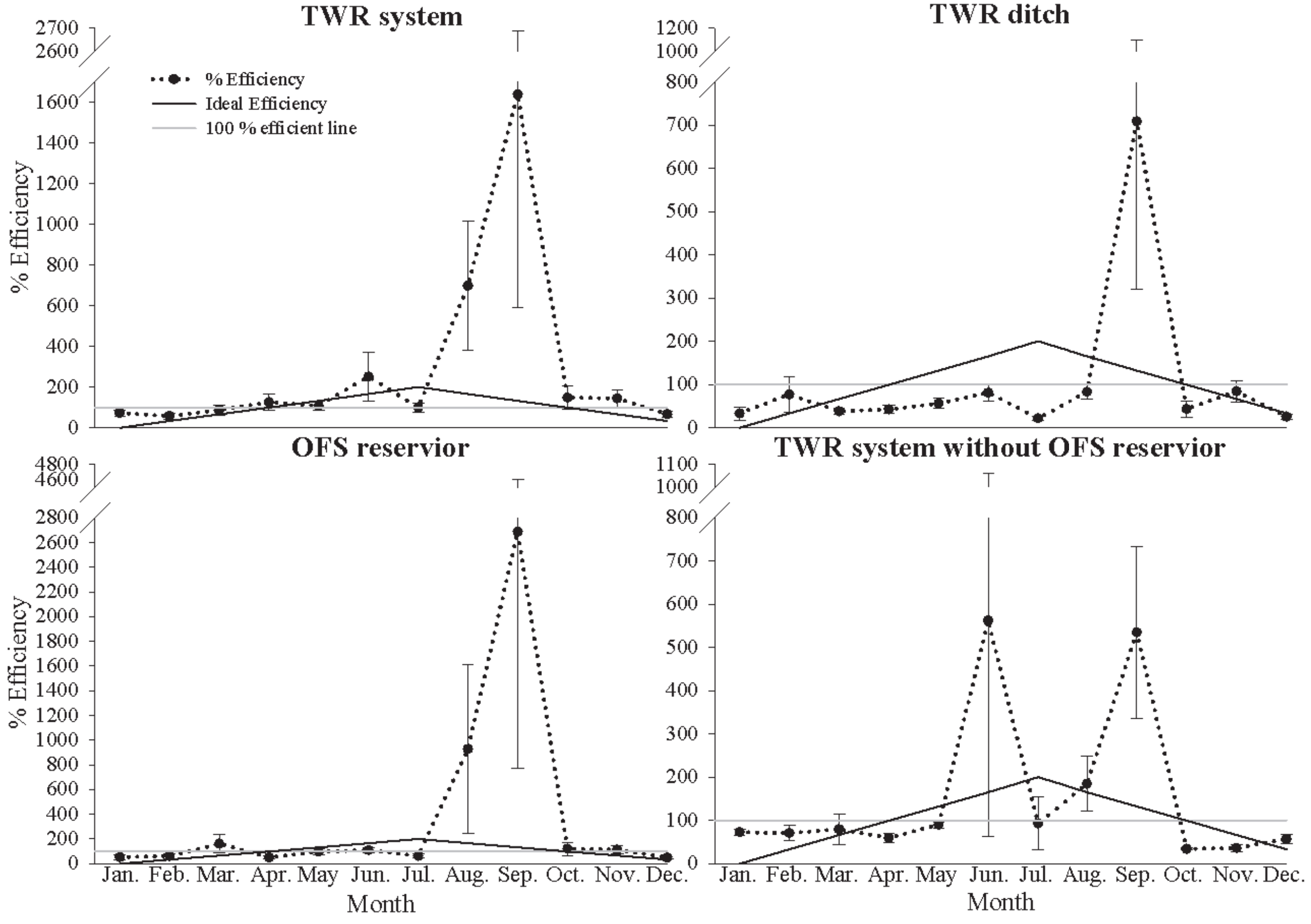


Figure 5.7 Efficiency of tailwater recovery (TWR) ditches, on-farm storage (OFS) reservoirs, TWR systems without OFS reservoirs (TWRwoOFS), and TWR systems to save and irrigate water

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CHAPTER VI

ECONOMIC ANALYSES OF TAILWATER RECOVERY SYSTEMS

6.1 Abstract

Tailwater recovery (TWR) systems are being implemented on agricultural landscapes to reduce nutrient loss and save water on the landscape for irrigation. These systems are a large financial investment for both government agencies (United States Department of Agriculture Natural Resources Conservation Service) and private producers with total costs ranging from $400,000-900,000. Although economic analyses of TWR systems have been modeled, analyses of implemented TWR systems have yet to be completed. Economic studies are necessary to guide adaptive management of conservation funding for appropriation in methods with the greatest return. Therefore, an analysis was conducted on the costs and benefits of TWR systems. Net present values (NPV) and benefit to cost ratios (BCR) of TWR systems were used to compare the benefits to the costs. Three discount rates of 3, 7, and 10% were used on both rented and owned land schemes. Five TWR system scenarios were used in the investigation including dryland, irrigated, irrigation improvements, TWR systems, and TWR systems with external benefits of sediment loss mitigation. Net present value and BCRs were positive and greater than one for TWR systems if producers owned the land but remained negative or less than one if land was rented. Beyond improvements to irrigation infrastructure, farms with a TWR system installed lost NPV of $51 to $328 per ha.

Therefore, TWR systems are not considered to be economically viable when land is not owned.

Keywords: tailwater recovery system, best management practices, water reuse, irrigation, water quantity, economic analysis

6.2 Introduction

Documentation, awareness, and understanding of agricultural impacts on the environment have led to growing implementation of conservation practices to reduce degradation of water quality. In the United States (US), the 2014 Farm Bill rendered an increase of funding for working lands programs while decreasing funding for land retirement programs (US Congress 2014). Expansion of funding toward working lands programs will result in amplified conservation practice implementation. Through the US Department of Agriculture (USDA) Regional Conservation Partnership Program, which matches federal funds with private funds to help shoulder the cost of conservation, more interest in determining monetary values of the benefits of conservation may arise. In addition, it has been shown that adoption rates of conservation practices increase when information programs include details about impacts on farm profitability and when practices are economically appealing (Feather and Amacher 1994; Feather and Cooper 1995; Cestti et al. 2003).

One region where large amounts of federal and private funds have been directed toward conservation practice implementation is the Lower Mississippi River Alluvial Valley, referred to as “the Delta” within Mississippi. This region encompasses the northwest region of the state and 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 agricultural producers in the Delta: (1) increased surface transport of nutrients contributing to eutrophication in receiving waters and to the Gulf of Mexico hypoxic zone (Rabalais et al. 1996; Turner and Rabalais 2003) and (2) unsustainable water withdrawal from the Mississippi River Valley Alluvial Aquifer for irrigation during the crop growing season when precipitation is minimal (Clark et al. 2011).

A practice that addresses both issues is a surface water capture and irrigation reuse system known as a tailwater recovery (TWR) system. Currently throughout the Delta region, TWR system implementation has been concentrated around the alluvial aquifer cone of depression (Paul Rodrigue, USDA NRCS, personal communication, 2015), located under Sunflower and Bolivar counties in Mississippi. Tailwater recovery systems are a combination of a tailwater recovery ditch that captures surface water runoff, an optional on-farm storage reservoir (OFS) to store additional captured water, and pumps to re-lift surface water to the OFS or back onto fields as irrigation water. Chapter 2 demonstrated TWR system capability to reduce solids and nutrient losses, as well as save surface water reducing groundwater reliance. Although TWR systems are effective, implementation is a major financial commitment for both producers and the USDA Natural Resources Conservation Service (NRCS), which provides financial assistance. The USDA NRCS has provided financial assistance for over 180 TWR systems in the Delta (Paul Rodrigue, USDA NRCS, personal communication, 2015) under conservation practice code 436 (USDA NRCS 2016a).

Previous economic analyses (Bouldin et al. 2004; Young et al. 2004; Falconer et al. 2015) focused on hypothetical scenarios which may not represent reality when these systems are implemented. Bouldin et al. (2004) modeled the cost and benefits of TWR systems using present values and benefit-cost ratios (BCR) to show that TWR systems are a positive investment; however, they included large monetary values for the external benefits of ecological services of wetlands. The capability of TWR systems to provide those services was an assumption due to the lack of research. In addition, Bouldin et al. (2004) included a monetary value for groundwater use; however, currently there is no monetary value in Mississippi for reducing groundwater use. In an adequate groundwater scenario in Arkansas, Young et al. (2004) used the differences in net present values (NPV) to show that TWR systems are not economical. These results have not influenced the implementation of TWR systems in Mississippi where groundwater is adequate but decreasing. Falconer et al. (2015) concluded from NPV on a hypothetical farm that TWR systems in Mississippi may not be economical due to lost income from land taken out of production for TWR ditch and OFS reservoir. They warned that each system is case-specific and should be considered as such. Research into implemented TWR systems would allow the NPV and BCR to be calculated for scenarios of actual external benefits and lost production land.

The continued expenditure of local and federal funds toward these practices necessitates an economic analysis comparing benefits and costs of implemented TWR systems. The overall objective of this study was to provide an economic analysis of TWR systems for decision makers to consider against other options for mitigation of sediment and nutrient losses from the agricultural landscape. This overall objective was investigated using two actions: (1) compare NPV and BCR of operation scenarios with and without TWR systems, as well as, with and without sediment reduction benefits and (2) evaluate the impact of the level of USDA NRCS financial assistance on NPV.

6.3 Materials and Methods

6.3.1 Tailwater recovery systems

Five TWR systems located in the Delta were used for analyses. With cooperation of both producers and local USDA NRCS offices, capital costs (table 6.1) and sizes (table 6.2) of individual systems were obtained. Information for the total tillable area before and after implementation of TWR systems were measured from National Agricultural Imagery Program ortho-imagery data. Crop type and rotation for each field were obtained from field observations and supplemented with USDA CropScape data (table 6.2). All TWR systems include management practices to direct water into the TWR system including irrigation land leveling (USDA NRCS practice 342), water control structures (riser board pipes, USDA NRCS practice 410), and grade stabilization (field perimeter pads, USDA NRCS practice 587).

6.3.2 Production budgets costs and benefits

Economic analyses were conducted over 15- and 30-year periods, beginning in 2012 and ending in either 2023 or 2041. The 15-year period of analyses is the USDA NRCS described lifetime of the TWR practice (Paul Rodrigue, USDA NRCS, personal communication, 2016). The 30-year lifetime period was used because the actual practice lifetime is unknown, given that installation of TWR systems in Mississippi are all recent (approximately < 7 years). Production budgets were utilized from Mississippi State University (MSU) Delta Planning Budgets (MSU 2014). Budgets for 2012 (MSU 2011), 2013 (MSU 2012), 2014 (MSU 2013) and 2015 (MSU 2014) were used for their respective years and crop rotations. The 2015-2024 budgets were adjusted using percent changes calculated from the Food and Agricultural Policy Research Institute (FAPRI) US Baseline Briefing Book (Food and Agricultural Policy Research Institute 2015). For long term forecasting (i.e. >10 years), linear regression of the FAPRI prices was used to project prices for the period from 2024 to 2041. These projections are shown for each FAPRI category in table 6.3. Two land rent scenarios were used for NPV analyses. In the first scenario, the producer owns the land and does not have a lease; in the second, the producer cash rents the tillable land. It was assumed that if a producer paid for landscape improvements he or she had a long-term lease that covered the lifetime of the system (i.e. 15 years) and the lease was assumed to be for the period of the analyses (i.e. 15 and 30 years). Cash rents were based on the surveyed 2015 dryland rent of \$306.41/ha and irrigated land rent of \$471.97/ha (Parman and Lewis 2016). Rents were adjusted according to:

$$ADA = Cash\,rent * \frac{PPI_{2012}}{PPI_{2015}} \tag{6.1}$$

where “cash rent” is based on the Delta cash rents surveyed (Parman and Lewis 2016), PPI_{2012} is Prices Paid by Farmers in 2012 (USDA NASS 2012), PPI_{2015} is Prices Paid by Farmers in 2015 (USDA NASS 2015). Adjusted cash rents used for non-irrigated land were \$600.47/ha and \$924.17/ha for irrigated land.

6.3.3 Irrigation energy use

To calculate energy used to irrigate with TWR water, it was assumed producers would initially start with and utilize a full TWR system (from winter precipitation collection) and over the course of the irrigation season be able to collect enough runoff thereafter to utilize an additional volume of water equal to the capacity of their system. This was considered the best-case scenario (i.e., the largest amount of TWR water used in a year, independent of growing season precipitation). It was also assumed that 1) systems were designed and constructed to utilize the maximum surface water holding capacity; 2) producers irrigated corn and rice acreage with surface water before using surface water for soybeans; and 3) producers used the recommended amount of water to grow crops based on each budget. Holding capacities of TWR systems are presented in table 6.2. Volume of water used for irrigation was monitored at each location using flow meters (McCrometer, Hemet, California) installed in the surface water and ground water irrigation pipelines. Energy use was monitored from 2013-2015 for both electrical and diesel service to both surface water and groundwater (table 6.4). Monitoring periods of pump operation for diesel service were used to obtain gallons of diesel per acre foot (L/ha cm^{-1}) of water pumped. Diesel stores were measured before and after operation while water flow meter readings were recorded. Electric service was monitored by recording usage during the irrigation season. These values were then used in production budgets to quantify energy and cost to irrigate crops. The average depth of ground water across all five sites from January 2012 to May 2015 was 8.47 m (Dave Kelly, Yazoo Mississippi Delta Joint Water Management District, personal communication, 2015).

6.3.4 Tailwater recovery system maintenance

Maintenance schedules were estimated under the assumption producers would need to maintenance the TWR ditch once the sump pipe becomes half full of sediment. Sedimentation was measured by accumulation around a post with a flange driven into the bottom of the TWR ditch. Measurements were taken from the flange to the sediment surface every three months for at least two years. The average of those measurements was used to estimate annual sediment accumulation, and was then divided by half the diameter of the sump pipe to calculate years until the pipe is half full. The price to perform maintenance on a TWR ditch was $6.56 per linear meter of ditch maintained (Pete Twiner, Twiners Trackhoe Service, personal communication, 2015). Linear meters of ditch length were measured from ortho-imagery data from the National Agricultural Imagery Program (table 6.5). Larger TWR ditches (e.g. site A) would require a tractor and dirt pan (larger equipment than the other TWR ditches) to clean out. Cubic yards of sedimentation were calculated based on measurements of sediment depth and dimensions of the TWR ditch bottom. The cost of $0.96 per cubic meter of soil moved (Trinity Long, USDA NRCS, personal communication, 2015) was used to calculate the cost to clean TWR ditches. Cost of maintenance schedules were discounted using the aforementioned projected prices pertaining to farm services, then applied to the NPV scenarios according to the years in which maintenance would be required.

6.3.5 Benefits (beyond production income)

Current hypothesized benefits of TWR systems include reduced energy use to irrigate crops, reduced cold stress on agronomic crops, saving ground water by creating an alternative water source, mitigation of sediment and nutrient loss, and potential waterfowl hunting opportunities (Bouldin et al. 2004; Young et al. 2004). In this investigation, the only direct benefit to the producer for switching from groundwater to surface water is the reduction in energy use to irrigate crops. This benefit was reflected in production budgets by using the measured cost of irrigating surface water and ground water. Benefits of reduced cold stress placed on crop yields were not included in this analysis due to the lack of research on the subject relative to the Delta. No financial incentive exists to use less ground water or to reduce sediment and nutrient loss. The USDA NRCS has provided financial assistance of these systems to reduce nutrient loss, and as such, those benefits were viewed in the USDA NRCS NPV scenario. The Delta is known for waterfowl hunting opportunities, and due to more attractive locations (i.e. oxbow lakes and flooded rice, millet, and corn fields) for those opportunities, hunting leases directly on TWR systems were not considered a monetary benefit.

6.3.6 Sediment reduction benefit methods

Nutrient concentrations and water flow data were collected from TWR inflow points, field runoff leading into TWR, and overflow leaving TWR on an event basis from February 1, 2014 to January 31, 2016. To investigate TWR systems' impact on solids and nutrients leaving the agricultural landscape, the influent was compared to effluent or the difference between the two (hereafter described as "performance") was used. Water samples were collected and data analyzed (Chapter 2).

Dollar valuation for reduction in TSS losses was based on a benefit transfer from Hansen and Ribaudo et al. (2008) (table 6.6). Those benefits for reduction in sediment losses were based on county estimates in the dollars of the year 2000 and were adjusted based on equation 6.1 and the Producer Prices Received by Farmers Index (PPRI) from June 2000 (USDA NASS 2000) and June 2012 (USDA NASS 2012). The adjusted dollar amount (ADA) was calculated by the following equation:

$$ADA = \sum BD * \frac{PPRI_{2012}}{PPRI_{2000}} \quad (6.2)$$

where “BD” is the benefit dollars, $PPRI_{2012}$ is the Prices Received by Farmers Index (USDA NASS 2012), $PPRI_{2000}$ is the Prices Received by Farmers Index (USDA NASS 2000). Tailwater recovery systems’ sediment reductions and dollar values of those reductions are shown in table 6.7.

6.3.7 Economic analyses

Net present value (NPV) was calculated as:

$$NPV = \sum_{t=0}^{T-1} \frac{NB_t}{(1+d)^t} \tag{6.3}$$

where “t” is equivalent to the time period index, “T” is the planning horizon of 15 or 30 years, NB_t are the annual net benefits of the system in year t. The discount rate is represented by “d”. Both 15- and 30-year planning horizons were used with three discount rates of 3, 7, and 10% (Office of Management and Budget 2015). The lower interest rate of 3% compares to the average of the previous seven-year rates set forth for federal water projects (USDA NRCS 2016b). The higher interest rates compare to other articles assessing the values of conservation practices which have been discounted using interest rates of between 6 and 10% (Heatwole et al. 1987; Magat and Viscusi 1990; Bazelon and Smetters 1999; Fang and Easter 2003; Bouldin et al. 2004; Bracmort et al. 2004; Rao et al. 2012; Falconer et al. 2015). Projects with a positive NPV indicate a rate of return greater than or equal to the discount rate (i.e., required rate of return) and are considered to be an acceptable investment (Green 2003; Griffin 2006). Greater NPV indicates a more profitable system. The BCR was calculated by:

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1-(\frac{1}{((1+d)^t)}))/d}}{\sum_{t=0}^{T} \frac{C_t}{(1-(\frac{1}{((1+d)^t)}))/d}} \tag{6.4}$$

where B_t is the present value benefits over the time period "t" and planning horizon "T"; C_t is the present value costs over the time period t; and "d" is the discount rate. Benefit to cost ratios are a dollar benefit of value per a dollar of cost. Benefit to cost ratios greater than 1 are considered to be acceptable investments.

Net present value analyses were calculated and examined for five scenarios (figure 6.1) as follows:

1. Dryland - used planning budgets and yields from non-irrigated land in the Delta.
2. Before irrigation - used planning budgets and yields for the crop rotations grown with irrigation method prior to the installation of any conservation practices. This scenario assumes no conservation practices are installed and producers would continue farming and irrigating the same.
3. After irrigation - used budgets and yields for the new irrigation method if implemented with the TWR system. This scenario also used the amount of tillable acreage post-install of land leveling, field perimeter pads, and riser board pipes. Those practices were necessary to convert fields from center pivot irrigation to furrow irrigation for soybeans (*Glycine max*) and corn (*Zea mays*), as well as, from terraced to side-inlet or zero grade irrigation for rice (*Oryza sativa*).
4. TWR system - includes the budgets and yields for the acreage post-TWR system installation, as well as the capital cost of the TWR system.
5. TWR/sediment - includes the budgets and yields for the acreage post-TWR system installation, the capital cost of the TWR system, and the benefit transfer for sediment reductions to downstream aquatic systems (table 5). It is important to note, when considering the sediment reduction benefits in this scenario, the producer's capital would be assumed to be an in-kind donation to the environment of downstream systems because the producers do not attain value added to their NPVs.

In theory, the appropriate percent of financial assistance for producers would be when NPV is equal to zero. To determine this amount, the TWR systems original capital started at zero percent assistance and increased to 100 percent in 5% increments. This was done over a horizon of 15 and 30 years, with rates of 3, 7, and 10%, and for the TWR system after irrigation type with TWR scenario. Analysis of the USDA NRCS financial assistance was calculated for each site using NPV (equation 6.1) of the financial assistance of the TWR system and the sediment reduction benefits.

6.4 Results and Discussion

6.4.1 Economic analyses of tailwater recovery systems

A larger NPV equates to a greater worth of the agronomic system, and a positive NPV and a BCR greater than one are considered an acceptable investment (Green 2003; Griffin 2006). Net present values (table 6.8) and BCRs (table 6.9) of owned land are positive for all scenarios including the ones with a TWR system implemented; however, NPVs (table 6.10) and BCRs (table 6.11) of systems on rented land were calculated to be less than one or negative for each scenario. Net present values of conservation systems show a large difference between owned and rented land. Most producers would not implement permanent conservation practices on rented land without a long-term lease or without sharing the expense with the landowner. This scenario of rented land also shows a negative balance for dryland scenarios, suggesting that producers would be taking large losses with the cash rent scenario even if the TWR system was not installed.

Previous economic analyses show similar results of losses of NPV due to TWR implementation. Falconer et al. (2015) used NPV to analyze a hypothetical TWR scenario of a 64.7-hectare soybean and corn farm with a 3.2 ha TWR ditch and a 4.2 ha OFS. They assumed owned land and found all NPVs to be positive, including TWR system implementation. Their NPV per hectare scenario showed a difference between irrigation systems and TWR systems indicating a loss of NPV from -\$3,472 to -\$1,970 for furrow irrigation and -\$1,662 to -\$1,659 for center pivot irrigation (Falconer et al. 2015). These losses are greater than those presented here (table 6.12) due to the amount of tillable land serviced by the TWR system in Falconer et al. (2015) being less than the five systems investigated in this analysis. In Arkansas, the Modified Arkansas Off-stream Reservoir Analysis (MARORA) model was used to evaluate a 146-hectare soybean and rice farm with a TWR system (Young et al. 2004). They found a TWR system is not economical in an adequate ground water scenario with a loss in NPV/ha of-$254 to -$1,936; however, in an inadequate groundwater scenario, the TWR system increased NPV/ha by $5,012 to $7,032. In addition to NPV, Young et al. (2004) found BCRs of 2 for a scenario comparable to after irrigation, which had an owned land BCR ranging from 0.2 to 1.37 (table 6.9). They also reported BCRs for inadequate groundwater scenario with a TWR system of 3.7, which was much higher than the owned land BCR for TWR systems in this study (1.21 to 1.27; table 6.9). Another study from Arkansas modeled a scenario of a 400 ha farm with a 51 ha OFS and TWR ditch system which determined a BCR for 5% and 10% interest rate of 2.42 and 3.89 for groundwater and 12.61 and 17.74 for TWR systems (Bouldin et al. 2004). Bouldin et al. (2004) also modeled a NPV/ha increase of $78 with the installation of a TWR system. The larger BCR and increase in NPV in Bouldin et al. (2004) compared to this study is due to their valuation of benefits of TWR implementation being much greater. In addition to the financial assistance provided by USDA NRCS, they used hunting club lease benefits; a 1% increased yield from crops due to decreased cold water stress; $75.19/ha value for decreased nutrients to downstream waterways; a $6,178/ha value for ecological services of wetlands; a $168/ha for enrollment of TWR system as wetland acres in wetland reserve program (WRP); and an increased groundwater storage value of $0.46 per m^3 of water saved. The BCR of TWR system without environmental services is 1.5, closer to this study's BCRs (table 6.9) (Bouldin et al. 2004). The TWR systems investigated in this study analyses did not receive benefits of hunting club leases, reduced cold water stress, ecological services, enrollment in WRP, or a value for saving groundwater. The ability of TWR systems to act as wetlands creating external benefits beyond sediment and nutrient removal is undocumented.

Scenarios presented in figure 1 represent baseline (Dryland); "do nothing" case (before irrigation); irrigation improvement from before installation of an irrigation system to the irrigation system used after TWR implementation (after irrigation) (e.g. switch from center pivot irrigation to furrow irrigation); agronomic system with TWR system (after TWR); and the TWR system with the sediment reduction benefits included as a dollar value (TWR/sediment). A mean difference across all sites of \$251 to \$423 for owned land (table 6.12) and -\$141 to -\$628 for rented land (table 6.13) differences between irrigated (before irrigation) and non-irrigated land (dryland) resulted in an increase in NPV/ha. Comparison of before irrigation, after irrigation, and TWR system to dryland could be considered metrics of the productivity valuation of irrigation on these farms for each respective scenario. The lower end of this valuation of irrigation is similar to a previous valuation of irrigation in the Mississippi Delta of \$89 for soybeans, \$279 for corn and \$264 for cotton (Miller et al. 2012). Falconer et al. (2015) found the value of irrigation (i.e. difference between irrigated and dryland scenarios) to be much greater at \$2,137 to \$3,973 per hectare for furrow irrigation and \$1,776 to \$2,278 per hectare for center pivot irrigation. In addition, Young et al. (2004) modeled the difference to be \$5,012 NPV/ha for a reservoir in an inadequate groundwater scenario.

Upgrade of irrigation equipment and change in the method of irrigation (center pivot to furrow) improved NPV through increased yields (i.e. after irrigation-before irrigation, tables 6.12 and 6.13). An increase of NPV/ha of $1,936 between no conservation practices and upgraded irrigation was found in a similar scenario to this study's after irrigation scenario (Young et al. 2004). This is greater than the mean increase in NPV/ha of $138 to $467 presented here. The difference between Young et al. (2004) and the current study may be due to their estimation of land leveling increasing yields by 10%. An increase in yield due to land leveling was not considered in the current study, although an increased yield was included to account for furrow irrigation compared to center pivot irrigation. The difference between the TWR system and after irrigation scenarios, -$203 to $26 NPV/ha owned land and -$313 to -$74 NPV/ha rented land (tables 6.12 and 6.13), reflect the impact of implementing a TWR system compared to implementation of typical (to the Delta region) conservation practices (i.e. land leveling, pads, riser board pipes) and irrigation system upgrades (i.e. switch from center pivot to furrow irrigation and upgraded irrigation pumps and engines). The conservation practice comparisons of TWR systems to before irrigation estimations resulted in increases and decreases in NPV, depending on the discount rate (tables 6.12 and 6.13). If the producer considers the dollar value of sediment as an "in-kind" donation to downstream systems, then the addition of sediment benefits added $1 to $13 to rented and owned land to NPV/ha (tables 6.12 and 6.13). The NPV and BCR results may improve with an increase in USDA NRCS financial assistance.

6.4.2 Impact of United States Department of Agriculture Natural Resources Conservation Service financial assistance

Changing the amount of USDA NRCS financial assistance results in the majority of the TWR systems maintaining a positive NPV/ha for owned land (figure 6.2) and a negative NPV/ha for rented land (figure 6.3). Results indicate that systems are economical regardless of the amount of financial assistance for owned land but are not economical for rented land. System 1 shows a lower NPV/ha than other TWR systems due to the location being the smallest in tillable acreage, therefore the smallest benefits through production yields to offset the cost of the TWR system.

Net present values of USDA NRCS capital were calculated using financial assistance and sediment benefits. Results for the actual financial assistance awarded for each TWR system are shown in table 6.14 and show large losses in NPVs and low BCRs. The NPV/ha remains negative across all amounts of financial assistance, discount rates, and both lifetime scenarios, although decreasing the financial assistance does decrease the loss of USDA NRCS funds in NPV/ha (figure 6.4). This analysis does not include costs of USDA NRCS personnel and equipment in planning and implementing TWR systems. In addition, these analyses do not include the benefit of the contribution of millions of dollars spent in Mississippi's Delta region for rural development, including regional economic development and other social effects (USDA NRCS 1998). In addition, regional benefits may include income and employment. It should be noted, that the transfer of regional benefits to the rest of the US is most likely minimal in TWR system development and may result in a recirculation of dollars within the Delta.

6.5 Summary and Conclusions

Economic analyses of NPVs and BCRs have shown that conservation systems including irrigation land leveling (USDA NRCS practice 342), water control structures (e.g. riser board pipes, USDA NRCS practice 410), and grade stabilization (e.g. field perimeter pads, USDA NRCS practice 587) remain economically feasible. However, when those practices are combined with TWR ditch and OFS reservoir to make a TWR system, the producer faces a decrease in NPV and BCR. Tailwater recovery systems still maintain a positive NPV for producers who own the land on which the system is installed, whereas producers installing TWR systems on rented land maintain a negative NPV even with 100% USDA NRCS assistance.

In conclusion, TWR systems are being implemented and investigated throughout the US. Aimed at mitigating the loss of sediment and nutrients to downstream waters and creating an additional source of irrigation water, these systems should only be considered in a scenario where the amount of lost tillable land is minimal. This will help to maintain a positive NPV with the TWR systems. In the future, reduced ground water levels or ground water pumping regulations for irrigating crops or waterfowl food plots may increase the value of TWR systems. Future considerations of widespread BMP implementation should utilize economic analyses of the benefits and costs to adaptively finance the best possible solution so all parties get the most out of their capital input.

6.6 Acknowledgments

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Table 6.1 Tailwater recovery (TWR) system implementation costs, producer capital costs and Unites States Department of Agriculture Natural Resources Conservation Service (NRCS) financial assistance

TWR system	Producers inputs	NRCS assistance	Total capital costs
1	$181,014.24	$434,350.30	$615,364.54
2	$192,318.00	$288,477.00	$480,795.00
3	$123,950.85	$641,025.90	$764,976.75
4	$99,961.17	$554,102.77	$654,063.94
5	$310,061.85	$509,293.41	$819,355.26

Table 6.2 Characteristics of tailwater recovery systems

TWR system	Layout	Volume (ML)	Crop rotation (irrigation method) pre-TWR installation	Crop rotation (irrigation method) post-TWR installation	Pre-conservation practices tillable land (ha)	Post-land leveling, pads and pipes tillable land (ha)	Post-TWR system including land leveling, pads and pipes tillable land (ha)	Total lost tillable land (ha)
1	TWRD	115.9	rice (contour)-soybeans (furrow)	rice (zero grade)-soybeans (furrow)	63.7	57.6	57.6	6.1
2	TWRD, OFS	94.0	corn (furrow)-soybeans (furrow)-rice (terrace)	corn (furrow)-soybeans (furrow)-rice (side inlet)	196.6	188.2	181.8	14.8
3	TWRD	37.0	corn (center pivot)- soybeans (center pivot)	corn (furrow)-soybeans (furrow)	124.0	117.2	112.4	11.6
4	TWRD, OFS	177.2	corn (center pivot- soybeans (center pivot)	corn (furrow)-soybeans (furrow)	142.7	141.4	129.9	12.8
5	TWRD (2), OFS (2)	346.7	rice (side inlet)-soybeans (furrow)	rice (side inlet)-soybeans (furrow)	132.3	128.4	122.4	9.9

Notes: TWR is tailwater recovery system, ML is mega liters, ha is hectares, TWRD is the tailwater recovery ditch, OFS is on farm storage reservoir. Crops in crop rotation include: rice (*Oryza sativa*), soybeans (*Glycine max*) and corn (*Zea mays*).

Table 6.3 Indices of prices paid by farmers, projected crop prices, and projected yields.

Year	Prod. items, interest, taxes and wages	Prod. items	Seeds	Fert.	Mixed fert.	Nitrogen fert.	Potash and phosphate	Ag. chem.	Fuels	Supplies and repairs	Autos and trucks
2014	112	113	114	96	87	104	100	110	98	106	104
2015	109	110	113	91	85	95	99	109	76	108	105
2016	109	109	114	89	84	92	98	110	81	109	108
2017	110	109	115	89	84	91	98	113	87	111	110
2018	112	111	118	90	85	93	99	117	94	113	112
2019	114	113	121	93	87	97	101	121	101	115	115
2020	117	116	125	96	90	100	104	126	110	118	117
2021	120	119	128	97	91	101	105	130	118	120	118
2022	122	121	131	96	90	100	105	133	123	122	120
2023	124	122	134	96	89	99	106	136	129	123	122
2024[a]	127	124	136	95	88	98	106	139	135	125	123
2025	127	124	138	97	90	99	107	142	138	127	126
2026	129	126	140	97	91	100	108	145	143	129	128
2027	130	127	143	98	91	100	109	149	148	131	130
2028	132	129	145	98	92	100	110	152	154	133	132
2029	134	130	148	99	93	101	111	155	159	135	134
2030	136	132	150	99	93	101	112	159	165	137	136
2031	138	133	153	100	94	101	113	162	170	139	138
2032	140	135	155	100	94	102	113	165	176	141	140
2033	141	136	158	101	95	102	114	169	181	143	142
2034	143	138	161	101	95	102	115	172	187	145	144
2035	145	139	163	102	96	103	116	175	192	147	146
2036	147	141	166	102	96	103	117	179	198	149	148
2037	149	142	168	103	97	103	118	182	203	151	150
2038	150	144	171	103	97	104	119	185	209	153	152
2039	152	145	173	104	98	104	120	189	214	155	154
2040	154	146	176	105	98	104	121	192	219	157	156
2041	156	148	178	105	99	105	122	195	225	159	158

Notes: Prod. is production; Ag. is agriculture; chem. is chemicals; and Fert. is Fertilization. Information adapted from 2015 Food and Agricultural Policy Research Institute (FAPRI) U.S. Baseline Briefing Book (Food and Agricultural Policy Research Institute 2015). All projections are averages across 500 outcomes. "a" Beyond 10 years of FAPRI predictions linear regression was used to project indices, prices, and yields.

Table 6.3 (continued)

Year	Farm mach.	Farm services	Int.*	Taxes+	Wage rates	Corn-farm price ($/Bu)	Soybeans-farm price ($/Bu)	Rice-farm price ($/100 lbs cwt)	Corn yield (Bu/ac)	Soybean yield (Bu/ac)	Rice yield (lbs/ac)
2014	111	109	101	105	108	$3.63	$10.02	$13.87	171.0	47.8	7572.0
2015	110	110	103	105	110	$3.89	$9.29	$13.86	165.1	44.5	7523.0
2016	112	113	107	107	113	$3.90	$9.44	$13.72	167.0	45.0	7618.0
2017	113	116	114	109	117	$4.01	$9.79	$13.71	168.7	45.4	7694.0
2018	117	120	117	112	121	$4.12	$10.26	$13.74	170.2	45.8	7760.0
2019	121	124	119	115	125	$4.17	$10.45	$13.82	171.9	46.2	7816.0
2020	125	128	122	120	129	$4.18	$10.36	$13.90	173.8	46.6	7873.0
2021	128	132	125	123	134	$4.16	$10.45	$13.91	175.5	47.0	7939.0
2022	131	136	127	127	138	$4.07	$10.18	$13.85	176.9	47.4	8005.0
2023	134	140	130	131	143	$4.01	$9.99	$13.84	178.4	47.7	8067.0
2024[a]	136	144	133	135	147	$3.90	$9.87	$13.88	180.4	48.1	8130.0
2025	139	147	137	136	150	$4.15	$10.32	$13.88	180.7	47.9	8185.0
2026	142	150	141	139	154	$4.18	$10.37	$13.89	182.0	48.1	8246.2
2027	145	154	144	143	158	$4.20	$10.42	$13.89	183.3	48.4	8307.4
2028	147	158	147	146	162	$4.22	$10.47	$13.90	184.7	48.6	8368.5
2029	150	161	150	149	166	$4.25	$10.53	$13.91	186.0	48.8	8429.7
2030	153	165	154	152	170	$4.27	$10.58	$13.92	187.3	49.1	8490.9
2031	156	169	157	155	174	$4.30	$10.63	$13.93	188.7	49.3	8552.1
2032	159	172	160	159	178	$4.32	$10.68	$13.94	190.0	49.5	8613.3
2033	162	176	163	162	182	$4.35	$10.73	$13.94	191.3	49.7	8674.5
2034	165	180	166	165	186	$4.37	$10.79	$13.95	192.7	50.0	8735.6
2035	168	183	170	168	190	$4.40	$10.84	$13.96	194.0	50.2	8796.8
2036	170	187	173	171	195	$4.42	$10.89	$13.97	195.4	50.4	8858.0
2037	173	191	176	174	199	$4.45	$10.94	$13.98	196.7	50.7	8919.2
2038	176	195	179	178	203	$4.47	$10.99	$13.99	198.0	50.9	8980.4
2039	179	198	183	181	207	$4.49	$11.04	$13.99	199.4	51.1	9041.5
2040	182	202	186	184	211	$4.52	$11.10	$14.00	200.7	51.4	9102.7
2041	185	206	189	187	215	$4.54	$11.15	$14.01	202.0	51.6	9163.9

Notes: *Interest per acre on farm real estate debt and interest rate on farm non-real estate debt. +Farm real estate taxes payable per acre; mach. is machinery, int is interest. All projections are averages across 500 outcomes. “[a]” Beyond 10 years of FAPRI predictions linear regression was used to project indices, prices, and yields.

Table 6.4 Energy use and costs of surface water and groundwater pumping for each tailwater recovery system

Site	Water source*	KWH/ML^{E}, liters diesel/ML^{D}	Conversion to KWH/ML^{A}	Cost U.S. dollars of energy/ML^{B}
A	SW^{D†}	43.02	462.56	$26.14
	GW^{D†}	59.72	639.97	$36.17
B	SW^{D†}	23.96	257.64	$14.56
	Relift^{D†}	23.11	248.51	$14.04
	Mean GW^{D} (n=4)	32.91	353.86	$20.00
	GW^{E}	168.20	168.20	$18.50
	SW+Relift	47.08	506.15	$28.60
C	SW^{D}	92.52	994.75	$56.21
	Mean GW^{E} (n=2)	170.39	170.39	$18.74
D	Mean SW^{E} (n=2)	43.30	43.30	$4.76
	Relift^{E}	121.26	121.26	$13.34
	Mean GW^{E} (n=2)	170.02	170.02	$18.70
	Mean SW+Relift	164.56	164.56	$18.10
E	Mean GW^{E} (n=3)	127.16	127.16	$13.99
	Mean SW^{E} (n=2)	58.84	58.84	$6.47
	Mean Relift^{E} (n=3)	70.28	70.28	$7.73
	Mean SW+ Mean Relift	129.12	129.12	$14.20

Notes: “†” represents same pump doing two functions, GW = ground water, SW= surface water, KWH = kilowatt hour, “^{E}” electric energy source, “^{D}” diesel energy source, “^{A}” Column is calculated based on the conversion of 1 liter US diesel fuel to 10.75 KWH, “^{B}” average cost for Delta region $0.61/L diesel (MSU 2014) and $0.11/KWH electric (MSU 2014).

Table 6.5 Sediment accumulation and cost of clean out for tailwater recovery (TWR) systems

TWR system	Sediment accumulation (cm)	Days monitored	Sediment accumulation (cm)/year	Size of intake pipe (cm)	Years until pipe is half full	Linear meters of ditch	Cost of clean out[a]
1	1.27	756	0.61	60.96	50	NA	\$51,364.50[b]
2	9.37	1,014	3.37	50.80	8	2,008.9	\$26,363.52
3	15.24	1,045	5.32	60.96	6	1,586.1	\$20,814.96
4	7.62	417	6.67	60.96	5	798.0	\$10,472.44
5	2.54	573	1.62	60.96	19	2,266.6	\$29,745.40

Notes: NA means not applicable due to the size of the TWR ditch clean out requires more than an excavator, "[a]" cost is estimated based on the quoted price of \$6.56 a meter for excavation of TWR ditch sediment (Pete Twiner, Twiner Trackhoe Service, personal communication, 2015), "[b]" cost is estimated based on the price of \$0.96 per cubic meter (Trinity Long, USDA NRCS, personal communication, 2015) excavated with a tractor and dirt pan.

Table 6.6 Benefit transfer values for sediment loss prevented

Benefit category	TWR system (US $/ton)		
	1, 2	3, 4	5
Irrigation ditches and canals	$0.12	$0.12	$0.12
Marine recreational fishing	$0.02	$0.02	$0.02
Freshwater fisheries	$0.12	$0.12	$0.12
Marine fisheries	$0.02	$0.02	$0.02
Flood damages	$0.71	$0.71	$0.71
Road drainage ditches	$0.20	$0.20	$0.20
Municipal and industrial water use	$0.68	$0.68	$0.68
Municipal water treatment	$0.04	$0.04	$0.04
Steam power plants	$0.44	$0.44	$0.44
Soil productivity	$0.43	$0.43	$0.43
Water-based recreation	$1.31	$1.25	$1.27
Navigation	$0.22	$0.12	$0.15
Reservoir services	$0.09	$0.12	$0.16
Total dollar benefits per metric ton of soil lost (year 2000 dollars)[a]	$4.00	$3.88	$3.96
Total dollar benefits per metric ton of soil lost (year 2015 dollars)[b]	$4.24	$4.12	$4.20

Notes: table adapted from results of Hansen and Ribaudo (2008). "[a]" year 2000 dollars and "[b]" adjusted dollar amount is equal to the summation of all the benefit dollars multiplied by the division of the year 2000 PPRI (USDA NASS 2000) by the year 2012 PPRI (USDA NASS 2012).

Table 6.7 Sediment reduction summary and benefit dollar value

Site	2014-2015 sediment leaving fields (kg)	2014-2015 sediment leaving TWR (kg)	Sediment caught by TWR system (metric tons) in 2014-2015	US $/metric ton sediment loss prevented	Total dollar benefit for sediment reduction 2014-2015	Mean annual dollar benefit for sediment reduction from TWRs
1	1,465,650.43	1,159,936.12	305.71	$4.24	$1,572.78	$786.39
2	271,044.30	163,054.47	107.99	$4.24	$555.56	$277.78
3	269,961.31	84,697.36	185.26	$4.12	$925.36	$462.68
4	265,489.83	23,656.07	241.83	$4.12	$1,207.92	$603.96
5	386,292.24	17,027.09	369.27	$4.20	$1,881.66	$940.83

Note: values from Chapter 2.

Table 6.8 Summary of net present value of producers' capital across scenarios for two lifespans (owned land) and three discount rates

Site	System	15-year lifespan			30-year lifespan		
		3%	7%	10%	3%	7%	10%
1	Dryland	$131,967	$115,071	$105,195	$127,593	$113,900	$139,478
	Before irrigation	$115,241	$201,108	$182,322	-$26,497	$144,267	$152,450
	After irrigation	$399,670	$215,828	$186,077	$346,688	$197,611	$177,788
	TWR system.	$159,166	$97,533	$63,132	$145,558	$95,929	$63,873
	TWR/sediment	$168,554	$104,695	$69,113	$160,971	$105,687	$71,286
2	Dryland	$158,079	$394,070	$359,608	$142,505	$389,740	$358,133
	Before irrigation	$1,160,188	$942,497	$822,930	$1,384,923	$1,045,960	$882,358
	After irrigation	$1,264,549	$1,009,211	$869,530	$1,615,593	$1,166,515	$958,484
	TWR system	$979,669	$749,786	$624,734	$1,324,040	$901,964	$709,965
	TWR/sediment	$982,985	$752,316	$626,846	$1,329,484	$905,411	$712,584
3	Dryland	$108,587	$223,895	$204,679	$100,075	$221,615	$203,964
	Before irrigation	$439,231	$367,934	$327,599	$487,271	$391,426	$341,683
	After irrigation	$701,735	$539,553	$452,000	$1,066,973	$697,890	$539,737
	TWR system	$618,718	$470,623	$390,641	$940,499	$610,527	$468,284
	TWR/sediment	$624,242	$474,838	$394,160	$949,568	$616,268	$472,646
4	Dryland	$124,938	$257,610	$235,500	$115,145	$254,987	$234,677
	Before irrigation	$226,903	$352,894	$318,234	$206,160	$347,568	$316,749
	After irrigation	$823,478	$639,566	$540,054	$1,228,769	$815,452	$637,558
	TWR system	$832,798	$647,390	$546,885	$1,234,703	$822,310	$644,037
	TWR/sediment	$840,008	$652,891	$551,479	$1,246,541	$829,804	$649,730
5	Dryland	$274,033	$238,948	$218,440	$263,532	$236,515	$217,676
	Before irrigation	$840,103	$682,942	$596,314	$957,117	$739,153	$629,415
	After irrigation	$785,649	$633,145	$549,084	$852,327	$667,154	$569,967
	TWR system	$466,737	$321,449	$241,363	$561,734	$367,057	$268,214
	TWR/sediment	$477,968	$330,018	$248,519	$580,175	$378,732	$277,083
Mean (SD)	Dryland	$159,521 ($66,454)	$245,919 ($99,675)	$224,684 ($90,882)	$149,770 ($654,88)	$243,351 ($98,542)	$230,785 ($79,782)
	Before irrigation	$556,333 ($436,453)	$509,475 ($298,848)	$449,480 ($257,137)	$601,795 ($570,950)	$533,675 ($357,480)	$464,531 ($289,867)
	After irrigation	$759,016 ($310,789)	$607,461 ($283,320)	$519,349 ($244,717)	$1,022,070 ($469,565)	$708,924 ($347,867)	$576,707 ($278,390)
	TWR system	$611,418 ($320,209)	$457,356 ($259,686)	$373,351 ($227,631)	$841,307 ($489,862)	$559,557 ($331,997)	$430,874 ($267,338)
	TWR/sediment	$618,752 ($317,863)	$462,952 ($257,861)	$378,023 ($226,085)	$853,348 ($485,946)	$567,181 ($329,496)	$436,666 ($265,420)

Note: SD is standard deviation.

Table 6.9 Summary of tailwater recovery system benefit/cost ratios for two lifespans (owned land) and three discount rates

Site	Scenario	15-year lifespan			30-year lifespan		
		3%	7%	10%	3%	7%	10%
1	Dryland	1.16	1.19	1.21	1.09	1.13	1.21
	Before irrigation	1.09	1.22	1.24	0.99	1.10	1.15
	After irrigation	1.32	1.21	1.21	1.14	1.13	1.15
	TWR system	1.11	1.08	1.06	1.05	1.06	1.05
	TWR/sediment	1.11	1.09	1.07	1.06	1.06	1.06
2	Dryland	1.06	1.22	1.24	1.03	1.14	1.18
	Before irrigation	1.36	1.38	1.41	1.23	1.29	1.33
	After irrigation	1.37	1.39	1.41	1.26	1.31	1.34
	TWR system	1.31	1.31	1.30	1.23	1.26	1.27
	TWR/sediment	1.31	1.31	1.30	1.23	1.26	1.27
3	Dryland	1.07	1.19	1.21	1.03	1.13	1.16
	Before irrigation	1.23	1.25	1.27	1.14	1.18	1.22
	After irrigation	1.38	1.38	1.38	1.33	1.35	1.36
	TWR system	1.36	1.36	1.35	1.32	1.33	1.33
	TWR/sediment	1.37	1.36	1.35	1.32	1.33	1.33
4	Dryland	1.07	1.19	1.21	1.03	1.13	1.16
	Before irrigation	1.10	1.21	1.23	1.05	1.14	1.17
	After irrigation	1.41	1.41	1.41	1.34	1.37	1.38
	TWR system	1.40	1.40	1.40	1.34	1.36	1.37
	TWR/sediment	1.40	1.41	1.41	1.34	1.36	1.38
5	Dryland	1.16	1.19	1.21	1.09	1.13	1.16
	Before irrigation	1.37	1.40	1.43	1.22	1.28	1.33
	After irrigation	1.35	1.38	1.40	1.20	1.26	1.31
	TWR system	1.19	1.17	1.15	1.13	1.13	1.13
	TWR/sediment	1.20	1.17	1.15	1.13	1.14	1.13
Mean (SD)	Dryland	1.11	1.19	1.22	1.06	1.13	1.17
		(0.05)	(0.01)	(0.01)	(0.03)	(0.01)	(0.02)
	Before irrigation	1.23	1.29	1.32	1.12	1.20	1.24
		(0.12)	(0.08)	(0.08)	(0.09)	(0.07)	(0.08)
	After irrigation	1.37	1.36	1.36	1.25	1.28	1.31
		(0.03)	(0.07)	(0.07)	(0.08)	(0.09)	(0.08)
	TWR system	1.27	1.26	1.25	1.21	1.23	1.23
		(0.11)	(0.12)	(0.13)	(0.11)	(0.12)	(0.12)
	TWR/sediment	1.28	1.27	1.26	1.22	1.23	1.23
		(0.11)	(0.12)	(0.13)	(0.11)	(0.11)	(0.12)

Note: SD is standard deviation.

Table 6.10 Summary of net present value of producers’ capital across scenarios for two lifespans (cash rent) and three discount rates

Site	System	15-year lifespan			30-year lifespan		
		3%	7%	10%	3%	7%	10%
1	Dryland	-$324,869	-$233,467	-$185,872	-$622,469	-$360,965	-$221,268
	Before irrigation	-$587,873	-$335,325	-$265,657	-$1,180,914	-$586,595	-$402,772
	After irrigation	-$184,492	-$269,305	-$219,061	-$645,618	-$463,358	-$324,337
	TWR system	-$476,709	-$387,601	-$342,007	-$898,461	-$565,040	-$438,252
	TWR/sediment	-$467,321	-$380,439	-$336,025	-$883,048	-$555,281	-$430,839
2	Dryland	-$1,251,303	-$681,202	-$538,359	-$2,171,506	-$1,075,260	-$754,800
	Before irrigation	-$1,008,985	-$712,449	-$559,127	-$2,176,558	-$1,208,814	-$830,552
	After irrigation	-$812,024	-$575,087	-$453,528	-$1,793,853	-$992,006	-$681,304
	TWR system	-$1,026,405	-$780,725	-$653,407	-$1,969,657	-$1,183,275	-$874,152
	TWR/sediment	-$1,023,089	-$778,195	-$651,294	-$1,964,212	-$1,179,828	-$871,533
3	Dryland	-$780,284	-$454,259	-$361,652	-$1,359,327	-$702,332	-$497,942
	Before irrigation	-$928,825	-$675,809	-$544,037	-$1,758,888	-$1,030,617	-$738,616
	After irrigation	-$591,402	-$447,031	-$371,902	-$1,056,179	-$646,278	-$481,402
	TWR system	-$621,019	-$475,220	-$399,240	-$1,094,979	-$678,134	-$510,688
	TWR/sediment	-$615,496	-$471,006	-$395,721	-$1,085,910	-$672,393	-$506,326
4	Dryland	-$897,781	-$522,662	-$416,110	-$1,564,018	-$808,092	-$572,924
	Before irrigation	-$1,347,158	-$848,018	-$684,656	-$2,378,231	-$1,288,610	-$926,224
	After irrigation	-$736,206	-$550,377	-$453,676	-$1,332,018	-$805,782	-$594,063
	TWR system	-$599,773	-$445,575	-$365,857	-$1,117,382	-$666,796	-$487,209
	TWR/sediment	-$592,563	-$440,074	-$361,263	-$1,105,544	-$659,301	-$481,515
5	Dryland	-$674,596	-$484,798	-$385,965	-$1,249,990	-$749,550	-$531,419
	Before irrigation	-$620,329	-$431,278	-$334,179	-$1,440,711	-$778,912	-$523,831
	After irrigation	-$631,117	-$447,761	-$353,588	-$913,297	-$590,119	-$440,403
	TWR system	-$883,951	-$709,043	-$619,208	-$1,655,908	-$1,036,933	-$798,371
	TWR/sediment	-$872,719	-$700,474	-$612,052	-$1,637,468	-$1,025,258	-$789,501
Mean (SD)	Dryland	-$785,767 ($336,930)	-$475,278 ($160,978)	-$377,592 ($126,896)	-$1,393,462 ($559,156)	-$739,240 ($256,032)	-$515,671 ($192,156)
	Before irrigation	-$898,634 ($311,564)	-$600,576 ($211,201)	-$477,531 ($172,788)	-$1,787,060 ($497,332)	-$978,710 ($293,834)	-$684,399 ($216,723)
	After irrigation	-$591,048 ($243,308)	-$457,912 ($120,492)	-$379,351 ($96,220)	-$1,148,193 ($437,862)	-$669,509 ($204,582)	-$504,302 ($138,186)
	TWR system	-$721,571 ($225,939)	-$559,633 ($173,878)	-$559,633 ($173,878)	-$1,347,277 ($447,368)	-$826,036 ($268,071)	-$621,734 ($199,380)
	TWR/sediment	-$714,238 ($226,951)	-$554,038 ($174,434)	-$471,271 ($148,601)	-$1,335,236 ($448,985)	-$818,412 ($268,925)	-$615,943 ($199,874)

Note: SD is standard deviation.

Table 6.11 Summary of TWR system benefit/cost ratios (cash rent) and three discount rates

Site	System	15-year lifespan			30-year lifespan		
		3%	7%	10%	3%	7%	10%
1	Dryland	0.74	0.76	0.77	0.72	0.74	0.78
	Before irrigation	0.70	0.77	0.78	0.67	0.73	0.75
	After irrigation	0.90	0.82	0.83	0.81	0.79	0.80
	TWR system	0.78	0.77	0.76	0.76	0.76	0.75
	TWR/sediment	0.78	0.77	0.76	0.76	0.76	0.76
2	Dryland	0.67	0.77	0.78	0.68	0.74	0.76
	Before irrigation	0.81	0.83	0.84	0.77	0.80	0.81
	After irrigation	0.85	0.86	0.87	0.81	0.83	0.85
	TWR system	0.80	0.80	0.80	0.78	0.79	0.79
	TWR/sediment	0.80	0.80	0.81	0.78	0.79	0.79
3	Dryland	0.68	0.76	0.77	0.69	0.74	0.75
	Before irrigation	0.72	0.73	0.74	0.70	0.71	0.72
	After irrigation	0.81	0.81	0.82	0.80	0.81	0.81
	TWR system	0.79	0.79	0.79	0.78	0.78	0.79
	TWR/sediment	0.79	0.79	0.79	0.78	0.79	0.79
4	Dryland	0.68	0.76	0.77	0.69	0.74	0.75
	Before irrigation	0.64	0.71	0.71	0.64	0.69	0.70
	After irrigation	0.80	0.80	0.80	0.78	0.79	0.80
	TWR system	0.83	0.84	0.84	0.81	0.82	0.83
	TWR/sediment	0.83	0.84	0.84	0.82	0.83	0.83
5	Dryland	0.74	0.76	0.77	0.72	0.74	0.75
	Before irrigation	0.83	0.85	0.86	0.79	0.81	0.83
	After irrigation	0.83	0.84	0.85	0.86	0.85	0.85
	TWR system	0.77	0.76	0.75	0.75	0.75	0.74
	TWR/sediment	0.77	0.76	0.75	0.75	0.75	0.75
Mean (SD)	Dryland	0.70 (0.03)	0.76 (0.00)	0.77 (0.00)	0.70 (0.02)	0.74 (0.00)	0.76 (0.01)
	Before irrigation	0.74 (0.07)	0.78 (0.05)	0.78 (0.06)	0.71 (0.06)	0.75 (0.05)	0.76 (0.05)
	After irrigation	0.84 (0.04)	0.83 (0.02)	0.83 (0.02)	0.81 (0.03)	0.82 (0.02)	0.82 (0.02)
	TWR system	0.79 (0.02)	0.79 (0.03)	0.79 (0.03)	0.78 (0.02)	0.78 (0.03)	0.78 (0.03)
	TWR/sediment	0.80 (0.02)	0.79 (0.03)	0.79 (0.03)	0.78 (0.02)	0.78 (0.03)	0.78 (0.03)

Note: SD is standard deviation.

Table 6.12 Summary of tailwater recovery systems mean (n=5) net present value per hectare and mean net present value per hectare scenario differences (owned land) and three discount rates

Scenario	15-year lifespan						30-year lifespan					
	3%		7%		10%		3%		7%		10%	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dryland	$219	$109	$302	$15	$276	$13	$207	$109	$299	$14	$293	$39
Before irrigation	$629	$365	$608	$195	$538	$164	$630	$553	$615	$261	$544	$197
After irrigation	$985	$53	$725	$107	$620	$94	$1,222	$236	$833	$189	$681	$131
TWR system	$782	$240	$577	$218	$465	$208	$1,057	$468	$701	$312	$535	$258
TWR/sediment	$795	$232	$586	$212	$473	$203	$1,077	$455	$713	$304	$545	$252
Before irrigation-dryland	$409	$373	$305	$188	$262	$158	$423	$580	$315	$253	$251	$211
After irrigation-dryland	$766	$111	$423	$99	$344	$86	$1,015	$342	$533	$184	$388	$164
TWR system-dryland	$563	$343	$275	$215	$189	$205	$850	$569	$402	$309	$242	$287
TWR/sediment-dryland	$575	$335	$284	$209	$197	$200	$870	$557	$414	$301	$252	$280
After irrigation-before irrigation	$356	$354	$118	$157	$82	$126	$209	$825	$163	$298	$111	$198
TWR system-after irrigation	-$203	$268	-$148	$178	-$155	$179	$26	$301	-$38	$222	-$36	$236
TWR/sediment-TWR system	$13	$9	$9	$7	$7	$6	$3	$27	$2	$17	$1	$13
TWR system-before irrigation	$154	$451	-$31	$334	-$73	$303	$427	$667	$86	$419	-$9	$348
TWR/sediment-before irrigation type	$166	$450	-$21	$331	-$118	$228	$448	$666	$99	$415	$1	$345

Note: SD is standard deviation.

Table 6.13 Summary of TWR systems mean and standard deviation of (n=5) net present value per hectare and mean and standard deviation net present value per hectare scenario differences (cash rent) and three discount rates

System	15-year lifespan						30-year lifespan					
	3%		7%		10%		3%		7%		10%	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dryland	-$955	$109	-$593	$15	-$472	$13	-$1,709	$126	-$921	$14	-$634	$39
Before irrigation	-$1,178	$364	-$771	$195	-$613	$164	-$2,337	$553	-$1,264	$260	-$883	$197
After irrigation	-$712	$146	-$589	$80	-$478	$72	-$1,441	$198	-$905	$174	-$658	$115
TWR system	-$1,025	$240	-$802	$218	-$686	$208	-$1,909	$468	-$1,178	$312	-$892	$258
TWR/sediment	-$1,012	$232	-$792	$212	-$679	$203	-$1,889	$455	-$1,165	$304	-$882	$252
Before irrigation-dryland	-$224	$373	-$178	$188	-$141	$158	-$628	$570	-$343	$253	-$249	$211
After irrigation-dryland	$243	$130	$4	$70	-$6	$63	$268	$193	$16	$171	-$19	$147
TWR system- dryland	-$70	$343	-$208	$215	$215	$205	-$200	$580	-$256	$309	$258	$287
TWR/sediment-dryland	-$58	$335	-$199	$209	-$207	$200	-$180	$567	-$243	$301	-$248	$280
After irrigation-before irrigation	$467	$419	$181	$146	$138	$115	$345	$1,016	$232	$348	$149	$232
TWR system- after irrigation	-$313	$364	-$212	$202	-$208	$199	-$110	$716	-$106	$397	-$74	$346
TWR/sediment- TWR system	$13	$9	$9	$7	$7	$6	$3	$27	$2	$17	$1	$13
TWR system-before irrigation	$154	$451	-$31	$334	-$73	$303	$427	$667	$86	$419	-$9	$348
TWR/sediment-before irrigation	$166	$450	-$21	$331	-$118	$228	$448	$666	$99	$415	$1	$345

Note: SD is standard deviation.

Table 6.14 United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) net present value (NPV) and benefit to cost ratios (BCR) summary at three different rates

Site	System	15-year lifespan			30-year lifespan		
		3%	7%	10%	3%	7%	10%
1	NPV	-$424,962	-$427,188	-$428,369	-$418,937	-$424,592	-$426,937
	NPV/ha	-$6,668	-$6,703	-$6,722	-$6,574	-$6,662	-$6,699
	BCR	0.022	0.016	0.014	0.022	0.016	0.014
2	NPV	-$285,161	-$285,947	-$286,364	-$283,032	-$285,030	-$285,858
	NPV/ha	-$1,450	-$1,454	-$1,457	-$1,440	-$1,450	-$1,454
	BCR	0.011	0.009	0.007	0.011	0.009	0.007
3	NPV	-$635,502	-$636,812	-$637,507	-$631,957	-$635,284	-$636,664
	NPV/ha	-$5,125	-$5,136	-$5,142	-$5,097	-$5,124	-$5,135
	BCR	0.009	0.007	0.005	0.009	0.007	0.005
4	NPV	-$546,893	-$548,602	-$549,509	-$542,265	-$546,608	-$548,409
	NPV/ha	-$3,833	-$3,845	-$3,852	-$3,801	-$3,831	-$3,844
	BCR	0.013	0.010	0.008	0.013	0.010	0.008
5	NPV	-$498,062	-$500,724	-$502,137	-$490,853	-$497,619	-$500,424
	NPV/ha	-$3,764	-$3,784	-$3,794	-$3,709	-$3,760	-$3,781
	BCR	0.022	0.017	0.014	0.022	0.017	0.014
Mean (SD)	NPV	-$478,116 ($132,246)	-$479,855 ($132,449)	-$480,777 ($132,559)	-$473,409 ($131,713)	-$477,827 ($132,212)	-$479,659 ($132,426)
	NPV/ha	-$4,168 ($1,925)	-$4,184 ($1,935)	-$4,193 ($1,940)	-$4,124 ($1,899)	-$4,165 ($1,924)	-$4,183 ($1,934)
	BCR	0.015 (0.006)	0.012 (0.005)	0.010 (0.004)	0.015 (0.006)	0.012 (0.005)	0.010 (0.004)

Notes: ha is hectare and SD is standard deviation. The NPV and BCR presented in this table are representative of the USDA NRCS actual financial assistance award at each site.

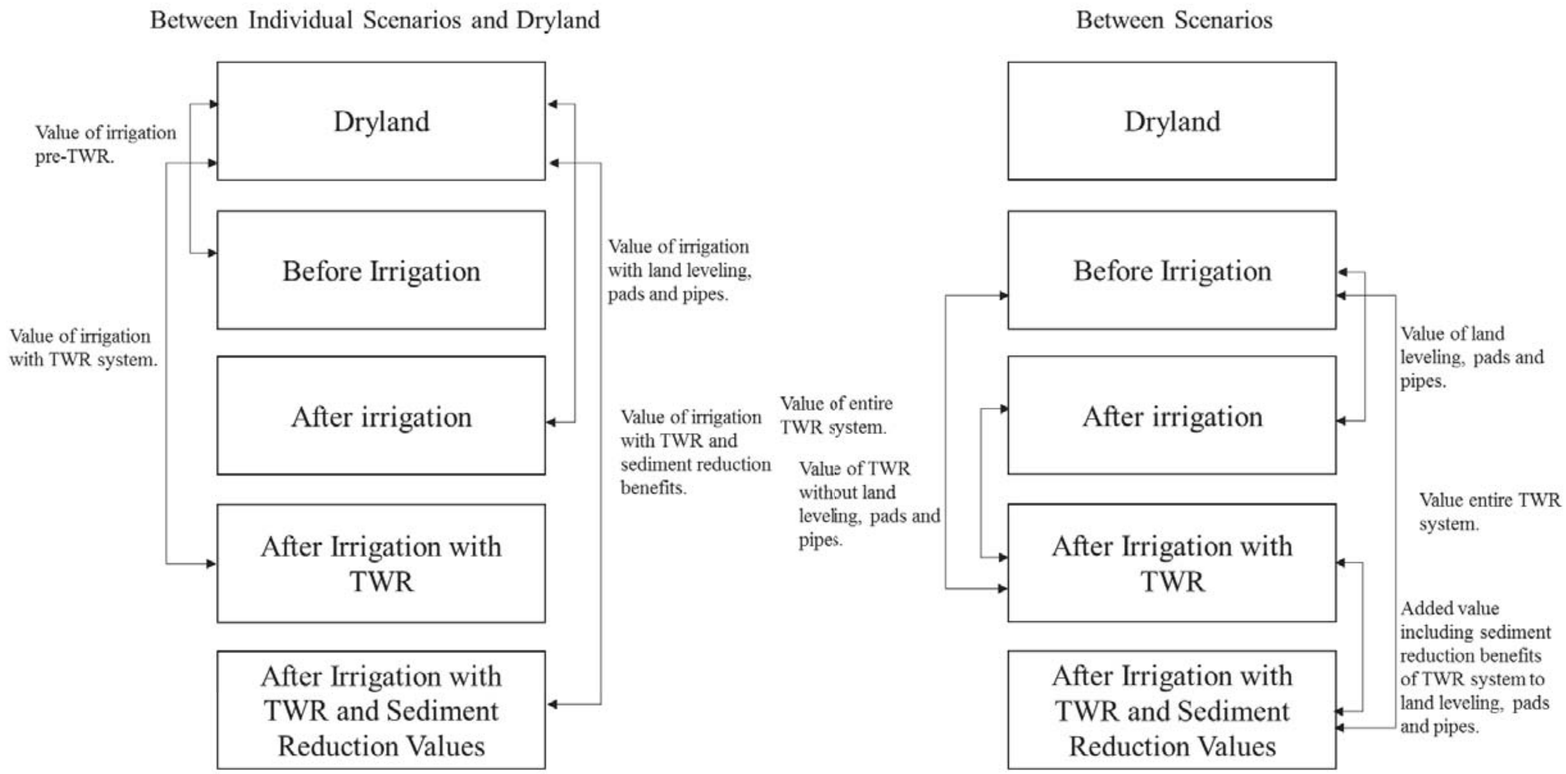

Figure 6.1 Scenarios of net present value differences and associated implications

Notes: TWR refers to tailwater recovery, land leveling refers to United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) practice code 342 irrigation land leveling, pipes refer to USDA NRCS practice code 410 “water control structures” and pads refer to berms around the edge of the field to direct water under USDA NRCS code 587 “grade stabilization”.

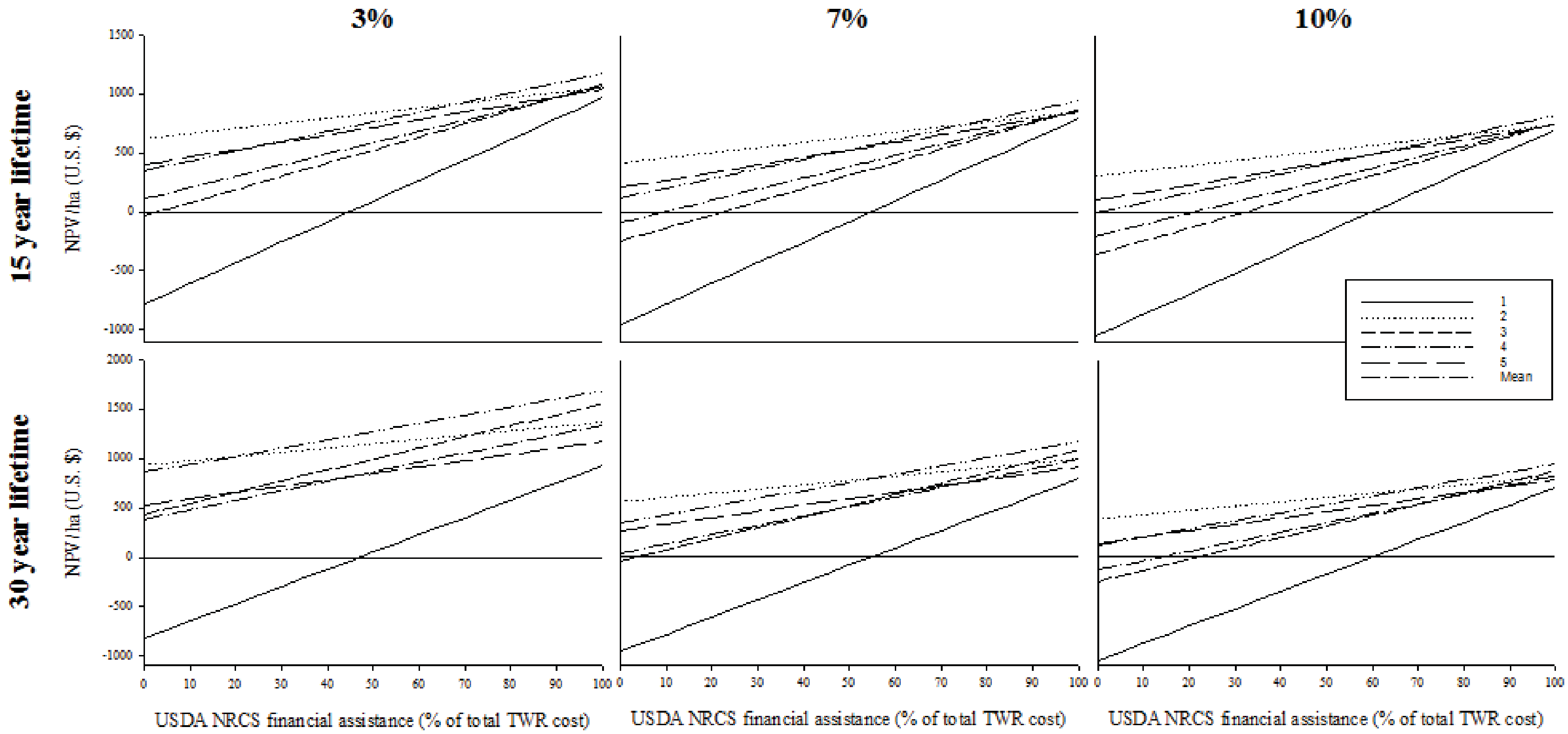

Figure 6.2 Net present value per hectare of producers’ capital on owned land over different amounts of United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) financial assistance

Notes: TWR is tailwater recovery system, NPV is net present value, ha is hectares.

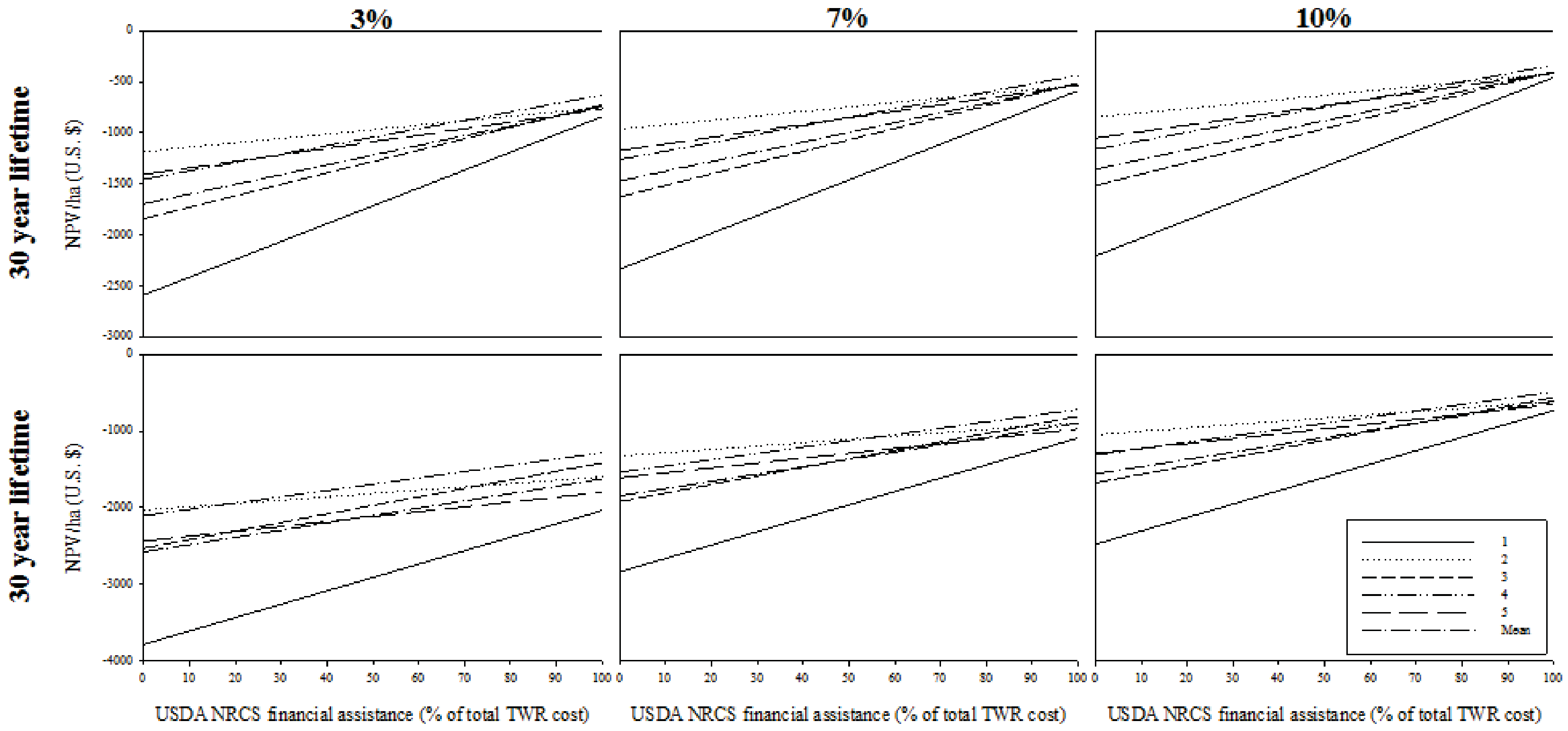

Figure 6.3 Net present value per hectare of producers' capital on rented land over different amounts of United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) financial assistance

Notes: TWR is tailwater recovery system, NPV is net present value, ha is hectares.

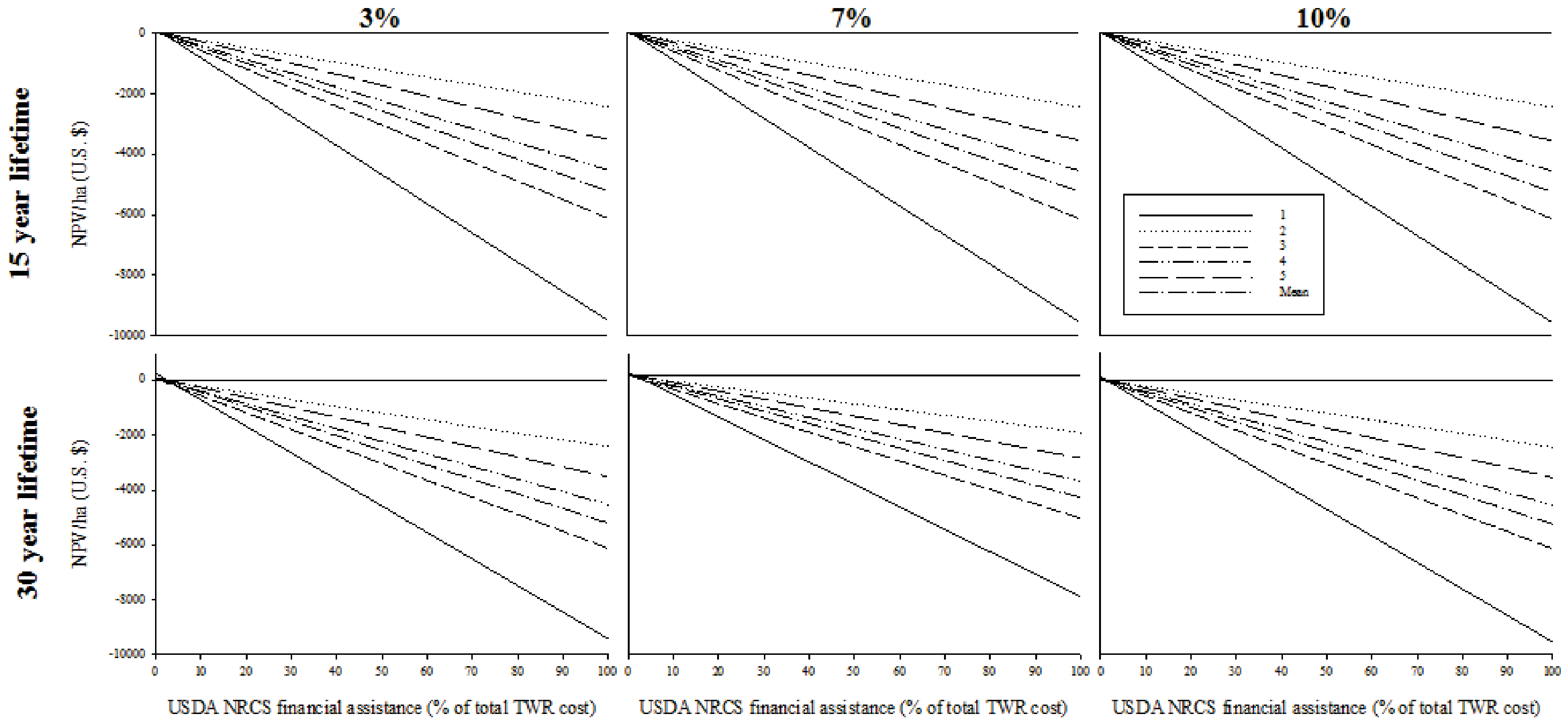

Figure 6.4 Net present value per hectare of United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) capital over different amounts of USDA NRCS financial assistance

Notes: TWR is tailwater recovery system, NPV is net present value, ha is hectares.

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CHAPTER VII

ECONOMIC COSTS OF USING TAILWATER RECOVERY SYSTEMS TO MITIGATE SOLIDS AND NUTRIENT LOSSES FROM AGRICULTURAL LANDSCAPES, AND RETAIN SURFACE WATER

7.1 Abstract

Best management practices (BMPs) are conservation efforts implemented to address environmental challenges associated with agricultural production. These practices necessitate economic analyses to facilitate informed decision-making by stakeholders regarding which BMP is the best fit for a production system. One such BMP, a tailwater recovery (TWR) system, has a dual purpose aimed at mitigating solids and nutrient losses from agricultural landscapes and creating an additional surface water source for irrigation. These systems have become widely implemented within the Lower Mississippi Alluvial Valley, however their economic costs to mitigate solids and nutrient losses and retain surface water for irrigation are undocumented. Therefore, this study analyzes the costs of using five TWR systems to reduce solids, nutrients (i.e., P, and N), and retain water. Costs to reduce solids and nutrients were calculated using annual payments and revenue losses due to lost tillable area from implementation of TWR systems. Similarly, cost to save and irrigate a mega-liter of water was determined as the annual payment for TWR systems, revenue losses and measured pumping cost. These costs were calculated for contributions from producers and financial assistors (i.e., United States Department of Agriculture Natural Resources Conservation Service). The range of mean total cost to reduce solids using TWR systems was \$0 to \$0.77 per kg; P was \$0.61 to \$3,315.72 per kg; and N was \$0.13 to \$396.44 per kg. The range of mean total cost to retain water using TWR systems was \$189.73 to \$628.23 per ML, compared to a range of mean cost of groundwater of \$13.99 to \$36.17 per ML. Compared to other BMPs designed to reduce solids and nutrients, TWR systems are one of the least expensive ways to reduce solid losses from the landscape but remain an expensive way to reduce nutrient losses. Using TWR systems to provide an additional source of irrigation water yields a wide range in costs from less expensive than water efficiency conservation practices to similar to the high costs of practices such as desalination. Therefore, TWR systems may be a more expensive BMP to retain nutrients and water on the agricultural landscape than other solutions.

Keywords: tailwater recovery system, best management practices, water reuse, irrigation, water quantity, economic analysis

7.2 Introduction

Documentation, awareness, and understanding of agricultural impacts on the environment have led to growing implementation of conservation practices to reduce degradation of water quality. In the United States (US), the 2014 Farm Bill rendered an increase of funding for working lands programs, while decreasing funding for land retirement programs (US Congress 2014). The expansion in funding toward working lands programs will result in amplified conservation practice implementation and therefore necessary adaptive management and selection. Auditing of conservation practices by providing the cost per unit of benefit will become more important as reliance of conservation on working lands increases.

One region where substantial federal and private funds have been directed toward conservation practice implementation is the Lower Mississippi Alluvial Valley, hereafter referred to as “the Delta”. This region encompasses the northwest region of Mississippi and 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 agricultural producers in the Delta: (1) intensive agricultural practices have resulted in increased surface transport of nutrient-laden sediments, contributing to eutrophication in receiving waters and to the increased size of the Gulf of Mexico hypoxic zone (Rabalais et al. 1996; Turner and Rabalais 2003); and (2) unsustainable water withdrawal from the Mississippi River Valley Alluvial Aquifer for irrigation during the crop growing season when precipitation is minimal (Clark et al. 2011).

A practice that addresses both issues is a surface water capture-and-irrigation reuse system known and as a tailwater recovery (TWR) system. Tailwater recovery system implementation has been concentrated around the cone of depression (Paul Rodrigue, USDA NRCS, personal communication, 2015) in the Lower Mississippi Alluvial Aquifer, located under Sunflower and Bolivar counties. Tailwater recovery systems are a combination of a tailwater recovery ditch that captures surface water runoff, an optional on-farm storage reservoir (OFS) to store additional captured water, and pumps to re-lift surface water to the OFS or back onto fields as irrigation water. Although preliminary data (Chapter 2) demonstrates TWR system capability to reduce solids and nutrient losses, as well as hold surface water reducing groundwater reliance, system implementation is a major financial commitment ($400,000-900,000) for both producers and the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), who provide 60-80% financial assistance. The USDA NRCS has provided financial assistance for over 180 TWR systems in the Delta (Paul Rodrigue, USDA NRCS, personal communication, 2015) under conservation practice code 436 (USDA NRCS 2016).

Analyzing cost per unit of benefit allows BMPs aimed at similar beneficial outcomes to be compared so decision makers may select the most economical option. This has been done for conservation practices aimed at solids reductions (Cestti et al. 2003), nutrient reductions (Heatwole et al. 1987; Doering et al. 1999; Roley et al. 2016), and water quantity conservation (Wahl 1989; Hannak et al. 2009; Grafton et al. 2011; Richter 2014). The majority of these studies used the annualized costs over the amount of benefit for the practices investigated. For analyses of TWR systems, the costs and benefits have been previously investigated (Bouldin et al. 2004; Young et al. 2004; Falconer et al. 2015; Chapter 6); however, the costs for specific solid and nutrient reductions and to retain water on the landscape have not been quantified.

The main objective of this study was to provide a cost per benefit analysis to guide decision makers for consideration of options for reducing sediment and nutrient losses from the agricultural landscape, as well as provide water for irrigation. This was accomplished by (1) obtaining a dollar value for costs incurred to reduce solids and nutrient loss using TWR systems; and (2) calculating the cost of surface water saved in TWR systems compared to the cost of groundwater.

7.3 Materials and Methods

7.3.1 Tailwater recovery systems

Five TWR systems located in the Delta were used for analyses. With cooperation of both the producers and the local USDA NRCS offices, capital costs (table 7.1) and sizes (table 7.2) of the individual systems were obtained. All TWR systems include management practices to direct water into the TWR system, including irrigation land leveling (USDA NRCS practice 342); water control structures (riser board pipes, USDA NRCS practice 410); and grade stabilization (field perimeter pads, USDA NRCS practice 587), although individual system characterization may vary (table 7.2). Total tillable hectares before and after implementation of TWR systems were measured from USDA National Agricultural Imagery Program ortho-imagery data (USDA 2015). Crop type and rotation for each field were obtained from field observations and supplemented with USDA National Agricultural Statistics Service (NASS) CropScape data (USDA NASS 2015a). Lost tillable hectares due to TWR system implementation ranged from 6.1 to 14.8 ha on farms growing crop rotations of continuous rice (*Oryza sativa*), rice-soybeans (*Glycine max*), and/or corn (*Zea mays*)-soybeans (table 7.2).

7.3.2 Revenue loss calculations

Average revenue losses for the first two years the TWR systems were in production were used to calculate costs. Production budgets were utilized from Mississippi State University (MSU) Delta Planning Budgets (MSU 2011). Budgets for 2012 (MSU 2011) and 2013 (MSU 2012) were used for their respective years and crop rotations. Production benefits and expenses were calculated based on tillable hectares before and after TWR system implementation. Revenue losses were calculated by the difference between income and expenses for pre- and post-TWR implementation. The benefit of fuel savings was reflected in the budgets by using the measured cost to irrigate crops with ground water or surface water (table 7.3). Other benefits for TWR systems beyond yield of commodities and fuel savings were not considered, as those benefits do not have monetary returns to the producers (Chapter 6).

7.3.3 Solids and nutrient loss mitigation monitoring

Nutrient concentrations and water flow data were collected from TWR inflow points, field runoff leading into TWR, and overflow leaving TWR systems from February 1, 2014 to January 31, 2016 (Chapter 2). To investigate TWR systems' impact on solids and nutrients leaving the agricultural landscape, influent was compared to effluent and the difference between the two was used. Solids and nutrient loss mitigation is documented in Chapter 2.

7.3.4 Cost per kilogram of nutrients and sediment captured

Water quality assessment enabled the quantification of water quality benefits for each system. This allowed calculation of a dollar value for solids and nutrients reductions (i.e. \$/kg reduced). The cost to reduce a kg of solids, nitrogen or phosphorus was calculated using producers' capital by:

$$Cost\ of\ reduction\left(\frac{\$}{kg}\right) = \frac{(annual\ payment + revenue\ losses)}{reduction} \tag{7.1}$$

where "annual payment" (equation 7.3), "revenue losses" are the average of year 1 and year 2 lost revenues, and "reduction" is the average annual loads of sediment or nutrient reduced (kg). The cost of reduction for USDA NRCS capital was calculated using:

$$NRCS\ cost\ of\ solids\ or\ nutrients\ removal\ \left(\frac{\$}{kg}\right) = \frac{\left(\frac{capital\ input}{lifespan}\right)}{reduction} \tag{7.2}$$

where “capital input” is the total dollars of financial assistance (actual financial assistance awarded); “lifespan” 15 or 30 year; and “reduction” is either solids, N, or P annually reduced (kg). Annual payment was calculated by the following equation (Gunter and Haney 1978):

$$Annual\ payment = PV\left[\frac{\left(i(1+i)^t\right)}{\left((1+i)^t-1\right)}\right] \tag{7.3}$$

where “PV” is the producer’s capital investment of the TWR system; “i” is 2.09% the average lending rate from 2012 for a 12-year term (USDA Commodity Credit Corporation 2012); and “t” is equal to the time periods which are interest bearing (i.e. 15 or 30 years). This includes the first two years lost revenues and the annual average of the solids and nutrient reductions during the two year monitoring period. Annual payments were used over two horizons, 15- and 30-year periods, beginning in 2012 and ending in either 2023 or 2041. The 15-year period of analyses is the USDA NRCS described lifetime of the TWR practice (Paul Rodrigue, USDA NRCS, personal communication, 2016), with a 30-year being twice the expected practice lifetime. The 30-year lifetime periods were used because the actual practice lifetime is unknown, given that installation of TWR systems in Mississippi are all recent (approximately < 7 years).

7.3.5 Irrigation energy use

To calculate energy used to irrigate with TWR water, it was assumed that producers would initially start with and utilize a full TWR system (from winter precipitation collection) and then be able to collect enough runoff thereafter to utilize an additional full capacity of their system over the course of the irrigation season. This was considered the best-case scenario (i.e., the largest amount of TWR water used in a year, independent of growing season precipitation). It was also assumed that 1) systems were designed and constructed to utilize the maximum surface water holding capacity; 2) producers irrigated corn and rice crops with surface water before using surface water for soybeans; and 3) producers used the recommended amount of water to grow crops based on each budget. Holding capacities of TWR systems ranged from 37 to 346.7 ML (table 7.2). Volume of water used for irrigation was monitored at each location using flow meters (McCrometer, Hemet, California) installed in the surface water and ground water irrigation pipelines. Energy use was monitored from 2013-2015 for both electrical and diesel service to both surface water and groundwater (table 7.3). Monitoring periods of pump operation for diesel service were used to obtain liters of diesel per ML of water pumped. Diesel stores were measured before and after operation while water flow meter readings were recorded. Electric service was monitored by recording usage during the irrigation season. These values were then used in production budgets to quantify energy and cost to irrigate crops. Ground water pumping across all five sites from January 2012 to May 2015 was from an average depth of 8.47 m (Dave Kelly, Yazoo Mississippi Delta Joint Water Management District, personal communication, 2015).

7.3.6 Cost of water

The cost of groundwater in the Delta was equated to the energy cost to pump the water out of the ground (table 7.3). The cost of surface water for producers was estimated using:

$$Cost\ of\ TWR\ water\ \left(\frac{\$}{ML}\right) = \frac{(revenue\ losses + annual\ payment + pumping\ costs)}{surface\ water} \quad (7.4)$$

where “revenue losses” are the average of year 1 and year 2 lost revenues; “annual payment” (equation 7.3); “pumping costs” are the cost to pump surface water (table 7.4) multiplied by the amount of water pumped; and “surface water” is either one, one and a half, or two times the capacity of the TWR system (ML). Equation 7.4 uses the annual payment (toward the original TWR system investment equation (equation 7.3)); average lost revenue to the first two years after the implementation of the TWR system; cost to pump surface water (table 4) multiplied by the amount of water pumped; and amount of water used from the TWR system. The amount of water used from a TWR system varies with the growing season’s precipitation. For this analysis, the amount of water used was calculated as one, one and a half, and two times the holding capacity of the TWR system. These amounts were used due to the producer starting the irrigation season after the rainy winter months with a full TWR system and the best-case scenario of enough precipitation and return irrigation flows (i.e. tailwater) during the irrigation season to utilize another capacity volume of the TWR. This also assumes the TWR system is designed to utilize all the water available. The cost of water for USDA NRCS’s capital investment was calculated based on:

$$NRCS\ cost\ of\ TWR\ water\ \left(\frac{\$}{ML}\right) = \frac{\left(\frac{capital\ input}{lifespan}\right)}{surface\ water} \tag{7.5}$$

where “capital input” is the total dollars of financial assistance (actual financial assistance awarded); “lifespans” 15 or 30 years; and “surface water” is either one, one and a half, or two times the capacity of the TWR system (ML).

7.4 Results and Discussion

7.4.1 Cost to reduce solids and nutrients using tailwater recovery systems

The total cost to reduce a kg of solids ranged from -$0.21 to $1.12; P ranged from -$447.42.61 to $3,712.40; and N ranged from -$91.53 to $443.87 (table 7.4). Producers' expenditures to reduce a kg of solids, P or N are greater than those of the USDS NRCS even though the USDA NRCS covered the majority of the capital input. This is due to the annual payment calculation (equation 7.6), containing a lending rate, whereas the USDA NRCS calculation did not. If the producer did not borrow money for the TWR system, and there was no way to make money with that existing capital, their cost to reduce solids, P and N would be less than the USDA NRCS costs.

Although the cost to reduce solids and nutrients using conservation practices is scarce in the literature, TWR system costs to reduce solids and nutrients are greater than other BMPs within the US (table 7.5). Tailwater recovery systems reduced sediment in large amounts leading to the most economical BMP to reduce sediment with the lower end of TWR systems mean cost being 91% cheaper than the next best BMP (table 7.5). However, TWR systems were the least cost-effective option for reducing P and N compared to other BMPs reviewed. In terms of BMP costs, the only published comparison of P reductions was row crop impoundments, which were 99% cheaper than the mean cost of TWR systems for a 30-year lifespan. The lowest cost to reduce N with TWR systems was less than animal waste management, but 45% more expensive than the next closest BMP. Therefore, although TWR systems reduce sediments and nutrients to downstream systems, they are one of the most expensive options for reducing nutrients.

7.4.2 Costs of water

The current cost of water in the Mississippi Delta is related only to the cost to pump the water from the underlying alluvial aquifer. This cost was measured and calculated according to methods in the section titled *7.3.5 Irrigation energy use*. Pumping groundwater ranged from \$13.99 to \$36.17 per ML with a mean of \$21.37/ML (table 7.6). Using the average of 3.03 ML/ha of water irrigated, average price is \$64.75/ha, which is less than the Mississippi average of \$84.36/ha electric energy use and \$90.09/ha diesel energy use (USDA NASS 2014).

The overall range of mean costs for producers to utilize TWR system water was greater than the cost of using ground water, with a mean of \$86.47 to \$200.55 per ML. Range of mean costs of water for USDA NRCS's capital was \$97.10 to \$388.42 ML. As with the cost to reduce solids, P or N, the producers' cost for water is greater than the USDA NRCS cost due to the producers' cost of capital. Calculated water costs in this study are greater than the Mississippi and US range of average cost of water for irrigation from off-farm suppliers of \$71.77 ML and \$40.50 ML (table 7.7). Assuming a producer irrigated 3.03 ML/ha, with the TWR system water cost ranging from \$86.47 to \$200.55 ML, this would result in a cost of \$262.00 to \$607.67 to irrigate a hectare of crops. This range is similar to the estimated worth of additional yields from irrigation calculated by comparing NPV/ha before irrigation- dryland scenario (productivity valuation), which was equal to a \$141 to \$628 increase in NPV/ha. This range was similar to the values of irrigation in Miller et al. (2012) who used annual net returns to estimate the value of irrigation in the Delta. Miller et al. (2012) valued irrigation in the Delta from \$220, \$653, and \$691 per ha for soybeans, cotton, and corn, respectively. This suggests that irrigation water saved in a TWR system is similar to the return from irrigating agronomic crops. However, Falconer et al. (2015) in Mississippi and Young et al. (2004) in Arkansas investigated hypothetical TWR system scenarios using NPV analysis and calculated an irrigation valuation of $1,776 to $3,975, and $5,012, respectively. This study's cost of TWR water is less than the benefit of increased yields provided by irrigation in Falconer et al. (2015) and Young et al. (2004) and therefore would increase their valuation from TWR system water use. The higher irrigation valuation in Falconer et al. (2015) and Young et al. (2004) were due to differences in assumptions of the amount of water irrigated from TWR systems and the difference in assumptions due to the location being in Arkansas, respectively.

As seen in other parts of the US, surface water storage is a costly source of new water supplies (table 7.8). The mean costs to retain water on the landscape using a TWR system ranges from $183.57 to $588.96 per ML (table 7.6). The lower end of this range is more expensive than other BMPs such as water transfers and improving agricultural water use efficiencies, however the high end of this range is similar in cost to improve urban water use efficiency and recycling municipal water (table 7.8). In this study, the lower costs of this range may have been higher, however, one producer switched irrigation methods from center pivot to furrow irrigation with the implementation of the TWR system and another switched from a soybean-rice rotation to growing continuous rice which resulted in increased yield and an increase in revenues instead of a loss. Thus these producers' TWR systems lowered the mean cost of water retention using TWR systems.

7.5 Summary and Conclusion

Tailwater recovery systems are one of the most economical BMPs to reduce sediment loss from the agricultural landscape, however, they are also one of the most expensive for reducing nutrients. In addition, TWR system surface water is a more expensive source of water than alternative water conservation methods and may not be worth the benefits to agronomic crops from irrigation.

Best management practices are being widely implemented throughout the US in order to improve water quality and conserve existing or create new sources of irrigation water. These practices necessitate evaluation of their cost for performance so stakeholders can make informed decisions on implementation and adaptive management. Aimed at mitigating the loss of sediment and nutrients to downstream waters and creating an additional source of irrigation water, TWR systems remain an expensive solution for both the producer and USDA NRCS. In the future, reduced ground water levels or ground water pumping regulations for irrigating crops or waterfowl food plots may increase the value of water in the Delta region. This would lead to an increase in the value of TWR systems, thereby increasing the justification for their costs. Comparing costs of BMPs will lead to implementation of the most economically efficient methods, expanding the impact of dollars spent on conservation, which may decrease in the future.

7.6 Acknowledgments

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Table 7.1 Tailwater recovery system implementation costs, producer capital costs and Unites States Department of Agriculture Natural Resources Conservation Service financial assistance

TWR system	Producers inputs	NRCS assistance	Total capital costs
1	$181,014.24	$434,350.30	$615,364.54
2	$192,318.00	$288,477.00	$480,795.00
3	$123,950.85	$641,025.90	$764,976.75
4	$99,961.17	$554,102.77	$654,063.94
5	$310,061.85	$509,293.41	$819,355.26

Table 7.2 Characteristics of tailwater recovery systems

TWR system	Layout	Volume (ML)	Crop rotation (irrigation method) pre-TWR installation	Crop rotation (irrigation method) post-TWR installation	Pre-conservation practices tillable land (ha)	Post-land leveling, pads and pipes tillable land (ha)	Post-TWR system including land leveling, pads and pipes tillable land (ha)	Total lost tillable land (ha)
1	TWRD	115.9	rice (contour)-soybeans (furrow)	rice (zero grade)-rice (zero grade)	63.7	57.6	57.6	6.1
2	TWRD, OFS	94.0	corn (furrow)-soybeans (furrow)-rice (terrace)	corn (furrow)-soybeans (furrow)-rice (side inlet)	196.6	188.2	181.8	14.8
3	TWRD	37.0	corn (center pivot)-soybeans (center pivot)	corn (furrow)-soybeans (furrow)	124.0	117.2	112.4	11.6
4	TWRD, OFS	177.2	corn (center pivot-soybeans (center pivot)	corn (furrow)-soybeans (furrow)	142.7	141.4	129.9	12.8
5	TWRD (2), OFS (2)	346.7	rice (side inlet)-soybeans (furrow)	rice (side inlet)-soybeans (furrow)	132.3	128.4	122.4	9.9

Notes: TWR is tailwater recovery system, ML is mega liters, ha is hectares, TWRD is the tailwater recovery ditch, OFS is on farm storage reservoir. Crops in crop rotation include: rice (*Oryza sativa*), soybeans (*Glycine max*) and corn (*Zea mays*).

Table 7.3 Energy use and costs of surface water and groundwater pumping for each tailwater recovery system

Site	Water Source*	KWH/ML^E, liters diesel/ML^D	Conversion to KWH/ML^A	Cost U.S. Dollars of Energy/ML^B
A	SW^{D†}	43.02	462.56	$26.14
	GW^{D†}	59.52	639.97	$36.17
B	SW^{D†}	23.96	257.64	$14.56
	Relift^{D†}	23.11	248.51	$14.04
	Mean GW^D (n=4)	32.91	353.86	$20.00
	GW^E	168.20	168.20	$18.50
	SW+Relift	47.08	506.15	$28.60
C	SW^D	92.52	994.75	$56.21
	Mean GW^E (n=2)	170.39	170.39	$18.74
D	Mean SW^E (n=2)	43.30	43.30	$4.76
	Relift^E	121.26	121.26	$13.34
	Mean GW^E (n=2)	170.02	170.02	$18.70
	Mean SW+Relift	164.56	164.56	$18.10
E	Mean GW^E (n=3)	127.16	127.16	$13.99
	Mean SW^E (n=2)	58.84	58.84	$6.47
	Mean Relift^E (n=3)	70.28	70.28	$7.73
	Mean SW+ Mean Relift	129.12	129.12	$14.20

Notes: table adapted from Omer (2016); "†" represents same pump doing two functions, GW = ground water, SW= surface water, KWH = kilowatt hour, "^{E}" electric energy source, "^{D}" diesel energy source, "^{A}" Column is calculated based on the conversion of 1 liter US diesel fuel to 10.75 KWH, "^{B}" average cost for Delta region $0.61/gallon diesel (MSU 2014) and $0.11/KWH electric (MSU 2014).

Table 7.4 Annual producer, United States Department of Agriculture Natural Resources Conservation Service (NRCS), and total cost of solids and nutrient reductions in tailwater recovery systems (US $/kg)

TWR system	Funding Source	15-year lifespan			30-year lifespan		
		Suspended solids	Nitrogen	Phosphorus	Suspended solids	Nitrogen	Phosphorus
1	Producer capital	-$0.02[a]	-$4.15[a]	-$21.59[a]	-$0.06[a]	-$12.03[a]	-$62.54[a]
	NRCS capital	$0.19	$38.00	$197.62	$0.09	$19.00	$98.81
	Total cost*	$0.17	$33.85	$176.03	$0.03	$6.98	$36.27
2	Producer capital	$0.76	$146.44	$669.80	$0.65	$123.83	$566.38
	NRCS capital	$0.36	$68.22	$312.02	$0.18	$34.11	$156.01
	Total cost*	$1.12	$214.65	$981.82	$0.82	$157.93	$722.39
3	Producer capital	$0.23	$146.99	$1,229.36	$0.18	$118.45	$990.65
	NRCS capital	$0.46	$296.88	$2,483.05	$0.23	$148.44	$1,241.52
	Total cost*	$0.69	$443.87	$3,712.40	$0.41	$266.89	$2,232.17
4	Producer capital	-$0.33[†]	-$147.04[†]	-$718.76[†]	-$0.36[†]	-$159.17[†]	-$778.08[†]
	NRCS capital	$0.31	$135.28	$661.32	$0.15	$67.64	$330.66
	Total cost*	-$0.03	-$11.75	-$57.45	-$0.21	-$91.53	-$447.42
5	Producer capital	$0.25	$36.62	$330.37	$0.19	$28.38	$256.04
	NRCS capital	$0.18	$27.22	$245.57	$0.09	$13.61	$122.78
	Total cost*	$0.43	$63.85	$575.94	$0.28	$42.00	$378.83
Mean (SD)	Producer capital	$0.18 ($0.37)	$35.77 ($110.18)	$297.83 ($665.82)	$0.12 ($0.33)	$19.89 ($103.92)	$194.49 ($603.23)
	NRCS capital	$0.30 ($0.16)	$113.12 ($109.51)	$779.91 ($923.60)	$0.15 ($0.08)	$56.56 ($54.75)	$389.96 ($461.80)
	Total cost*	$0.48 ($0.45)	$148.89 ($176.68)	$1,077.75 ($1,433.33)	$0.27 ($0.37)	$76.45 ($128.07)	$584.45 ($940.87)

Notes: SD is standard deviation, "*" is the total annual cost including Producer and NRCS contributions to reduce solids, N, and P; "[†]" negative value a result of producer switching from center pivot irrigation to furrow irrigation and a yield increase resulting in a long term increase in revenues not a loss; "[a]" negative value a result of producer switching from rice-soybean rotation to growing continuous rice resulting in a long term increase in revenues not a loss.

Table 7.5 Summary of the cost of using best management practices (BMP) to reduce sediment and nutrient loss from agricultural landscapes

BMP	Average Cost (US $/kg)			Source
	Sediment	P	N	
TWR systems	0.27- 0.48	584.45- 1,077.75	76.45- 148.89	current work
Conservation tillage	5.83	NR	5.83	Cestti et al. 2003
Cropland protection	5.83	NR	5.83	Cestti et al. 2003
Strip-cropping	9.32	NR	9.32	Cestti et al. 2003
Vegetative cover	13.98	NR	7.95-13.98	Cestti et al. 2003; Roley et al. 2016
Terrace	19.81	NR	19.81	Cestti et al. 2003
Diversion	17.48	NR	17.48	Cestti et al. 2003
Waterway	26.80	NR	24.47	Cestti et al. 2003
Two-stage ditches	NR	NR	4.61-11.63	Roley et al. 2016
Buffer	NR	NR	27.70	Doering et al. 1999
Fertilizer reduction	NR	NR	0.73-3.03	Doering et al. 1999
Fertilizer tax (500%)	NR	NR	15.47	Doering et al. 1999
Critical area planning	25.63	NR	26.80	Cestti et al. 2003
Wetlands	NR	NR	2.04-12.70	Doering et al. 1999; Roley et al. 2016
Sediment and water control	44.28	NR	33.79	Cestti et al. 2003
Row crop impoundment	NR	0.09-1.27	0.12-2.82	Heatwole et al. 1987
Stream protection	31.46	NR	25.63	Cestti et al. 2003
Grazing land protection	68.74	NR	41.94	Cestti et al. 2003
Animal waste management	NR	NR	90.88	Cestti et al. 2003

Notes: P is phosphorus and N is nitrogen; kg is kilograms; NR is not reported. Costs adjusted to 2015 dollars using prices paid by farmers' indices (USDA NASS 1987; USDA NASS 1999; USDA NASS 2003; USDA NASS 2015b).

Table 7.6 Annual cost of groundwater and tailwater recovery system surface water (United States $/ML)

TWR system	Irrigation source	15-year lifespan			30-year lifespan		
		1[#]	1.5[*]	2[+]	1[#]	1.5[*]	2[+]
1	Groundwater	$36.17	$36.17	$36.17	$36.17	$36.17	$36.17
	Producer TWR water	-$1.18[a]	$7.93	$12.48	$-52.93[a]	-$26.57[a]	-$13.39[a]
	NRCS TWR water	$249.74	$166.49	$124.87	$124.87	$83.25	$62.44
	Total TWR water	$248.56	$174.42	$137.35	$71.94	$56.68	$49.04
2	Groundwater	$19.25	$19.25	$19.25	$19.25	$19.25	$19.25
	Producer TWR water	$467.44	$321.16	$248.02	$399.67	$275.98	$214.13
	NRCS TWR water	$204.45	$136.30	$102.23	$102.23	$68.15	$51.11
	Total TWR water	$671.89	$457.46	$350.24	$501.90	$344.13	$265.25
3	Groundwater	$18.74	$18.74	$18.74	$18.74	$18.74	$18.74
	Producer TWR water	$627.91	$437.34	$342.06	$516.88	$363.32	$286.55
	NRCS TWR water	$1,154.86	$769.91	$577.43	$577.43	$384.95	$288.72
	Total TWR water	$1,782.77	$1,207.25	$919.49	$1,094.31	$748.28	$575.26
4	Groundwater	$18.70	$18.70	$18.70	$18.70	$18.70	$18.70
	Producer TWR water	-$237.40[†]	-$152.24[†]	-$109.65[†]	-$258.49[†]	-$166.29[†]	-$120.19[†]
	NRCS TWR water	$235.07	$156.71	$117.53	$117.53	$78.36	$58.77
	Total TWR water	-$2.33	$4.48	$7.88	-$140.95	-$87.94	-$61.43
5	Groundwater	$13.99	$13.99	$13.99	$13.99	$13.99	$13.99
	Producer TWR water	$145.97	$102.04	$80.08	$116.32	$82.28	$65.26
	NRCS TWR water	$97.96	$65.31	$48.98	$48.98	$32.65	$24.49
	Total TWR water	$243.92	$167.35	$129.06	$165.29	$114.93	$89.75
Mean (SD)	Groundwater	$21.37 ($7.64)	$21.37 ($7.64)	$21.37 ($7.64)	$21.37 ($7.64)	$21.37 ($7.64)	$21.37 ($7.64)
	Producer TWR water	$200.55 ($312.84)	$143.25 ($212.35)	$114.60 ($162.14)	$144.29 ($284.94)	$105.74 ($193.59)	$86.47 ($147.96)
	NRCS TWR water	$388.42 ($386.88)	$258.94 ($257.92)	$194.21 ($193.44)	$194.21 ($193.44)	$129.47 ($128.96)	$97.10 ($96.72)
	Total TWR water	$588.96 ($635.08)	$402.19 ($428.11)	$308.81 ($324.63)	$338.50 ($431.02)	$235.22 ($291.85)	$183.57 ($222.27)

Notes: SD is standard deviation, “#” one full capacity of TWR water is saved, “*” one and a half the full capacity of TWR water is saved, “+” two times the full capacity of TWR water is saved, “†” negative value a result of producer switching from center pivot irrigation to furrow irrigation and a yield increase resulting in a long term increase in revenues not a loss; “a” negative value a result of producer switching from rice-soybean rotation to growing continuous rice resulting in a long term increase in revenues not a loss.

Table 7.7 Average cost for irrigation water from off-farm suppliers in the United States

Location	Number of farms reporting cost for off-farm water	Mean Cost (US $/ML)
Alabama	171	$501.36
Alaska	30	$161.66
Arizona	1,832	$36.20
Arkansas	165	$33.85
California	23,440	$56.08
Colorado	6,006	$20.86
Connecticut	81	$191.15
Delaware	32	$246.00
Florida	222	$79.61
Georgia	120	$51.20
Hawaii	1,292	$186.28
Idaho	6,323	$21.71
Illinois	178	$142.50
Indiana	207	$132.31
Iowa	191	$96.87
Kansas	294	$58.01
Kentucky	513	$1,547.43
Louisiana	225	$86.75
Maine	163	NA
Maryland	55	$696.76
Massachusetts	254	$535.28
Michigan	275	$243.79
Minnesota	120	$12.09
Mississippi	128	$71.77
Missouri	217	$236.91
Montana	3,033	$13.51
Nebraska	1,726	$51.89
Nevada	693	$16.73
New Hampshire	88	$251.13
New Jersey	137	$278.39
New Mexico	2,758	$51.00
New York	309	$500.27
North Carolina	309	$78.35
North Dakota	89	$47.79
Ohio	342	$745.40
Oklahoma	176	$10.77
Oregon	3,747	$24.82
Pennsylvania	519	$785.76
Rhode Island	75	$1,007.58
South Carolina	97	$65.41
South Dakota	330	$20.66
Tennessee	271	$258.78
Texas	2,503	$38.19
Utah	6,034	$16.41
Vermont	114	$98.40
Virginia	170	$36.90
Washington	4,666	$39.37
West Virginia	94	$151.91
Wisconsin	180	$41.94
Wyoming	2,420	$10.01
United States	73,414	$40.53

Notes: table adjusted from USDA NASS (2014); ML is mega liters.

Table 7.8 Summary of the cost (United States $/ML) of water conservation or source creation based on method used to conserve or create source

Method	Low	High	Source
TWR systems	$183.57	$588.96	Current work
Conjunctive use and ground water storage	$20.20	$1,211.94	Hannak et al. 2009
Water transfer	$24.63	$5,444.04	Hannak et al. 2009; Grafton et al. 2011; Richter 2014
Agricultural water use efficiency	$236.70	$1,203.21	Hannak et al. 2009; Richter 2014
Urban water use efficiency	$464.58	$1,439.91	Hannak et al. 2009; Richter 2014
Recycled municipal water	$605.97	$2,879.82	Hannak et al. 2009; Richter 2014
Surface storage (reservoirs)	$686.77	$2,161.30	Hannak et al. 2009; Richter 2014
Desalination (brackish)	$966.51	$1,817.92	Wahl 1989; Hannak et al. 2009; Richter 2014
Desalination (seawater)	$1,817.92	$5,049.77	Hannak et al. 2009; Richter 2014

Notes: ML is mega liter; costs adjusted to 2015 dollars using prices paid by farmers' indices (USDA NASS 1989; USDA NASS 2009; USDA NASS 2011; USDA NASS 2015b).

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CHAPTER VIII

SYNTHESIS

8.1 Conclusion

This dissertation is a collection of research aimed at providing stakeholders with information on the collection of surface water for storage and subsequent irrigation. In the US, tailwater recovery (TWR) systems were hypothesized to reduce solid and nutrient losses from agricultural landscapes, however, their performance to do this had not been investigated. The purpose of Chapter 2 was to investigate TWR system performance to reduce solid and nutrient losses to downstream systems. In addition, they were hypothesized through irrigation of the surface water runoff to add nutrients back onto the landscape possibly reducing fertilizer applications. Chapter 2 investigated grab sampling methods so that Chapter 3 could use grab samples to describe the potential for TWR systems to irrigate nutrients back onto crops. The main purpose of TWR systems is to save surface water for irrigation, however their capability and efficiency to do this had not been investigated until Chapter 4 used water budgets to describe their savings and losses, as well as their efficiencies. One of the most important parts of a conservation practice investigation is an economic analysis for adaptive implementation to justify private and federal investments. Using the findings from Chapters 2 and 4, Chapter 5 assessed TWR systems using economic analyses and Chapter 6 quantified the cost per unit of benefit so stakeholders can compare TWR systems to other practices. Through the aforementioned aims this research came to the following conclusions for each chapter.

The first research chapter (Chapter 2) in this dissertation aimed to assess TWR system performance, investigate how that performance changed between seasons, and evaluate the influence of variables of TWR design on performance. This chapter provides evidence that TWR systems did not reduce concentrations of the majority of solids and nutrients. However, loads (i.e., concentration * volume) of solids and nutrients were reduced through retention of surface water. Tailwater recovery (TWR) system performance was similar across all seasons. Nevertheless, seasonal and variable influences on performance were equivocal and warrant further consideration in any future studies. Variables in this study that influenced TWR system performance were: how full the system was prior to an event, time since the previous event, amount of overflow in the event, and the size of the TWR system. Based on current design of TWR systems, how full the systems are prior to an event and the time since the previous event are variables which are precipitation driven and cannot be managed. The amount of overflow in an event and the size of the TWR system can be addressed by using existing riser board pipes to store additional water.

The second research chapter's (Chapter 3) objective was to determine if solid and nutrient concentrations in grab samples collected from surface water in TWR systems are representative of solid and nutrient concentrations in water used for irrigation from TWR systems. Systematic grab sampling methods from six TWR systems were representative of solid and nutrient concentrations being applied through surface water irrigation. This research provides evidence toward sampling accuracy and methodology for determining sound measurements of irrigation water quality in surface water irrigation systems. Stratification or other factors within TWR systems did not lead to a difference between TWR system grab samples and irrigated water. Stratification may occur in TWR systems; however, the mixing caused by irrigation pumps results in similar solid and nutrient concentrations as surface water grab samples.

The fourth chapter of this dissertation was to determine the potential to recycle solids, P, and N captured by TWR systems onto production fields through irrigation applications. Grab samples were used to assess the potential for irrigating solids and nutrients back on to fields. Tailwater recovery systems capture surface water and allow for producers to use water for irrigation, thereby irrigating nutrients back onto the agricultural landscape. Temporal differences by season indicate it is more advantageous to irrigate surface water associated with the greatest number of nutrients to the landscape in spring; however, summer is when the all of water is irrigated. Nutrient loads available to be irrigated back onto the landscape are most likely too low to justify lowering synthetic fertilizer applications.

While Chapter 4 provided evidence toward a single benefit of TWR systems, Chapter 5 further described and used a water budget to investigate the surface water savings and use. Tailwater recovery systems retain water on the landscape, thereby decreasing reliance of agricultural irrigation on groundwater and allowing recharge to the underlying alluvial aquifer. However, the amount of surface water irrigation and infiltrated water projected for all TWR systems in the Delta is 15% of the annual alluvial aquifer's deficit. Although 2% of Delta farms reduced 15% of the deficit, contributions to the deficit include not only agriculture, but also industry, municipalities and recreational waterfowl hunting. This suggests additional TWR systems and/or conservation measures are needed.

Chapter 6 compared net present value (NPV) and benefit cost ratios (BCR) of operation scenarios with and without TWR systems, as well as, with and without sediment reduction benefits. In addition, this chapter investigated the impact of the level of financial assistance on NPV. Economic analyses of NPV and BCR showed conservation systems including irrigation land leveling (USDA NRCS practice 342), water control structures (i.e. riser board pipes, USDA NRCS practice 410), and grade stabilization (i.e. field perimeter pads, USDA NRCS practice 587) remain economically feasible. However, when those practices are combined with TWR ditch and on-farm storage (OFS) reservoir to make a TWR system, the producer faces a decrease in NPV and BCR. Tailwater recovery systems still maintain a positive NPV for producers who own the land on which the system is installed, whereas producers installing TWR systems on rented land maintain a negative NPV even with 100% United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) assistance.

The last research chapter (Chapter 7) aimed to obtain the cost in dollars to reduce solid and nutrient losses to downstream systems with TWR systems and the cost in dollars to save a quantity of water using TWR systems. When looking at the cost per unit of benefit, TWR systems are one of the most economical ways to reduce sediment loss from the agricultural landscape. However, TWR systems are one of the most expensive best management practices (BMP) for reducing nutrients. In addition, TWR system surface water is a more expensive source of water than alternative water conservation methods and may not be worth the benefits to agronomic crops from irrigation. Aimed at mitigating the loss of sediment and nutrients to downstream waters and creating an additional source of irrigation water, TWR systems remain an expensive solution for both the producer and USDA NRCS.

8.2 Management implications

Without a value or regulation placed on water in Mississippi's Alluvial Valley (Delta), it is difficult to value a conservation practice aimed at water conservation. Future considerations of widespread BMP implementation should utilize economic analyses of benefits and costs to adaptively finance the best possible solution so all parties get the most out of their capital input. Reduced ground water levels or ground water pumping regulations for irrigating crops or waterfowl food plots may increase the value of surface water in the Delta region. This would lead to an increase in the value of TWR systems, thereby increasing the justification for their costs. Research into BMPs prior to widespread implementation is necessary to utilize the most effective and economical BMPs on the landscape. Comparing costs of BMPs will lead to the most economically efficient BMPs being implemented and expanding the impact of dollars spent on conservation, which may dwindle in the future.

Management of TWR systems should begin with implementation. Observations show failure to establish vegetation around the edges of the ditches and OFS reservoirs lead to TWR system erosion and suspension of solids. In addition, producers should adaptively learn from their individual system to determine what works best. Installing riser boards in pipes may allow the greatest sediment and nutrient reduction, keeping both on the field. Utilizing riser boards, the entire landscape may be used to save the greatest amount of water with the least amount of pumping. This may be achieved by storing water in the OFS reservoir only in the late winter or early spring. By doing this, producers allow OFS reservoirs to fill with direct rainfall and still maintain enough water on the fields to fill them prior to spring. A trade off exists with the previous schematic if the riser board pipes do not prevent enough water from flowing off of the landscape. Without keeping an OFS reservoir as full as possible throughout the fall, winter and spring, less solids and nutrients are being pumped into the OFS reservoir and therefore prevented from overflowing from the TWR system. Additional research is warranted to optimize the size of the components of these systems to the landscapes.

8.3 Future applied research on tailwater recovery systems

Tailwater recovery systems are effective in their purpose to reduce solid and nutrient losses from the agricultural landscape and retain water for subsequent irrigation. However, stakeholders need to decide if the large investment is worth the benefit. Economic analyses show these systems are one of the most expensive methods for their means and may necessitate additional research. Future research on TWR systems is warranted to provide a holistic outlook. Future research outlined below includes:

- additional water budget analyses using sensitivity analyses with climate change scenarios
- using water budget results to optimize the size of the TWR ditch and OFS reservoir, re-lift pump size, irrigation area, and catchment area.
- Postel (1999) suggested that recycling and reuse always have downstream consequences whether positive or negative creating the need for careful evaluation. Additional research into the downstream consequences of multiple TWR systems implemented in a watershed should be evaluated.

8.4 Final sentiments

It seems as though human kind is always looking to build things, when in some circumstances we should look to use what we already have in a more intelligent manner. I believe it goes back to humans' need to conquer his/her surroundings. We do this with agricultural conservation practices, by looking to engineer edge-of-field practices when we should be looking at why we are losing nutrients within the field or why one producer is growing rice with a total of 91 cm of water but his neighbor is yielding the same with 31 cm. Alfred Deakin in 1890 said "It is not the quantity of water applied to a crop, it is the quantity of intelligence applied which determines the result-there is more due to intelligence than water in every case." Improvements in irrigation should come prior to creating new sources. This leads to some broad suggestions for future BMP implementation in the Delta region, which improves upon three areas: 1) changing the way we prevent nutrient loss, 2) using economics to decide how to save water, and 3) improving USDA NRCS funding protocols for conservation.

An example of this "over engineering" is how the Delta region is looking to reduce nutrients leaving agricultural fields. We should start within the field and when we have exhausted all our options within the field through nutrient application and soil management, then move to edge-of-field BMPs. Once we move to edge-of-field practices using natural areas already in place such as local natural bottomland forest and reconnecting them to their flood regime may be the most effective nutrient sink and most economical option. Edge-of-field BMPs necessitate a large federal subsidy unless they have direct benefits to producers. The major reasoning for producers to begin to use surface water was not to prevent nutrient losses but to provide a long-term supply of water for their farm's future.

For sustainable irrigation in the Delta region it should start at the tap from which groundwater flows. Numerous sources have shown all over the world that water conservation is cheaper at the tap than recycling water and creating new sources (Richter 2014). Yet, in the US we continually gravitate toward large engineering projects so that we may continue to ignore at the tap conservation.

Currently, USDA NRCS funding operates on a "bid" basis where producers willing to add the most practices and money to the project are considered priority. Although this may seem advantageous for the USDA NRCS to obtain the largest number of private funds to match public funds, this creates an inefficient system of putting practices on any landscape, not fitting the practice to the landscape. A recent observation provides an example of this: currently, producers are implementing TWR systems where small ditches may exist and no reservoirs exist, therefore creating the need to move a large quantity of soil. When other producers who do not qualify or will not obtain USDA NRCS funding because their projects involve less funding but create the same practice by using existing landscape features such as a small oxbow or larger ditches. United States Department of Agriculture Natural Resources Conservation Service would obtain more implemented practices for less federal subsidy if it took advantage of the landscapes instead of the amount of private funding. It should be noted that using existing infrastructure may cause harm to local biota, which may require research to provide guidelines for water use (e.g. critical depth needed to maintain fish populations).

In addition to BMP funding adjustments, federally subsidized BMPs should only be widely implemented with research to justify the expenditure. With this sentiment, the scientific and private industry communities need to work together to develop equipment and methods for rapid assessment procedures. Research necessitates funding and a percent of the total federal expenditure on conservation should be appropriated for research and economic analyses.

The above three sentiments are overall ideas which would help to maximize conservation effectiveness and monetary investments, however any conservation effort which ignores the farmers and people within the agricultural industry will inevitably be ineffective. We as a society need to begin to do things in our everyday lives with thought and purpose, not out of habit or convenience (Montgomery 2012). Water conservation movements all over the world are showing that real solutions lie in people's energy, labor, time, care and solidarity (Shiva 2002). Farmers need to be the center of any conservation movement making agricultural stewardship a top priority. Using the word "stewardship" has been suggested to further embrace the idea that resources are neither inherited nor owned, but borrowed by the present generation from future ones (Feldman 2012). We should view ourselves as part of all creation and not apart from it (Feldman 2012). This is expressed in a water ethic calling for protection of water ecosystems which should be a central goal in our daily lives (Postel 1997) and even more so for land managers including farmers who may be able to make the largest impact. Aldo Leopold stated this notion in care for resources, including freshwater (Leopold 1949). Prior to Leopold, E.H. Carrier in 1928 forewarned humankind that although Earth holds a great reservoir of fertility, we should not forget the importance of husbandry (Carrier 1928).

He stated that we should ask ourselves if are we trading current bounty and profits from present day fertility and water resources for future crises of reduced yields and unquenchable drought (Carrier 1928). Well, are we?

8.5 References

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