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Aquifer Depletion in the Lower Mississippi River Basin: Challenges and Solutions

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Abstract: The Lower Mississippi River Basin (LMRB) is an internationally-important region of intensive agricultural crop production that relies heavily on the underlying Mississippi River Valley Alluvial Aquifer (MRVAA) for irrigation. Extensive irrigation coupled with the region's geology have led to significant aquifer decline. The response to the decline has been multi-faceted. Research related to three responses are highlighted: innovation in rice irrigation, on-farm reservoirs, and managed aquifer recharge. Irrigated rice grown in Arkansas, which is nearly 50% of annual U.S. rice production, accounts for a significant portion of aquifer withdrawal. As a result, strategies for using less water while maintaining rice yields are being developed. The Rice Stewardship Partnership (RSP) began in 2015 and aims to improve irrigation management in rice lands of the LMRB. Early results from the RSP are presented. Secondly, on-farm reservoir-tailwater recovery systems (R-TWRS) are increasingly used to store abundant surface water in the LMRB. Over 700 R-TWRS are currently used in rice producing areas of Arkansas. The confining clay layer that overlies the MRVAA in many locations limits rates of aquifer recharge. Locations where the confining layer is thin or non-existent may provide opportunities for artificial (i.e., managed) recharge. A 10-m deep excavation pit from a highway project provided an opportunity to measure infiltration rates of the uppermost section of the alluvial aquifer. Findings from this and other studies are used to demonstrate how conservation, off-season rainfall capture and storage, and managed recharge are being investigated as means to reduce the on-going decline of the alluvial aquifer that is both economically and ecologically important to the LMRB.

Keywords: *Lower Mississippi River Basin, aquifer decline, irrigation, on-farm reservoir, surface water, groundwater*

Agricultural crop production in the LMRB relies heavily on irrigation (Figure 1). Though rainfall is abundant, its timing and quantity often do not coincide with crop needs. Thus, producers have increasingly turned to irrigation to optimize yields and mitigate risks associated with drought (Vories and Evett 2010). Between 2007 and 2012 alone, the amount of irrigated cropland in Arkansas, Louisiana, and Mississippi increased by 7.7, 14.5, and 20.7%, respectively (NASS 2013). As a result, Arkansas now ranks third behind Nebraska and California in terms of irrigated cropland (Figure 1) (NASS 2013). The MRVAA is the primary irrigation water source in the Mississippi-Delta region of Eastern Arkansas due to its accessibility. In Arkansas, groundwater use rates for irrigation have increased more than tenfold from 1950 to 2010 (Kresse et al. 2014). Arkansas leads the nation in rice production, and that crop accounts for approximately one-half of groundwater used in the state (NASS 2013; Kresse et al. 2014).

Agriculture is challenged to increase productivity while using fewer inputs and reducing its environmental footprint. In 2016, approximately 2 million ha soybean, 800,000 ha

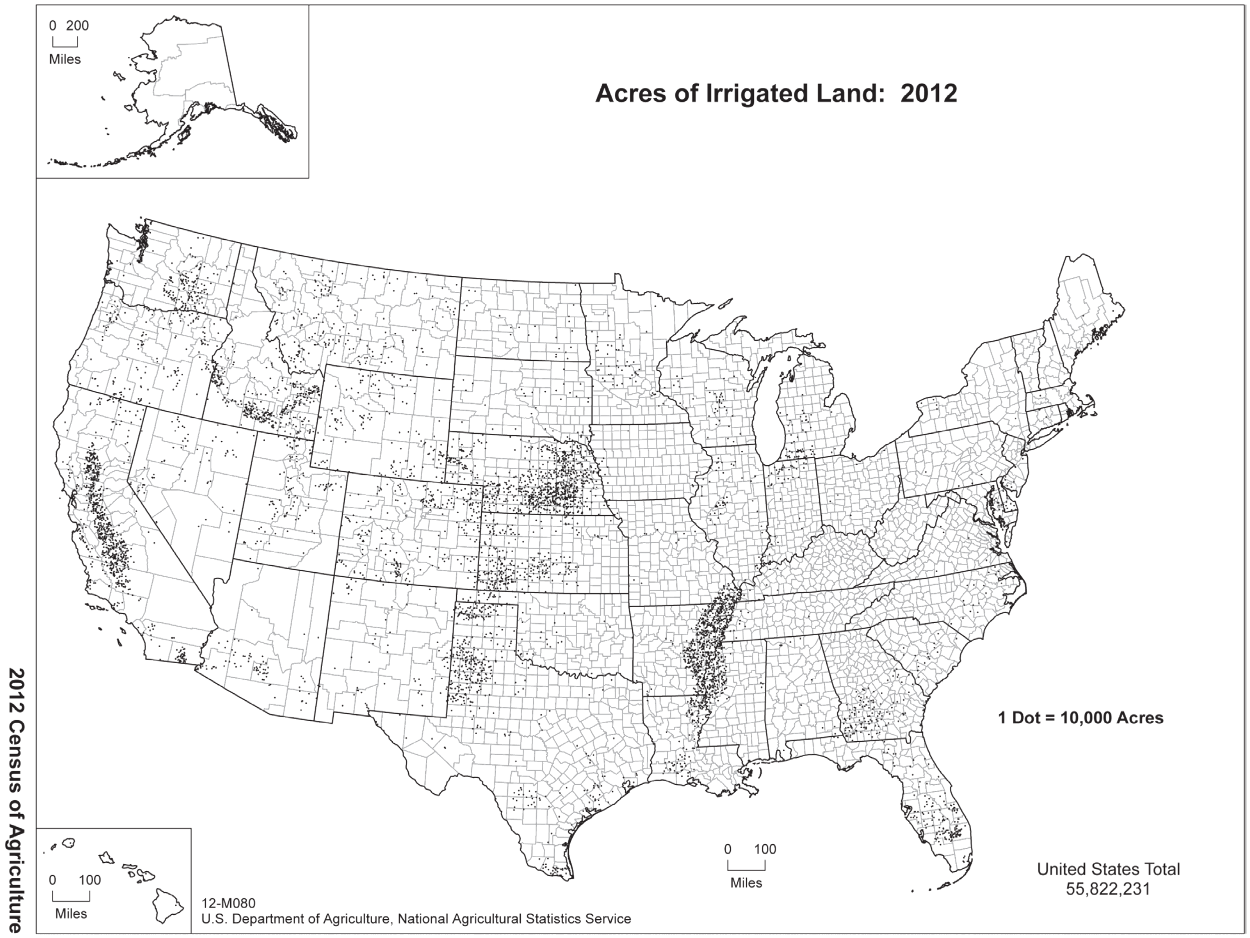


Figure 1. Irrigated land in the United States in 2012 (NASS 2013).

corn, 800,000 ha rice, and 400,000 ha cotton were planted in the LMRB (NASS 2016). Reported evapotranspiration (ET) values for soybean, corn, and cotton grown in the MS Delta are 546, 588, and 552 mm, respectively (Tang et al. 2016), while that of rice was found to vary between 500 to 650 mm (Reavis 2017). In practice, rice receives nearly three times the irrigation that is applied to corn and soybean (Massey et al. 2017). In addition to aquifer decline, excessive irrigation has the potential to contaminate water via surface runoff and/or deep-percolation losses. Hence, improvements in irrigation efficiency are generally expected to not only improve crop water productivity and reduce over-pumping of the MRVAA, but also potentially reduce non-point source pollution.

Groundwater levels in the MRVAA

Groundwater recharge throughout Arkansas primarily comes from precipitation, which slowly infiltrates into the groundwater system. Recharge estimations range from ~ 50 mm yr^{-1} (2 in yr^{-1}) to as little as 10 mm yr^{-1} (0.4 in yr^{-1}) (Broom and Lyford 1981). The 1981-2010 climate normals for Eastern Arkansas are approximately 1200 mm annual precipitation and 16.2°C average temperature (NOAA 2017). Aquifer thickness averages 30 m and tends to decrease moving southward (Ackerman 1996; Pugh et al. 1997). Thicker aquifer sections (up to 48 m) occur in Poinsett County (Pugh et al. 1997). The confining unit of the MRVAA exhibits tremendous spatial variability and varies in thickness (up to 45 m) and occurrence (thick, thin, or absent) across Eastern Arkansas (Gonthier and Mahon 1993).

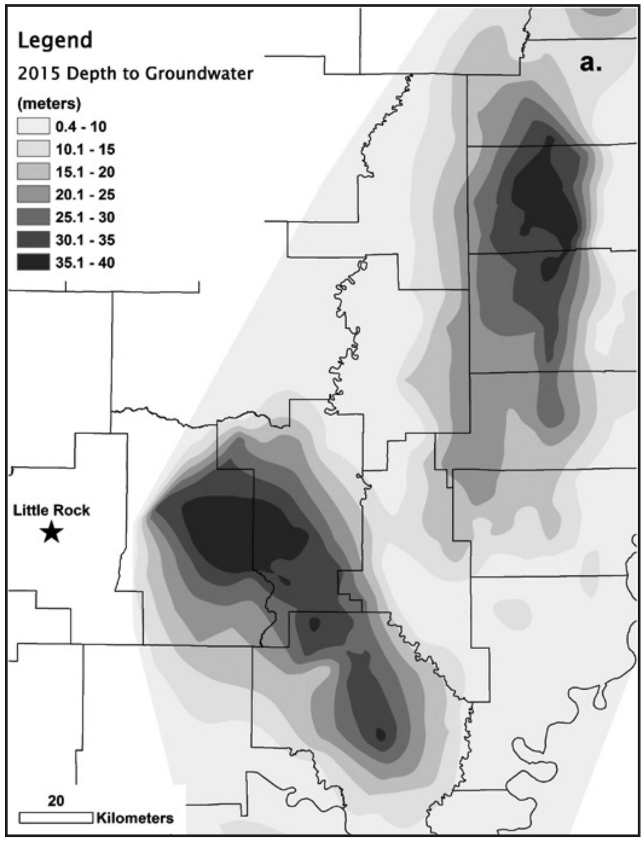
As of 2015, there were two primary cones of depression in the MRVAA in Arkansas, one east of Little Rock in the Grand Prairie and the other west of Crowley's Ridge (Figure 2a). The depth to groundwater was generated from data collected from 436 spring-measured United States Geological Society (USGS) monitoring wells and interpolated using the natural neighbor method (ANRC 2016). Groundwater level declines have been observed as early as 1929 in portions of the Grand Prairie. The cone of depression west of Crowley's Ridge formed in the 1980s. The sustainable yield of the MRVAA in 2012 was 147 $m^3 s^{-1}$ (3374 Mgal d^{-1}) while withdrawals during that same year were approximately twice that rate (ANRC 2016). Based on model projections, groundwater withdrawals are expected to increase to more than 394 $m^3 s^{-1}$ (9,000 Mgal d^{-1}) by 2050 (Clark and Hart 2009; Clark et at. 2011; Clark et al. 2013; ANRC 2014). Water level declines below one-half of the saturated thickness are forecasted across the MRVAA under current rates of pumping, indicating large areas of depleted aquifer in parts of the Grand Prairie and Cache River Critical Groundwater Areas (CGA) (Clark et al. 2013) (Figure 2b).

Agriculture in the state of Arkansas accounts for one in six jobs and contributed $20.1 billion to the economy in 2012, which is double the national average contribution to state gross domestic product (GDP) (English et al. 2014). Continued aquifer decline has the potential to cause severe negative economic impacts in the future due to the importance of agriculture in the region. Also, streamflow depletion may occur as the aquifer is increasingly disconnected from overlying rivers and streams (Barlow and Leake 2012), causing ecological and economic impacts. These aquifer declines have in some cases led to increased usage of the Sparta, the confined aquifer underlying the MRVAA, for irrigation (ANRC 2016). While this aquifer is mainly used for drinking water in the MRVAA region, further south, a cone of depression that had formed in the more unconfined section of the Sparta resulted in the declaration of the first CGA in Arkansas, the South Arkansas CGA (ANRC 2016).

Addressing Groundwater Declines in the MRVAA

The Arkansas Water Plan consistently calls for additional use of surface water in order to offset groundwater pumping in the state (ANRC 2013). In the Grand Prairie CGA, the U.S. Army Corps of Engineers is constructing two surface water diversion projects: the Bayou Meto Project and the Grand Prairie Area Demonstration Project (GPADP). These projects are intended to support continued irrigation of agricultural crops, while minimizing further aquifer depletion (USACOE 1999). The projects have been under construction since the 1990s and will capture excess surface water from the Arkansas and White Rivers, respectively, to supply and supplement a network of on-farm R-TWRS. Modeling results from the USGS Mississippi Embayment Regional Aquifer Study (MERAS) indicate that when in operation, the Bayou Meto and GPADP will meet approximately 73% and 100%, respectively, of the current groundwater demand of its service area (Clark et al. 2011). Both projects have experienced construction delays owing to environmental-impact concerns and funding hindrances. However, near the Grand Prairie CGA and along the Arkansas River, two irrigation projects have been completed. The first, Plum Bayou, located southeast of Little Rock, was completed in 1993 and serves about 5,750 ha of cropland. The second, Point Remove, located northwest of Little Rock, was completed in 2006 and serves 5,665 ha of cropland as well as 2,430 ha of wildlife refuge. Though smaller than the projects in the Grand Prairie CGA, these provide examples of the potential for successful surface water irrigation systems in the region.

In contrast to the Grand Prairie, no large-scale projects are currently planned for the Cache River CGA owing to a relative lack of surface water resources (ANRC 2016). In the Cache River CGA, producers have increased construction of on-farm R-TWRS. R-TWRS are made up of a complex network of ditches, water control structures, reservoirs, re-lift pumps, and pipelines designed to control and condition water movement. Reservoirs allow winter-spring precipitation to be stored for eventual irrigation use. Research using the Arkansas-specific MARORA economic model



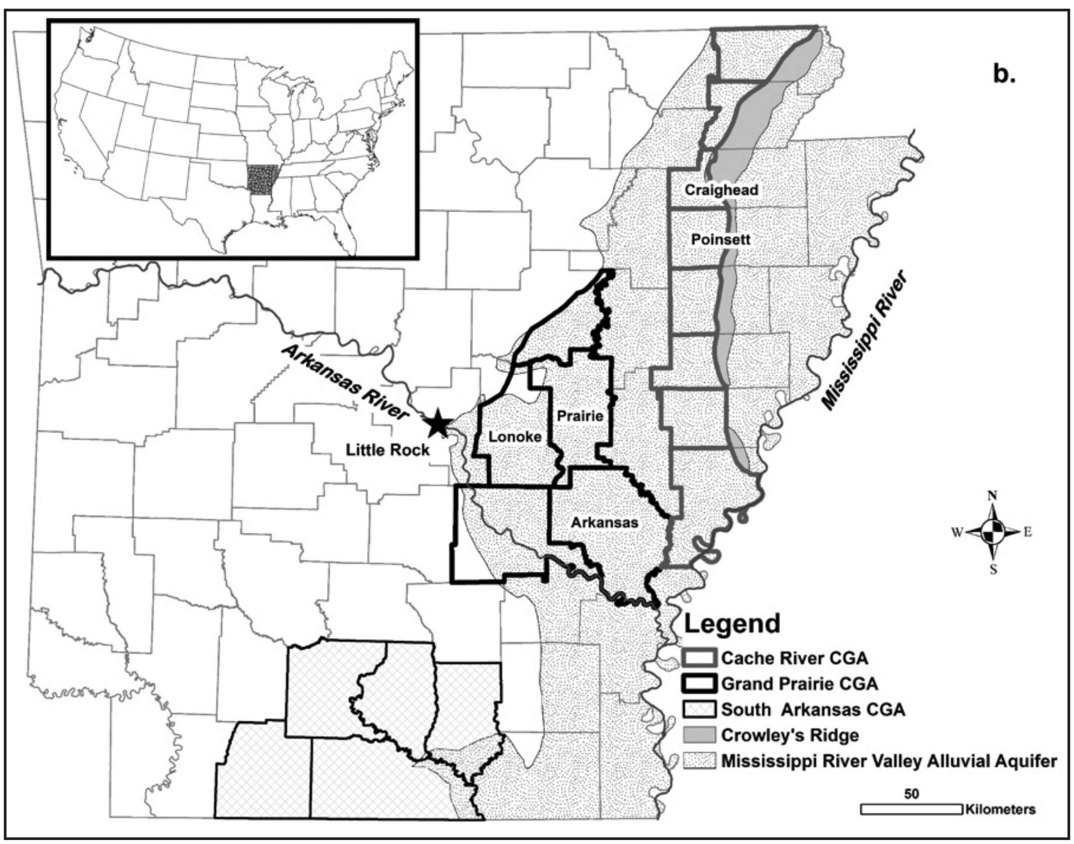


Figure 2. Inset) Location map of U.S. with Arkansas highlighted. a) Depth to groundwater in Eastern Arkansas in 2015 (ANRC 2016). b) Critical groundwater areas (CGA) in Arkansas.

has suggested that as groundwater availability becomes more limited, use of R-TWRS could improve economic returns, especially when combined with water conservation measures that increase irrigation efficiency (Young et al. 2004). In some areas where these systems have been used for over ten years, smaller declines in the MRVAA have been reported compared to those without surface water systems (Fugitt et al. 2011). Little is known about how these systems interact hydrologically with their surrounding landscape, impact water quality, and whether they might play a role in aquifer recharge.

Improving Irrigation Efficiency to Address Groundwater Decline

Evans and Sadler (2008) contend that the "largest potential for basin-wide water savings will likely come from carefully scheduled, reduced irrigation levels." Thus, in addition to efforts to develop new supplies of irrigation water, programs have also been designed to foster conservation practices through in-kind financial support to producers. In 2015, the United State Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) spent $45.86 million on the Environmental Quality Incentives Program (EQIP) (NRCS 2011). The EQIP priorities in Arkansas are to reduce erosion and pollution from animal wastes, improve irrigation efficiency, and reduce dependence on groundwater. Examples of these practices and the associated NRCS conservation practice numbers include irrigation water management (449), cover crops (340), nutrient management (590), irrigation reservoir (436), tailwater recovery (447), drainage water management (554), and grassed waterways (412). Employing computerized hole selection software has improved application efficiency of furrow irrigation through the use of PHAUCET (Pipe Hole And Universal Crown Elevation Tool) which has been updated and made available free of charge to producers and consultants as Pipe Planner software (http://www.pipeplanner.com/). Other related water-saving technologies include remote pump control, surge valves, and various soil moisture sensors that help farmers with their irrigation timing and management decisions.

Rice in the LMRB is grown using a dry-seeded, delayed-flood culture (Wilson et al. 2016) on low permeability soils that reduce deep percolation losses (Snipes et al. 2005). Sizable portions of the LMRB rice growing area have been precision-graded to improve irrigation uniformity (Snyder and Slaton 2001; Walker et al. 2003). Grading to a uniform slope allows use of uniformly-spaced (i.e., straight) levees that divide the field into separate paddies (Snipes et al. 2005). The most common rice flood distribution method is cascade flooding where water is applied to the uppermost paddy and allowed to gravity-flow from one paddy to the next via metal or tarp-style gates installed in the levees. In contrast, multiple-inlet rice irrigation (MIRI) (Tacker et al. 2001; Vories et al. 2005) uses poly-tubing to distribute water to each paddy simultaneously. When properly managed, MIRI reduces irrigation applications by about 25% relative to cascade flooding (Vories et al. 2005; Massey et al. 2017). Additional opportunities exist to improve rice irrigation efficiency and reduce runoff by combining MIRI with intermittent flooding methods (Massey et al. 2014) that were first developed in Asia (Bouman and Tuong 2001; Dong et al. 2001). Intermittent rice flooding, also known as alternate wetting and drying (AWD) has been shown to reduce field runoff by nearly 50% (Martini et al. 2013).

Agricultural production, particularly rice cultivation, is responsible for a significant portion of global anthropogenic greenhouse gas (GHG) emissions (Ciais et al. 2013). Additionally, rice cultivation has a higher global warming potential (GWP) than other cereal crops (Linquist et al. 2012), largely due to methane (CH_4) emissions associated with continuous flooding. Changing water management strategies may help address both GHG and water issues. Currently, the most prominent strategy to accomplish this is AWD. AWD was developed at the International Rice Research Institute (IRRI) as a water-saving technology to help Asian farmers cope with water scarcity (Bouman et al. 2007). This practice has been adapted across Asia to reduce water usage and CH_4 emissions. In the U.S., research has been conducted under a range of conditions and scales (Linquist et al. 2014; Massey et al. 2014). AWD has been found to reduce GHG emissions through reductions in CH_4 (Linquist et al. 2012).

Case Studies

Three case studies are described that highlight efforts to reduce aquifer depletion through improved irrigation management, expanded surface water use, and managed aquifer recharge.

Rice Irrigation

The Regional Conservation Partnership Program (RCPP) began with the 2014 U.S. Farm Bill legislation. The Rice Stewardship Partnership (RSP) RCPP is a collaboration among USDA-NRCS, Ducks Unlimited (DU), and the U.S. Rice Federation (USRF) that began in January 2015. DU provides the project management while the USRF provides coordination with all activities conducted through the EQIP and the Conservation Stewardship Program (CSP). The funds provided through the RCPP were divided between the rice producing states of Arkansas, California, Louisiana, Texas, Mississippi, and Missouri in proportion to the total amount of rice each state contributes to national total production. Each state set priorities focused on water conservation, nutrient management, and wildlife habitat enhancement.

The RSP in Arkansas focused on water management, nutrient management, and waterfowl habitat. It was designed to address the issues of day-to-day water management issues rather than water management infrastructure (e.g., land leveling, on-farm reservoir construction, drainage pipes). This plan was defined at three levels of irrigation water management (IWM): basic, intermediate, and advanced. At the time the RSP was initiated there were no farmers enrolled beyond the basic IWM plan.

Of the 270 applications, a total of 70 contracts were awarded. A majority of these contracts were made at the intermediate IWM plan. In this plan the grower must: 1) irrigate using a scheduling program of their choice; 2) keep records of all irrigations and all calculations that lead to decisions concerning irrigation timing and amount; and 3) provide copies of these irrigation records and a written plan that evaluates the irrigation process for the season with a proposal on what improvements will be implemented for the next season to improve irrigation strategies on the contracted land. The grower must select three of the following options: a) determine soil moisture via in-field sensors (or water depth rice paddies) equipped with data loggers that can be manually downloaded by the operator; b) install permanent or portable manual flowmeters to obtain irrigation flow rates and volumes applied throughout the growing season; c) maintain either an electronic or written record for each irrigation cycle, where duration and volume are recorded for each field under contract; d) install a weather station at the farm level to record temperature, rainfall amount, and windspeed; e) use a surge valve to improve irrigation efficiency; f) utilize software such as computer hole selection (i.e., PHAUCET or Pipe Planner); and/or g) implement AWD (includes row-rice cropping). A majority of the farmers enrolled under this program selected a, b, d, and g.

By June 2016 it was estimated that a total of 29,298 ha of rice was contracted under this project in the mid-south, with the majority of the projects occurring in Arkansas. On approximately half of this land, IWM was initiated and included AWD. Initial data collected from the contract reports from these fields indicated a reduction in the amount of water applied. All contracted fields from 2016 were included in the 2017 season, with additional fields being added through the NRCS-CSP program that was introduced in 2017. An additional $7 million was awarded to the RSP at the end of 2016. These funds were again targeted to the mid-south rice production areas in Arkansas, Mississippi, Louisiana, and Missouri to further implement water conservation, nutrient management, and wildlife habitat enhancement.

On-farm Reservoirs-Tailwater Recovery Systems

Agricultural drainage ditches linked to a surface water storage reservoir are often used as a contiguous system to recycle surface water in areas of aquifer decline and to limit off-farm nutrient and sediment transport. The systems are designed to accumulate, store, and allow the reuse of irrigation tailwater and rainfall runoff. As such, they can provide improved efficiency of irrigation and positively affect water quality, while reducing costs through a reduction in deep groundwater pumping (Young et al. 2004). While farmer-based initiatives and government-subsidized programs have led to the wide-spread construction of these systems, the actual numbers and sizes of the reservoirs are not known. For this reason, a remote sensing inventory using the most recent year of imagery provided by the National Agricultural Imagery Program was conducted to determine the number, surface area, and location of on-farm irrigation reservoirs present in the primary counties of the Grand Prairie CGA and the Cache River CGA (Figure 2b) (Yaeger et al. in press).

Overall, the Grand Prairie CGA had approximately 4.5 times as many reservoirs and total reservoir surface area as the Cache River CGA. The 632 reservoirs totaling 9,336 ha surface area in the Grand Prairie CGA were clustered mainly in the northwestern portion of Arkansas County, southwestern Prairie County, and the central portion of Lonoke County. The 143 reservoirs totaling 2,019 ha surface area in the Cache River CGA were mainly located throughout Poinsett County and in southern Craighead County.

In the Grand Prairie CGA, reservoir size distribution was consistent among the three counties, with the most common size being 5-10 ha, followed closely by 10-20 ha. Less consistency was observed in the Cache River CGA. In Poinsett County, 10-20 ha reservoirs were most common, followed by 5-10 ha. In Craighead County, small reservoirs (1-5 ha) were most common. Large reservoirs (>60 ha) were found in Arkansas and Prairie Counties in the Grand Prairie CGA, and in Craighead County in the Cache River CGA. In both regions, these larger reservoirs were a small proportion (<3%) of the total number of reservoirs.

Managed Aquifer Recharge

A managed aquifer recharge experiment was conducted to determine if an infiltration basin could augment local groundwater recharge in the Cache River CGA. In 2015, the highway department contracted sand excavation of unfarmed land owned by a collaborating producer. This excavation pit would serve as a test case to measure the rate of infiltration into the MRVAA using nearby surface water as the recharge source. Prior to excavation, soil core analyses revealed soil properties within the confining clay layer of red-brown clay and silty clay soils (0-3.7 m deep) with sand below. Once excavation was completed to a depth of about 6 m, the uppermost-unsaturated section of the MRVAA, consisting of well-sorted medium-grain size sand, was exposed and free of the confining clay layer. The excavation pit was about 27 m above the existing water table, and this unsaturated aquifer section could be utilized to improve water quality of infiltrated water by soil aquifer treatment (SAT) through a combination of physical, chemical, and biological processes (Bouwer 1991). The excavation pit was used to conduct an experiment to measure infiltration rates of water pumped from a surface water source through the unsaturated zone above the water table.

The experiment began with instrument installation in early February 2016 and ended June 2016. Submersible pressure transducers were installed at the bottom of the excavation pit to monitor water level changes. Two staff gauges, associated with automatic game cameras, were installed on the north and south sides of the pit to visualize the water level depth once the excavation pit was filled. Another pressure transducer was deployed in an irrigation well 0.3 km away to monitor groundwater levels. To measure the components of the water budget, an on-site weather station was set up to collect meteorological data of air temperature, precipitation, relative humidity, wind velocity, and evaporation rate. Sediment samples from the excavation pit floor and sidewalls were collected pre- and post-experiment for analysis of organic matter, soil texture, and sand composition. Prior to adding water, the pit's location and elevation were determined so that changes in groundwater storage could be estimated.

Input water from a nearby surface water source was pumped through an underground pipe to a riser and delivered to the excavation pit via plastic irrigation tubing. Beginning 5 February 2016, water was pumped into the excavation pit continuously for 24 hours, representing a volume of 4.2 ML. Total precipitation during the experiment was 593 mm. This was 47% of the 30-yr climate normal (NOAA 2017). Two large precipitation events occurred on 8-10 March 2016 and 30-31 March 2016, totaling 100 and 152 mm, respectively.

Analysis of water level data indicated continuous infiltration throughout the experiment with water levels rising only following precipitation. Major precipitation events in March 2016 raised water levels to about half of the initial water input. An initial infiltration rate of 188 mm d^{-1} and 191 mm d^{-1} was measured at two locations and both values exponentially decreased until March 2016, with rates varying between 0-120 mm d^{-1}. Groundwater levels fluctuated approximately 0.3 m during the experiment; however, the extent of recharge and the relationship between change in excavation pit water level and groundwater level are not clear. Expanded monitoring near the pit and through the full-unsaturated zone would be required to confirm if excavation pit water level changes corresponded directly to groundwater fluctuations. Using the infiltration rate calculated from one of the pressure transducers and an initial excavation pit floor surface area of 0.17 ha, the total groundwater storage increase was 8.8 ML (7.2 acre-feet), more than double the initial water input.

These results suggest that infiltration basins warrant further study as a means to help offset groundwater decline. For example, fourteen exposed borrow pits have been identified within Craighead County (Yaeger et al. in press). With the permission of landowners, these existing excavation pits might be rehabilitated to act as infiltration basins, with the assumption that they are at a depth below the confining layer and are suitably permeable to allow recharge. Removal of the bottom surface of these pits might be necessary as debris and/or silt may have accumulated over time to form layers that decrease infiltration (Bouwer and Rice 1989). Unless widely adopted, managed aquifer recharge would not address the region-wide challenges of groundwater decline in eastern Arkansas, but has the potential to augment local groundwater recharge in the Cache River CGA and merits further research.

Conclusions

Agriculture in the LMRB relies heavily on the MRVAA for irrigation. Declines in the aquifer necessitate improved management of water resources in the region. Three case studies that aimed to mitigate aquifer decline were described. An effort to improve rice irrigation management in the LMRB through several collaborating partners as part of the Rice Stewardship Partnership was found to reduce the amount of water applied on nearly 30,000 hectares. An inventory of on-farm reservoir tailwater recovery systems shows that significant investments have been made as part of efforts to use more surface water in critical groundwater areas. Lastly, a novel test of managed aquifer recharge was described that will be used as the basis for further testing of this approach in areas where large-scale surface water projects are unlikely. It is anticipated that the case studies described will impact the long-term sustainability and resiliency of water resources in the region.

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