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Extending irrigation reservoir histories for improved groundwater modeling and conjunctive water management in two Arkansas critical groundwater areas

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ABSTRACT

Agricultural land managers in the Mississippi Alluvial Plain rely on the Mississippi River Valley Alluvial Aquifer for the majority of the water used for irrigation in the region. Pumping that outpaces recharge has resulted in significant cones of depression in the region, increasing pumping costs and forcing producers to use more surface water, often in the form of constructing on-farm storage reservoirs. At the same time, efforts are underway to improve groundwater models to run scenarios of conjunctive water management in the region. The improved models require accurate depiction of how the system is being managed including the use of on-farm storage reservoirs. This study extends our knowledge of on-farm storage reservoir construction from those established by a previous study that tracked reservoir construction between 1996 and 2015 backward an additional 20 years to 1976. This was accomplished by using older multi-band satellite and aerial imagery. The study area covers portions of two Critical Groundwater Regions in eastern Arkansas. Reservoir construction was classified into five-year bins starting in 1976 and ending in 2015. Details of how older imagery was processed and analyzed are provided. Previously, nearly 50% of the on-farm storage reservoirs had unknown construction dates, but this research study resolved construction dates for 85% and 72% of the reservoirs in the two study areas. Relationships between time and depth to groundwater, reservoir size, previous land use, and saturated aquifer thickness are described and contrasted in the two study areas across the 40-year study period. Use of the information provided will help guide policy and resource allocation for future reservoir construction activities and help improve conjunctive water management of the region. Specifically, the addition of this historic information will allow modelers to further refine groundwater-surface water models and should improve water resources scenarios that include reservoirs as a tool to reduce groundwater decline.

1. Introduction

Irrigation in Arkansas began in the early 1900 s and has steadily increased on the larger Mississippi alluvial plain (MAP), whose dynamic landscape produces a diverse set of row crops (i.e., cotton, maize, peanut, soybean, rice). These crops benefit greatly from access to on-demand, dependable, economical irrigation. Consequently, a serious issue facing the future of MAP irrigated agriculture is the steady decline of two major aquifers from which ca. 80% of irrigation is derived: the Mississippi River Valley Alluvial (MRVA) aquifer and the deeper, much less productive Sparta aquifer.

The MRVA has been a source of irrigation water in the region since the early 1900 s. The alluvial aquifer is a highly productive water source, with 54% of its structure underlying Eastern Arkansas (Pugh et al., 1997). Arkansas currently irrigates the third most land area of any state in the US, after Nebraska and California. The largest single period of expansion in irrigated land occurred between 1974 and 1978, when Arkansas irrigation expanded from 384,500 ha (950,000 ac) to 681,000 ha (1683,000 ac), representing a 77.4% increase over a four-year period (NASS, 2019). The 1980–1981 droughts in the southern US (Andreadis et al., 2005) also influenced an increase in irrigated land. By 1988, Arkansas irrigated approximately 730,899 ha (1860,909 ac).

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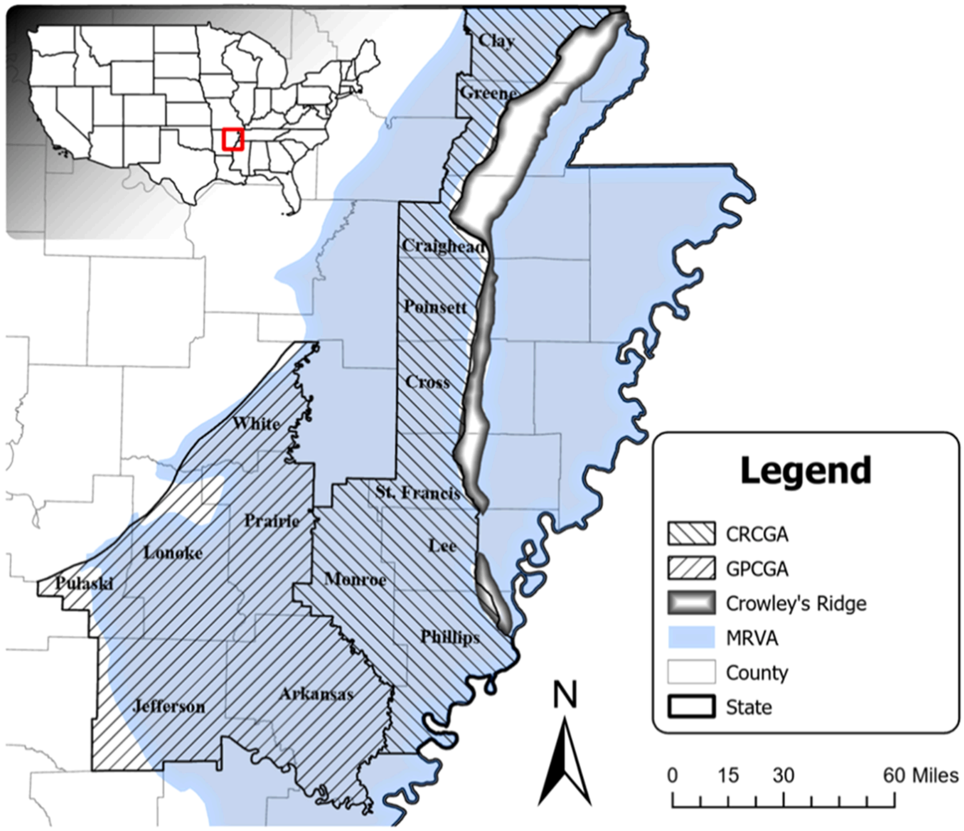

Fig. 1. Locations of the Mississippi River Valley Alluvial Aquifer (MRVA) and associated critical groundwater areas (CGA) in the Grand Prairie (GP) and Cache River (CR) regions of Arkansas.

The water level within the aquifer has declined due to a combination of over-pumping of farm wells (Konikow, 2013) and limited aquifer recharge in the area owing to the geology of the area. Aquifer depletion was recognized in Eastern Arkansas as early as 1915 and officially since the 1930 s (Gates, 2005; Vories and Evett, 2014). Pumping has outpaced recharge and threatens future water availability in the MRVA (Forrest, 2021). Groundwater recharge in this region is limited by the presence of a confining clay layer of varying thickness which restricts infiltration rates (Broom and Lyford, 1981). These factors have resulted in several regional cones of depression in the water table of Eastern Arkansas (Forrest, 2021).

In response, the state designated several sections of Eastern Arkansas as Groundwater Study Areas (Forrest, 2021), and portions of these study areas were elevated to the status of Critical Groundwater Area (CGA) (Fig. 1). The Groundwater Study Areas of the Grand Prairie became known as the Grand Prairie CGA (GPCGA) in 1998, while the Cache River CGA (CRCGA) was established in 2009 (ANRC, 2014). Both areas have been expanded to include neighboring counties: As of 2021, the GPCGA includes Arkansas, Lonoke, Prairie, Jefferson, southern Pulaski, and southeastern White while CRCGA includes Monroe, and the sections of Clay, Greene, Craighead, Poinsett, Cross, St. Francis, Lee, and Phillips Counties west of Crowley's Ridge. These cones of depression are expected to reach critically low levels if irrigation demand continues to exceed recharge (Clark et al., 2011).

Concerted efforts to address groundwater decline were not actively pursued until the 1980s, a time that also corresponds with increasing irrigation demand that rose significantly as a result of a drought that struck the region in 1980 (Karl and Quayle, 1981; Clark et al., 2013). A key effort was to shift irrigation sources from ground to surface water where feasible. As of 2015, approximately 143 and 632 on-farm irrigation reservoirs had been constructed in the CRCGA and GPCGA, respectively (Yaeger et al., 2017). The reservoirs, which may include tailwater recovery systems, are used to store water during the late winter and early spring when the majority of precipitation occurs in the region. These systems have been constructed across Eastern Arkansas (Yaeger et al., 2017, 2018) and their numbers are expected to grow as groundwater resources are increasingly depleted.

Improved understanding of the environmental conditions under which reservoirs were constructed is likely linked to declines in the MRVA. In addition, land managers will need a comprehensive inventory of these systems to know how many are being placed on streams and ditches. Given variability in precipitation, scenarios could be run to ensure that surface water sources are sufficient to fill existing and planned reservoirs at the sub-watershed scale.

Groundwater models are a common tool used to improve our understanding of these aquifer systems. The Mississippi Embayment Regional Aquifer Study (MERAS) documents the construction and calibration of a finite-difference groundwater model of the Lower Mississippi River Basin. The first version of the model was used to quantify groundwater availability in the embayment area through a 137-year period that began in 1870 and ended in 2007 and was first described by Clark and Hart (2009). This model was the basis for several studies that assessed the groundwater response to different management scenarios or smaller modeling domains within the MERAS (Barlow and Clark, 2011; Haugh, 2012; Clark et al., 2013).

Current efforts are underway that aim to improve the MERAS model and include the development of an interactive MERAS Hydrologic Framework. In addition to the entire MAP model domain, three inset models are also being developed and include the Mississippi Delta, Grand Prairie, and Cache River. The calibration period for this model runs from 31 December 1955 to 31 December 2018. Accurate depiction of this period requires understanding of activities that impact withdrawal and recharge, and will set the stage for conjunctive use management and conservation target scenarios. One component of

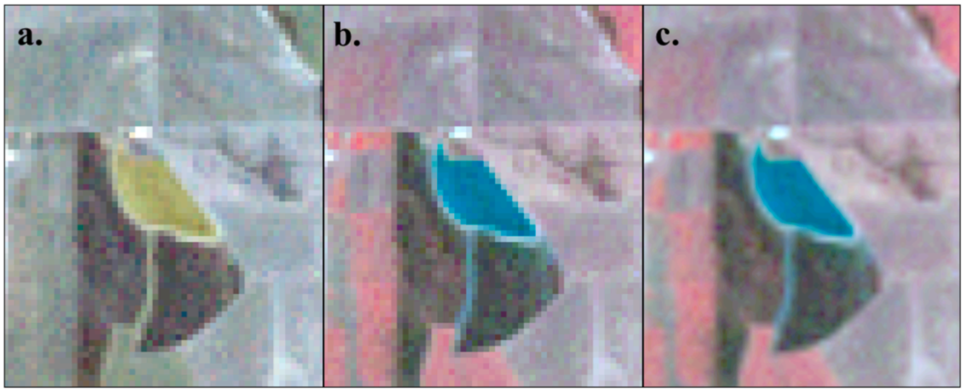

Fig. 2. Example processing of low-resolution imagery to identify on-farm reservoirs constructed post-1976 in Arkansas. (A) Low-resolution image using 3–2-1 (Red-Green-Blue) band combination. (B). False-color band combination using 4–3-2 (NIR-Red-Green) band combination with Nearest Neighbor interpolation. (C) False-color band combination using 4–3-2 (NIR-Red-Green) band combination with Bilinear interpolation to reduce pixilation.

accurately depicting the system is how on-farm reservoirs relate to groundwater response and offsets. This research used low-resolution imagery and presence-absence analysis to expand the construction histories of irrigation reservoirs constructed between 1975 and 1995. This back-in-time analysis results in finer resolution of reservoir construction histories by up to 20 years which will lead to more accurate model parameterization.

Yaeger et al. (2018) used county-scale National Agricultural Imagery Program (NAIP) digital aerial orthoimagery from USDA (Maxwell et al., 2017) to determine reservoir construction dates back to 1996. Using older multi-band satellite and aerial imagery sources allowed for dating of reservoir construction earlier than 1996. The image quality and resolution were considerably lower prior to 1996 (1 m to 30 m); therefore, it becomes difficult to differentiate water from land, especially when creating a reservoir dataset based on the method of Yaeger et al. (2017) for locating reservoirs. This study showed how low-resolution NIR imagery (i.e., Landsat 5 with 30-m resolution) and high-resolution panchromatic imagery (i.e., Digital Orthophoto Quadrangle (DOQ) with 1-m resolution) can be used to detect water. The objectives of this research were to (1) use low-resolution imagery to detect on-farm irrigation reservoirs to refine reservoir construction histories of two critical groundwater areas in Arkansas, (2) analyze reservoir construction trends in relation to previous land use, depth to groundwater, and percent aquifer saturation, and (3) use this information to help guide policy and resource allocations for future reservoir construction activities.

2. Data and methods

2.1. Study site

The study area includes portions of both of the CGAs in Eastern Arkansas (Fig. 1). The areas studied in the CRCGA are portions of Craighead, Poinsett, Cross, and St. Francis Counties west of Crowley's Ridge while the areas studied in the GPCGA in East Central Arkansas include Prairie, Lonoke, and Arkansas Counties (Fig. 1). Crowley's Ridge is a prominent geological formation that rises above the alluvial plain and runs generally north south from southeastern Missouri through Arkansas to Helena, AR. Though more counties are included in the CGAs, the counties included in the study are those nearest to the cones of depression.

2.2. Reservoir data set

National Agriculture Imagery Program (NAIP) is a collection of aerial images acquired during "leaf on" conditions in the United States (Maxwell et al., 2017). In 2003, NAIP was collected every five years and changed to every three years in 2009. The spatial resolution is one meter, and includes four bands: red, green, blue, and Near-Infrared (NIR). The NIR band was not collected until 2007 and is collected only for certain states.

Yaeger et al. (2017) was the first to survey on-farm irrigation storage reservoirs in Arkansas and included the same counties as those presented here. The authors used NAIP to locate 632 and 143 reservoirs in the GPCGA and CRCGA, respectively. The combined surface areas were determined to be 9,300-ha for the GPCGA and 2,000-ha for the CRCGA. The reservoirs averaged 14.6-ha in both areas. Yaeger et al. (2018) identified patterns of reservoir construction from 1996 to 2015, related the construction to groundwater decline, and identified the prior land use before construction.

2.3. Imagery used

Landsat 1 collected imagery from 1972 to 1978 at a temporal resolution of 18 days. It was equipped with the Return Beam Vidicon (RBV) and the Multispectral Scanner System (MSS) sensor. Both the RBV and the MSS had a ground resolution of 80 m. The RBV used three bands: Band 1 (blue-green), Band 2 (orange-red), and Band 3 (Visible red to NIR). The MSS used four bands: Band 4 (green), Band 5 (red), Band 6 (NIR), and Band 7 (NIR). Landsat 2 was launched in 1975 and decommissioned in 1983; it was equipped the same as Landsat 1 to prevent a lapse in data.

Landsat 5 collected imagery data between 1984 and 2013 at a temporal resolution of 16 days. It was equipped with the Multispectral Scanner (MSS) and the Thematic Mapper (TM) sensors. The MSS sensor had a pixel size of 80 m with four spectral bands: Band 4 (green), Band 5 (red), Band 6 (NIR 0.7 to 0.8 μm) and Band 7 (NIR 0.8 to 1.1 μm). The TM had a pixel size of 30 m with the exception of the thermal band at 120 m and it had a total of seven bands: Band 1 (blue), Band 2 (green), Band 3 (red), Band 4 (NIR), Band 5 (NIR), Band 6 (Thermal), Band 7 (Mid-Infrared; USGS 2016). A DOQ is a georeferenced aerial photograph image and has a spatial resolution of one meter. It can be black and white (B/W or panchromatic), natural color, or color-infrared (CIR). The production of the computer-generated DOQ images spans from 1987 to 2006.

Using the reservoirs identified by Yaeger et al. (2017), Landsat 1, Landsat 2, Landsat 5, DOQ, NAIP Imagery, and *ArcGIS Pro Version 2.7.3* were manually evaluated to record when each waterbody was constructed. All imagery was obtained from United States Geological Survey Earth Explorer database (United States Geological Survey, 2020). To update and extend before 1996, Landsat 1 imagery for 1975 and 1976, Landsat 2 imagery for 1980, Landsat 5 imagery for 1985, 1990, and 1995, and DOQ imagery for 1989 and 1996 were used to record and verify the date that the reservoir appeared in the imagery. Waterbodies identified in Yaeger et al. (2017) were classified into systems constructed prior to 1976 and then into five-year bins spanning from 1976 to 2015.

Landsat 5 has seven spectral bands; all but one band has a resolution of 30 m. The thermal band has a resolution of 120 m. The first four bands of Landsat data were used in this study. To improve the ability to identify water with a 30-m resolution image, the Composite Band tool in the ArcGIS Data Management toolbox was used to generate a band combination of 3–2-1 (RGB) representing a true-color image (Fig. 2a). This method is common when looking at aerial imagery, but resulted in a hazy image with the 30-m resolution. Water was difficult to differentiate from land using the 3–2-1 band combination with a low-resolution image. Therefore, a “false color” band combination of 4–3-2 (NIR-red-green) was used (Fig. 2b & c). This band combination created more contrast between land and water, making it easier to determine the presence of water. Nearest Neighbor interpolation yielded a pixilated image (Fig. 2b). Bilinear interpolation of the surrounding four pixels was used to further remove the pixilation and create a more refined edge to distinguish different landscape features (Fig. 2c).

2.4. Presence-absence analysis

Reservoir construction date and prior land use/land cover were determined using available land cover surfaces and imagery and evaluated at five-year intervals. The National Land Cover Database NLCD) land cover surface was obtained from United States Geological Survey Earth Explorer (United States Geological Survey, 2020). The Cropland Data Layer (CDL) land cover surface was obtained from Geospatial Data Gateway (USDA-Farm Service Agency, 2020). The NLCD and CDL were used from 1997 to 2015, while DOQs and Landsat 1, 2, and 5 were used from 1976 to 1997. Reservoir polygons were overlaid onto the historical imagery. The year that the reservoir was no longer visible allowed us to place the construction date into the appropriate five-year interval. Land use/land cover of the area was also determined. Land use/land cover was categorized as wooded, cropland, mixed, or lowland similar to Yaeger et al. (2017). However, to reduce the number of categories, they were combined to “cropland mixed” and “other” (wooded or lowland).

2.5. Depth to groundwater

To assess depth to water (DTW) values across the GPCGA and CRCGA, an interpolation was made using Water Depth Below Land Surface points derived from the USGS (United States Geological Survey, 2021) This allowed for a generalized prediction of DTW in the CGAs. Before generating the interpolation, the data was cleaned to remove duplicate sites and filtered for Jan-May months only to exclude data captured during active groundwater pumping. The objective was to reduce redundancy and visualize the well depths prior to the irrigation season. Data were retrieved for 1975, 1980, 1985, 1990, 1995, 2000, 2005, 2010, and 2015 to assess the DTW at each reservoir near the time of its construction. Using the reservoir polygons, a centroid was created to sample the DTW interpolation at each site to assign the DTW value back to the reservoir polygons. The construction time was given in a five-year range, therefore the DTW assigned to each range was determined from the final year of the range. For example, reservoirs constructed between 1981–1985 were assigned the DTW from 1985, and reservoirs constructed prior to 1975 were assigned DTW from 1975.

2.6. Saturated aquifer thickness

To assess the saturated aquifer thickness of the MRVA, a dataset created by Torak and Painter (2019) was used to compare MRVA bottom elevation, top elevation, aquifer thickness, land surface elevation, and DTW values. The aquifer bottom elevation and thickness were interpolated across the study area and rasterized. Rasterization of the different data characteristics allowed for universal calculations to be made with a raster calculator in ArcGIS Pro. The DTW rasters (1970–2015 in five-year increments) were subtracted from the land surface elevation above MSL (mean sea level) value relative to the well site (where the DTW was measured), resulting in an elevation above MSL value of the DTW. Since the MRVA bottom elevations were already relative to MSL, this allowed for a simple subtraction to determine the saturated aquifer thickness. Once the saturated aquifer thickness was calculated, it was divided by the aquifer thickness raster and multiplied by 100 to convert to the percent of saturated aquifer thickness.

The centroid of each reservoir polygon was determined. These locations were then used to sample the percent of saturated aquifer thickness interpolation to assign a value to each reservoir polygon. Once the sample was collected, the data were joined back to the original dataset for assessment. The construction was given in a five-year range, therefore the percent of saturated aquifer thickness assigned to each range was determined from the final year of the range. Similar to DTW, reservoirs constructed between 1981–1985 were assigned the percent of saturated aquifer thickness from 1985 and reservoirs constructed prior to 1975 were assigned percent of saturated aquifer thickness from 1975.

2.7. Survival model: statistical analysis

To quantify the influence of various factors on time of reservoir construction, we fit a Bayesian proportional hazards time-to-event regression model. We treated the reservoir construction timespan data as interval-censored data because the time of reservoir construction is known to within a five-year time interval. In addition, the earliest time interval, for reservoirs constructed before 1976, was treated as left-censored because only the upper bound is known for those reservoirs. The predictors in the regression model were CGA region (binary predictor with two levels: Grand Prairie and Cache River), prior land use class (binary predictor with two levels: cropland and all other prior land uses), reservoir area, and percent of saturated aquifer thickness at the time of reservoir construction. In addition, two-way interactions between CGA and the other three predictors were included, as well as two three-way interaction terms: CGA by prior land use by reservoir area and CGA by prior land use by percent saturation. Reservoir area was log-transformed and standardized, and percent saturation was standardized, allowing the model coefficients to be directly compared.

The Bayesian proportional hazards model was fit with a baseline log-logistic distribution. The parameters were estimated using Markov Chain Monte Carlo with four chains, 9000 discarded burn-in iterations per chain, and 10,000 post-burn-in iterations which were thinned by retaining every 10th sample. This resulted in 4000 posterior samples (1000 per chain). We examined parameter trace plots to ensure that the model converged. We calculated the median and quantile credible intervals (QCI; 66%, 90%, and 95%) using the posterior samples for each parameter. To visualize modeled trends in reservoir construction, we also calculated posterior population-level expected values of percent of reservoirs constructed at several different combinations of predictors. Specifically, we calculated expected values for each five-year period, CGA region, and prior land use class for the median value of area and median value of percent saturation, the median value of area crossed with the 25th and 75th percentiles of saturation, and the median value of saturation crossed with the 25th and 75th percentiles of area. We calculated the medians and quantile credible intervals for these predictions, which were used to construct the modeled trend plots. Model predictions are also expressed as hazard ratios, the expected ratio of change in probability associated with an increase of a predictor variable by one unit.

Analysis was done using R software version 4.1.2 (R Core Team, 2021), including the packages **survival** v3.3–1 (Therneau, 2022) and **icenReg** v2.0.15 (Anderson-Bergman, 2017) for fitting the proportional hazards model. Data and code are available for download at Ag Data Commons (Read et al., 2023).

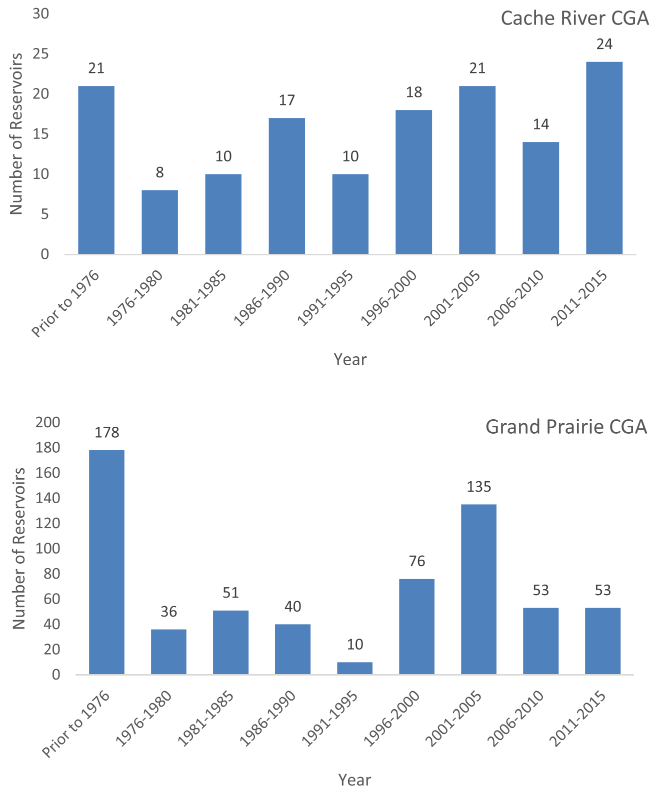

Fig. 3. Number of reservoirs in the (top) Cache River CGA and (bottom) Grand Prairie CGA from prior to 1976 to 2015 in five-year intervals.

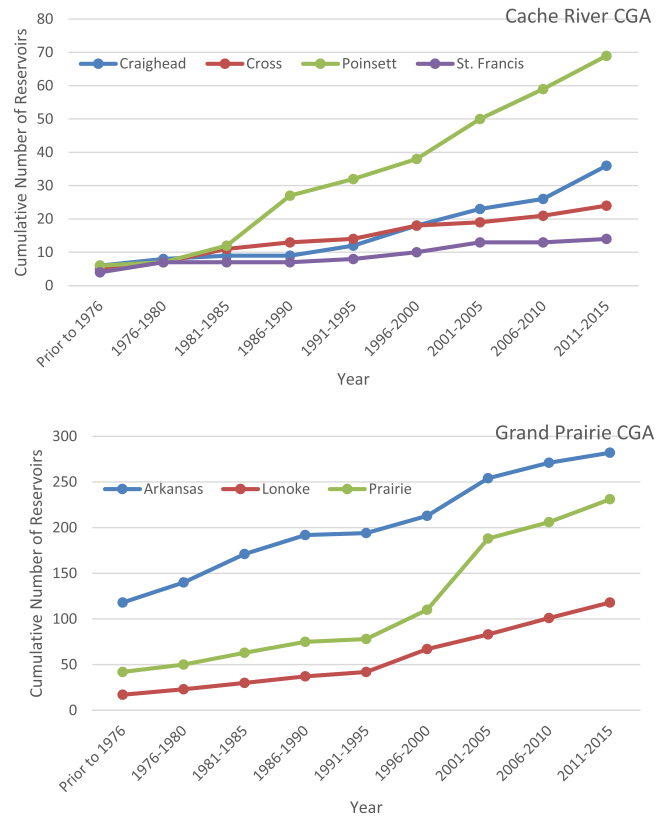

Fig. 4. Cumulative number of reservoirs from prior to 1976 to 2015 in five-year intervals in the (top) Cache River CGA by county- Craighead, Cross, Poinsett, and St. Francis and (bottom) Grand Prairie CGA by county-Arkansas, Lonoke, and Prairie.

3. Results and discussion

As of 2015, 143 CRCGA reservoirs with a total surface area of 2000 ha and 632 GPCGA reservoirs with a total surface area of 9300 ha were identified (Yaeger et al., 2017). The Yaeger et al. (2018) dataset was generated with three-band NAIP imagery and was compared against the use of two different datasets, Landsat 5 and DOQs. For the reservoirs that appeared after 1996, the appearance dates in Yaeger et al. (2018) agreed with those determined here except for two sites where reservoir polygons were inundated fields. According to Yaeger et al. (2018), approximately half of the reservoirs had construction dates prior to 1996. There were 66 and 315 reservoirs constructed prior to 1996 in the CRCGA and GPCGA, respectively. The present study reduces the number of reservoirs with unknown construction dates (though sometime prior to 1976) to 21 and 178 in the CRCGA and GPCGA, respectively (Fig. 3), resulting in 85% and 72% of the construction dates.

Between 1976 and 1996, 45 and 137 reservoirs were constructed in the CRCGA and GPCGA, respectively. Of the reservoirs built during this period, approximately 60% and 51% were built between 1980 and 1990 in the CRCGA and the GPCGA, respectively. A graphical depiction of reservoir construction in five-year periods is shown in Fig. S1. There was roughly a doubling in reservoirs built per year when comparing the first 20 years of this study to the last 20 years. The annual construction rate in the CRCGA and GPCGA between 1976 and 1995 was 2 and 7 reservoirs per year, respectively, and between 1996 and 2015 was 4 and 16 reservoirs per year, respectively. There were roughly four times the number of reservoirs built in the GPCGA compared to the CRCGA, with roughly a doubling between the first 20 years and the second 20 years. However, in 1991–1995, there were only ten reservoirs built in each of the CGAs. For the CRCGA, this is a typical number but ten is the lowest number constructed in any of the time spans analyzed in the GPCGA.

The surface area of reservoirs appears to remain relatively constant from 1976–2015 in both study areas. The average size of reservoirs in both study areas is approximately 14.1 ± 15.4 ha and 14.8 ± 21.0 ha for the CRCGA and GPCGA, respectively. Evaluating average reservoir size by timespan reveals weak evidence for an overall tendency for larger reservoirs to have been built earlier (hazard ratio associated with increasing reservoir area by one standard deviation is 1.237, 95% QCI [0.977, 1.557]). However, the 20-year average reservoir size between 1976 and 1995 is 10 ha and 15 ha, while between 1996 and 2015 it is 15 ha then 10 ha in the CRCGA and GPCGA, respectively, potentially pointing to a general reduction in reservoir size in the GPCGA and an increase in the CRCGA. Because a majority of the GPCGA reservoirs will be regularly filled using water diverted from either the Arkansas or White Rivers, those reservoirs do not need to have as much long-term storage capacity as compared to CRCGA reservoirs that rely on surface runoff driven mostly by winter and spring precipitation. Based on this analysis, one could reasonably expect that the size of CRCGA reservoirs may continue to increase over time while those in the GPCGA, especially those served by the surface diversion projects, will remain more or less the same size.

Prior to 1975, the distribution of reservoirs in the Cache is very similar by county, suggesting similar conditions in each county at this time (Fig. 4 top). Changes in the number of reservoirs between counties begin to become evident in the mid-1980 s. In addition, the need for a reservoir and the construction of a reservoir is not instantaneous. Projects funded with NRCS assistance take several years to go from design to completed construction. In addition to aquifer decline and availability of cost-share funding, the rate of reservoir construction is also a function of landowner approval, weather, and the availability and, ultimately, the capacities of local earthmoving services.

There is a sharp increase in the number of reservoirs built in Poinsett County between 1986–1990, with that county accounting for over 50% of constructed reservoirs. In addition, only two of the sixteen reservoirs built between 1986 and 1990 were located outside of Poinsett County.

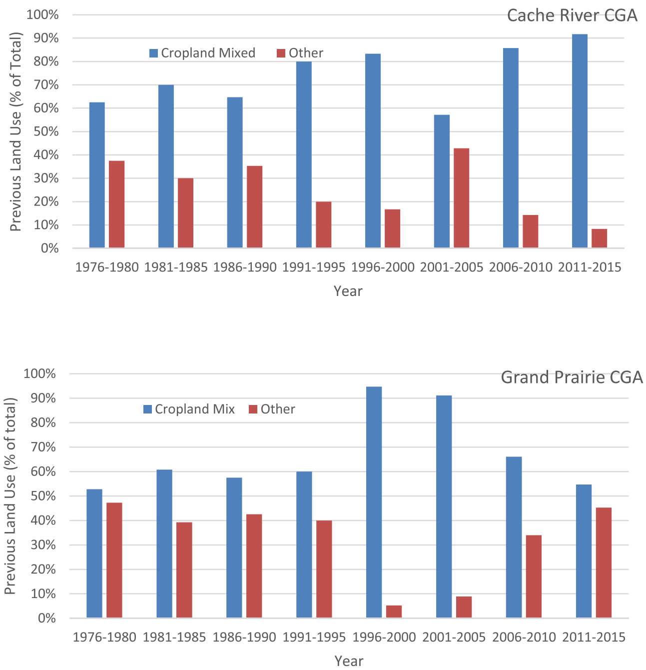

Fig. 5. Land use prior to reservoir constructed between 1976 and 2015 as a percentage of total reservoirs located in Cache River CGA (top) and Grand Prairie CGA (bottom).

The cone of depression in the CRCGA was centered in Poinsett County in 1980 (Kresse et al., 2014). After 1995, construction of reservoirs in Craighead County increased and remained similar that of Poinsett County. An equal number of reservoir construction projects occurred in 2011–2015 in Craighead and Poinsett, signaling a migration of the cone of depression northward from Poinsett to Craighead. The increase in Craighead County is also influenced by a cone of very low saturated aquifer thickness that began to form in 1996 at the border between Poinsett and Craighead County and continued to expand into 2015 (Yaeger et al., 2018).

In the Grand Prairie, however, Arkansas County has the majority of all reservoirs built (Fig. 4 bottom). The construction by county was likely fueled by the development and migration of the cone of depression in Grand Prairie that began in Arkansas County. Pre-development, the potentiometric contours in the Grand Prairie counties ranged from 140 ft in the southeast corner of Arkansas County to 230 ft in the far western edge of Lonoke County (Kresse et al., 2014). A cone of depression centered in the middle of Arkansas County with a potentiometric contour of 130 ft was clear in 1929 (Kresse et al., 2014). The cone of depression migrated in a northwesterly direction toward Prairie County and into Lonoke County by 1972. This trend continued such that by 1998, the deepest Arkansas County potentiometric contour was at 90 ft, a small contour of 100 ft had formed in southern Prairie County and 110 ft into eastern Lonoke County (Kresse et al., 2014). By 2008, the cone of depression ran from central Arkansas County at 90 ft contours through southern Prairie County to another deep cone in eastern Lonoke County.

Of the 632 reservoirs in the GPCGA, 211 were built between 1996–2005. This was due, in large part, to the Bayou Meto and White River irrigation projects. These projects required on-farm water storage in reservoirs as part of the system design. Of the reservoirs built during this period, approximately 50% were built in Prairie County, and 28% and 19% built in Arkansas and Lonoke counties, respectively.

In both critical groundwater areas, the previous land use prior to reservoir construction is dominated by “Cropland Mix” (Fig. 5). In the CRCGA, there is a steady decline in the “Other” (wooded or lowland) category in all time spans except for 2001–2005. The “other” category begins at 37% in 1976–1980, is reduced to less than 20% by 1991–1995, and finally less than 10% by 2011–2015. This trend aligns with the hypothesis that areas where construction of a reservoir is relatively straight forward, e.g., low-lying land, are reduced as more reservoirs are constructed. This trend is also supported by estimates from the survival model showing that in both CGAs, reservoirs built on non-cropland were more likely to be built earlier (Fig. 6; hazard ratio 1.976, 95% QCI [1.233, 3.087]) as a means to avoid foregone production (Bouldin et al., 2004). Size of reservoirs is also related to prior land use (Fig. 7). Larger reservoirs were built somewhat earlier than smaller ones only on non-cropland in the GPCGA (Fig. 7, lower right panel; hazard ratio 1.183, 95% QCI [0.977, 1.423]), whereas there was little to no effect of reservoir area on construction time on cropland in the GPCGA and everywhere in the CRCGA.

In the GPCGA, the balance between cropland mix and other as the previous land use of the site remains similar for all time spans except 1996–2005. This time span is dominated by reservoir construction in support of the two CGAs and were dominated by reservoirs constructed on cropland.

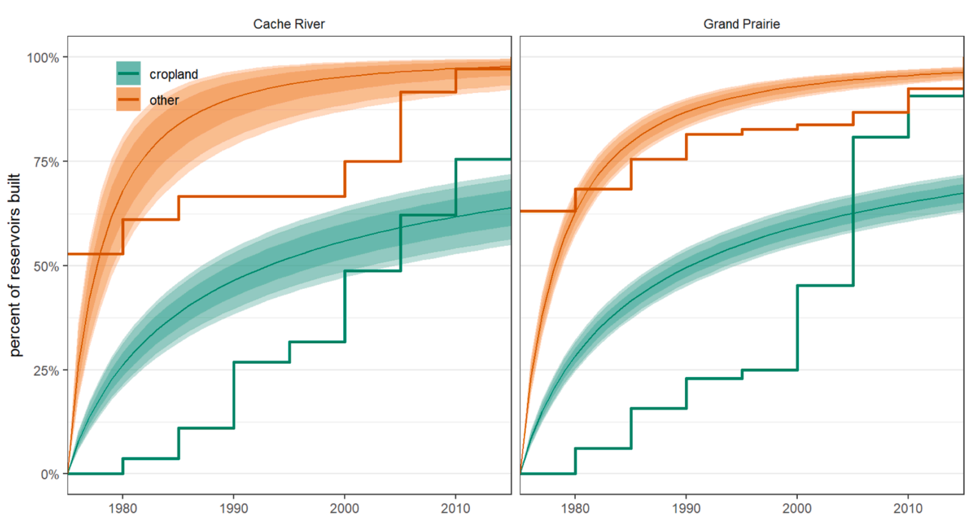

Fig. 6. Cumulative percentage of construction by prior land use for irrigation reservoirs constructed in Cache CGA (left) and Grand Prairie CGA (right). Solid stair-step lines represent the observed cumulative percentage of reservoirs constructed at each five-year interval, colored by prior land use class. Trends fitted from the model (posterior medians) are surrounded by progressively shaded regions indicating the 66%, 90%, and 95% quantile credible intervals of the trend.

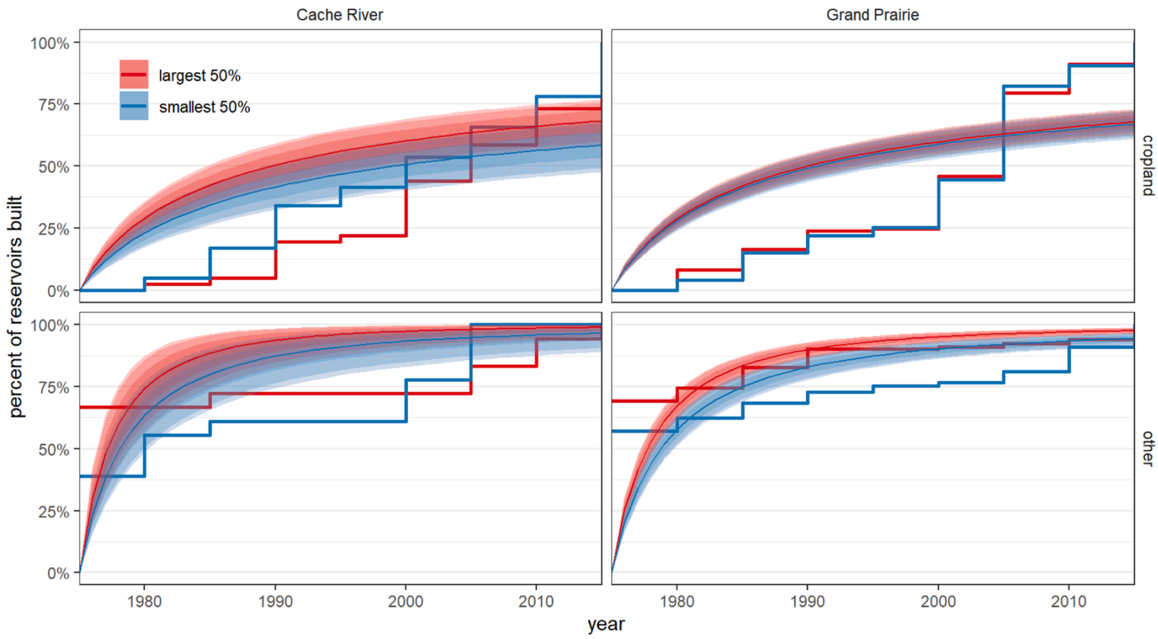

Fig. 7. Cumulative percentage of construction by prior land use (cropland mix, upper panels; other, lower panels) and reservoir area for Cache CGA (left panels) and Grand Prairie CGA (right panels). Solid stair-step lines represent the observed cumulative percentage of reservoirs constructed at each five-year interval, colored by reservoir size class. Trends fitted from the model (posterior medians) are surrounded by progressively shaded regions indicating the 66%, 90%, and 95% quantile credible intervals of the trend.

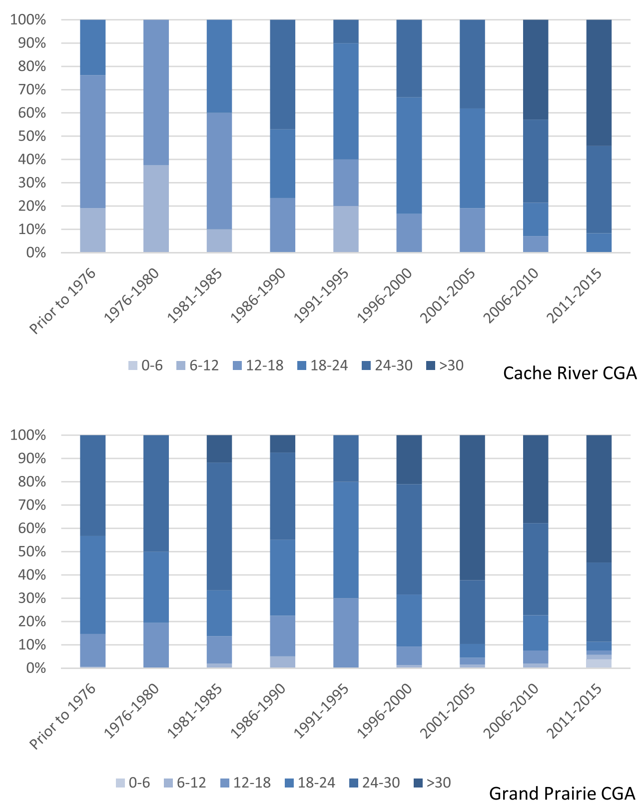

Fig. 8. Range of depth (m) to groundwater at the reservoir location at the time of construction in the Cache CGA (top) and Grand Prairie CGA (bottom) from prior to 1976 to 2015 in five-year intervals.

Depth to Groundwater.

Prior to 1975, reservoirs were constructed in one of three DTW ranges in both CGAs. However, reservoirs were built on sites with DTW between 6 and 24 m and 12 and 30 m in the CRCGA and GPCGA, respectively (Fig. 8). After 1981 in GPCGA, the range of DTW is expanded to include all categories except 0–6 m, while in CRCGA there is a steady increase in the range of DTW where reservoirs were built. This is likely a reflection of the need for reservoirs as water storage for the irrigation projects versus being driven by increases in DTW. As time passes, reservoirs were being built in areas where depth to groundwater is deepening. Nearly all ranges of depth to groundwater are represented as reservoir locations. In the CRCGA the category of greater than 30 m is not evident until 2006; whereas, in the GPCGA approximately 11% of the reservoirs were built in areas with this depth to groundwater as early as 1981–1985.

Saturated aquifer thickness.

By using the Torak and Painter (2019) dataset, there was a noticeable difference in the depth of the aquifer relative to the land surface. When using the MRVA bottom elevation and adding the aquifer thickness value, a MRVA top elevation was the result. It was found that the distance between land surface and the top of the MRVA was typically higher in the Cache River CGA versus the Grand Prairie. At the land surface in the Grand Prairie, the MRVA top elevation may be nearly the same as the land surface, whereas in the Cache River CGA, the MRVA top elevation may be 4.5 m below the land surface. The MRVA is thicker overall in the Cache River CGA ranging from 21 to 82 m versus the Grand Prairie CGA ranging from 6 to 64 m.

The saturated aquifer thickness (SAT) generated in Yaeger et al. (2018) used estimates of aquifer thickness from Hart et al. (2008). Depth to groundwater measurements for each study year were subtracted from the aquifer thickness to estimate saturated thickness, and the ratio of saturated thickness to aquifer thickness was used to calculate the saturated percent of aquifer thickness. This methodology assumed that the top of the estimated aquifer thickness is coincident with the land surface and reference for the depth to groundwater measurement. The difference in methodology generated similar percentages of saturated aquifer thickness in the GPCGA, but the methods in Yaeger et al. (2018) reported less saturated aquifer thickness in the CRCGA than the methods used in this study.

The trend of reservoir area added each five-year period did not differ from the number of reservoirs added except when very large reservoirs

Table 1
Numbers of reservoirs constructed in Cache River and Grand Prairie critical groundwater areas (CGA) of Arkansas in relation to saturated thickness (%) of the Mississippi River Valley Alluvial aquifer.

Cache River CGA									
Saturated Aquifer Thickness (%)	Prior to 1976	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
0-10									125
10-20									41
20-30							26		123
30-40				54	4	158	33	69	95
Sub-Total	**0**	**0**	**0**	**54**	**4**	**158**	**58**	**69**	**385**
40-50			23	97	41	67	125	75	45
50-60	17		31	64	6	33	64	34	7
60-100	392	86	51	4	4	17	7	3	
Sub-Total	**409**	**86**	**105**	**165**	**50**	**117**	**196**	**111**	**52**
Grand Total	**409**	**86**	**105**	**219**	**54**	**275**	**254**	**181**	**437**
Grand Prairie CGA									
Saturated Aquifer Thickness (%)	Prior to 1976	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
0-10						5	176	34	26
10-20			11	6		119	408	62	231
20-30	88	95	145	140		144	376	197	145
30-40	2189	309	439	118	37	430	198	189	75
Sub-Total	**2277**	**404**	**596**	**264**	**37**	**698**	**1159**	**481**	**478**
40-50	803	119	86	139	15	118	38	31	0
50-60	445	32	63	369	16	118	51	8	11
60-100	187	49	12	122	16	8	31	3	54
Sub-Total	**1435**	**199**	**161**	**630**	**47**	**244**	**120**	**43**	**65**
Grand Total	**3712**	**603**	**757**	**893**	**84**	**942**	**1279**	**524**	**543**

were constructed. For this reason, the numbers of reservoirs added are shown in Table 1 while the corresponding reservoir areas are provided in Table S1.

Generally, reservoirs were built at locations with progressively less SAT (Table 1; hazard ratio associated with an increase in SAT of one standard deviation = 1.859, 95% QCI [1.439, 2.379]). In the CRCGA, until 1985, the majority of reservoirs were built on SAT between 60 to 100%. However, beginning in 1986, an increasing majority of reservoirs were built above portions of the aquifer with decreasing SAT such that by 2015, more than 55% of the reservoirs were built on SAT of less than 30%; nearly half of those built between 2001 and 2005, and 2011 and 2015 were built on SAT less than 20%. The first systems installed in areas with less than 10% SAT occurred in the CRCGA between 2011 and 2015 but occurred as early as 1996 to 2000 in the GPCGA. Because SAT continues to decline in both CGAs, these data suggest that construction will continue to occur in areas with less SAT. Zones with less than 30% SAT are particularly targeted, as shown in the GPCGA (Table 1). As such, studies focusing on areas with 30% SAT in the CRCGA should be conducted to assess the capacities of streams and ditches that will be expected to fill existing and future reservoirs.

4. Conclusions

Agricultural land managers in the Mississippi Alluvial Plain rely on the Mississippi River Valley Alluvial Aquifer for the majority of the water used for irrigation in the region. The heavy use of the aquifer and limited recharge in some areas have resulted in regional cones of depression which prompted the state to define critical groundwater areas, namely the Cache River and Grand Prairie Critical Groundwater Areas. In these areas, a key strategy to reduce groundwater decline was to shift irrigation sources from ground to surface water where feasible. This study demonstrated how existing, available imagery can be used to detect water features such as irrigation reservoirs. As these sources extend back farther in time, we were able to determine the approximate period of their establishment, the depth to groundwater at the construction location, and the prior land use back to 1976, extending previous work back 20 years. The timespans generated now include reservoirs established prior to 1976 along with those implemented in five-year increments from 1976 to 2015. A more complete view of the influences on reservoir construction is evident in both critical groundwater areas. Extending back to 1976 allows one to understand the response to expanding and deepening cones of depression in the Grand Prairie that began in Arkansas County and migrated north and west. In addition, we were able to identify a noteworthy increase in reservoir construction in Poinsett County, the center of the Cache River cone of depression, after the drought of 1980. Finally, a focus on areas with saturated aquifer thickness values of less than 30% should be targeted when planning new reservoir construction in both critical groundwater areas to better understand the capacity of streams and ditches that will be used to fill new and existing reservoirs. This additional historic information is now available for modelers to further refine groundwater-surface water models and should improve water resources scenarios that include reservoirs as a tool to reduce groundwater decline.

CRediT authorship contribution statement

Shults Daniel D.: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Reba Michele L.:** Writing – review & editing, Supervision. **Nowlin John:** Writing – review & editing, Methodology, Data curation. **Massey Joseph:** Writing – review & editing, Methodology, Formal analysis. **Read Quentin:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and code are available for download at Ag Data Commons (Read, Q.D, M.L. Reba, and D.D. Shults, Ag Data Commons, 2023). https://doi.org/10.15482/USDA.ADC/24659127.v1.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108678.

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