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Examining Patterns and Drivers of Spatial and Temporal Variability in Playa Hydroperiod in the High Plains Region of Western Kansas

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Examining patterns and drivers of spatial and temporal variability in playa hydroperiod in the High Plains region of western Kansas.

By

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Table of Contents

List of Tables

List of Figures

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ABSTRACT

Playa wetlands are some of the most important natural features of the High Plains of the central United States. Playas provide a range of ecosystem services such as groundwater recharge, surface water storage, and wetland habitat. However, playa functions are declining due to land cover change, climate change, and playa and watershed modifications. There are only a few studies that have examined the variability and controls on playa water storage. This project aims to determine how playa and watershed morphology, watershed land cover, and precipitation patterns affect timing and duration of water storage in 92 playas distributed throughout a 10-county region in western Kansas.

Playa and watershed morphology were calculated in a GIS environment and classified into quartiles based on playa surface area and watershed area. Watershed tilled index was determined using 2016, 2017, 2018, and 2019 Cropland Data Layers available from the National Agricultural Statistics Service and classified as either cropland (>75% cropland), grassland (>75% grassland), or mixed. Monthly precipitation data for 2016-2019 were compiled from the Oakley 22S High Plains Regional Climate Center weather station. Playa water status for 2016-2019 was classified monthly as dry/moist soil or standing water by visually examining 4-band satellite imagery with 3.7 m resolution and pre-defined image enhancements available from Planet Explorer (www.planet.com).

Playa water status is only moderately influenced by playa and watershed morphology and watershed land cover, with playas in the largest size class and cropland TI class having slightly greater standing water observations. However, standing water within playas is most strongly correlated with monthly precipitation. Playas in all size classes, TI classes, and counties have similar responses to precipitation patterns. Dry/moist observations increase during periods of drought, and standing water observations increase with wetter periods. Playas are critical resources for the High Plains, providing a range of ecosystem services dependent upon the playa's ability to store water. Playa functions are under continued threat from cropland expansion, climate change, and playa and watershed modifications. More research is required to understand better the spatial and temporal variability in playa water status driven by precipitation patterns.

Chapter 1. Introduction

Playas are small, depressional wetlands with internally drained watersheds. They are the dominant surficial hydrogeomorphic feature of the High Plains (Smith, 2003). They represent the most critical habitat for much of the High Plains, including Kansas (Fig. 1). Playas are located at the lowest point in closed watersheds (Haukos and Smith, 1994). Direct precipitation and runoff are the primary sources of water to these features (Haukos and Smith, 1994). Playas vary in size, ranging from <0.1 ha to >1,000 ha (Bowen et al., 2010; Smith, 2003). An estimated 66,000 playas are distributed throughout the southern Great Plains (Gurdak and Roe, 2009), and an estimated 22,000 playas are distributed throughout western Kansas (Bowen et al., 2010).

Playas are critical resources for the High Plains, providing several essential ecosystem services such as groundwater recharge, surface water storage, and wetland habitat (Smith et al., 2011). Playas represent ~95% of the overall recharge to the underlying Ogallala Aquifer (United States Department of Agriculture, 2006). The aquifer supports about 30% of the entire United States' irrigation system (Dennehy et al., 2002) and provides more than 70% of all water used in the state of Kansas (Buchanan et al., 2015). As a result of this intensive use, the Great Plains region has used approximately 30% of the available groundwater, and it is projected that another 39% will be depleted over the next 50 years given existing trends in crop demand (Steward et al., 2013). Groundwater recharge from playas is essential to reduce aquifer declines (Smith et al., 2011)

As a result of converting prairie ecosystems to row-crop agriculture, playas are the only source of surface water and natural habitat remaining to support biodiversity for large tracts of the High Plains (Smith et al., 2011). Despite their ecological importance, many playas have become severely impacted by landscape modifications. Agricultural activity in the Kansas High Plains region has become a significant threat to playa hydrology, with impacts including physical modifications and increased erosion from upland soils leading to excessive sediment deposition in playa basins (Bowen and Johnson, 2017; Smith, 2003). Accelerated sediment accumulation is one of the most detrimental factors affecting playa hydrology (Bowen and Johnson, 2019, 2017; Luo et al., 1999, 1997a; Smith, 2003; Tsai et al., 2007). Given the extent of land conversion from grassland to cropland on the High Plains, sediment input to playas has increased, resulting in significant loss of playa water storage volume. In Kansas, playas within cropland watersheds have lost about 30% of their original storage volume (Bowen and Johnson, 2017). Luo et al. (1997a) found that cropland watersheds contribute to excessive sediment delivery in runoff that far exceeds losses due to deflation. They found that on the Southern High Plains, sedimentation rates for playas in cropland are higher than any other wetland system, and result in 100% loss of the hydric soil storage volume. Additionally, water loss rates are higher in playas with cropland watersheds than playas with native grassland (Tsai et al., 2007).

Several programs are available in the High Plains to support playa conservation (Smith, 2003). The Conservation Reserve Program (CRP) is one of the most extensive conservation programs in the High Plains. On average, $97 million are distributed annually to participating landowners (U.S. Department of Agriculture Farm Service Agency, 2010). Since 1986, 12.9 million hectares of agricultural land have been enrolled nationally in CRP to protect highly erodible soil. The High Plains is one of the most intensively cultivated regions globally and has the highest density of property enrolled in CRP, occupying ~23% of local landscapes (Smith et al., 2011). The CRP land has a significant impact on playa hydrology, water budget, and runoff. Although CRP is effective at reducing sediment accumulation in playa basins (Bowen and Johnson, 2019; Smith, 2003), the dense non-native grass plantings associated with CRP inhibit water runoff into playas, reducing playa hydroperiod (Cariveau et al., 2011)

Climate change is also projected to impact playa water storage over the coming decades. Mean annual temperature has increased by ~2 ºC since 1901, and climate models project >4 ºC increase in the 21st century, with more intense and less frequent precipitation in the region (Romero-Lankao et al., 2014). Higher temperatures result in greater evaporation and surface water losses. The number of days with temperatures >37.7°C is expected to double in the Northern Plains by 2050 (Shafer et al., 2014). The Southern Plains are anticipated to experience more extreme heat, with four times the number of days >37.7°C (Shafer et al., 2014). Increasing temperatures without a significant change in precipitation will likely result in increased evaporation from playas and decreased hydroperiods; however, no study to date has examined trends in local weather data and playa hydroperiod. Given the dramatic changes in land cover and climate that will continue through this century, it is believed that playa hydroperiod has declined and will continue to decline due to accelerated sediment delivery and increased evapotranspiration rates.

There is abundant evidence that land use and erosion are two primary issues impacting playa functions (Bowen and Johnson, 2019, 2017; Burris and Skagen, 2013; Skagen et al., 2008; Tsai et al., 2007). Ecological alterations can occur as playas lose the ability to provide ecosystem services. It is essential to understand the rate of sediment accumulation and monitor water storage volumes to determine if these wetlands can continue to provide essential ecosystem services (Bowen, 2011; Bowen and Johnson, 2017). Research on the Southern High Plains has shown that accelerated sediment accumulation in playas reduced water depth and increased water surface area, which increased evaporation rates and decreased playa hydroperiod (Tsai et al., 2007).

This study aims to determine how playa and watershed morphology, watershed land cover, and precipitation patterns affect timing and duration of water storage in playas. The objectives are to 1) measure playa and watershed morphology for 92 playas on the High Plains of western Kansas; 2) calculate watershed land cover from 2016-2019 for each playa; and 3) track monthly variability in playa water status (i.e., dry/moist soils or standing water).

Chapter 2. Regional Settings

This project focuses on 92 playas distributed throughout ten counties in western Kansas (Finney, Gove, Greeley, Lane, Logan, Scott, Sherman, Thomas, Wallace, and Wichita counties) (Fig. 2; Table1). All research playas are within the High Plains physiographic province and Major Land Resource Area – Central High Tableland (Fig.3). The Central High Tablelands primarily consist of nearly level uplands with steep slopes into deeply incised river and stream valleys (United States Department of Agriculture, 2006). Rivers and streams within the study area include the Smoky Hill River and its tributaries in the central portion, as well as ephemeral/intermittent tributaries of the Solomon and Republican Rivers in the northern portion (Fig. 4). Playas and associated watersheds were selected to encompass a range of cropland and grassland (native and CRP) coverage (i.e., from 100% cropland to 100% grassland).

High Plains Physiography

The High Plains is the largest physiographic sub-province of the Great Plains and forms most of the region's western one-third (Hirmas and Mandel, 2017). The High Plains includes portions of Nebraska, Texas, Colorado, New Mexico, Kansas, and Oklahoma. The Kansas portion of the High Plains includes 30 counties in the western third of the state and contains about 22,000 playas

(Fig.3) (Bowen et al., 2010). Elevation within the High Plains rises from east to west, with the highest point in Kansas being 4,039 feet at Mount Sunflower in Wallace County (University of Kansas, 2020). The High Plains formed due to the buildup of eroded materials from the Rocky Mountains about 66 million years ago (University of Kansas, 2020). Large amounts of sediment, sand, gravel, silt, and other rock debris were eroded off the mountains and transported eastward, which filled stream valleys over time (University of Kansas, 2020).

Climate

Climate on the High Plains of western Kansas is semi-arid in the west and dry sub-humid to the east (Veregin, 2005). The region is also characterized by strong winds and high solar radiation absorbance (Hirmas and Mandel, 2017). Dodge City, Kansas, is the nearest city to the study area (112 km) that records wind speed. The annual average wind speed is 15.05 mph (24.2 km/h) (National Ocean and Atmospheric Administration, 2020).

Oakley 22S (precipitation) and Oakley 4W (temperature) weather stations, located near the center of the study area, had an average precipitation of 44.5 cm per year from 2016 to 2019, ranging from a low of 39.3 cm in 2016 to a high of 53.2 cm in 2017; ~70-90% of the precipitation was delivered from April to September in each year (High Plains Regional Climate Center, 2020). Mean annual temperature for the nearby Oakley 4W weather station from 2016-2019 averaged 10.21°C and ranged from a low of 10.12 °C in 2019 to a high of 11.87 °C in 2016;

January was the coldest month at -0.90 °C and July the hottest month at 25.12 °C. Thus, 2016 was the hottest and driest year, 2017 was the wettest and second hottest year, and 2019 was the second wettest and coolest year for the 2016-2019 study period (Table 2).

For the period of record (i.e., 1989-2019) at Oakley 22S, mean annual precipitation was 47.9 cm per year, and at Oakley 4W mean annual temperature was 11.8 °C for the same period (High Plains Regional Climate Center, 2020). Comparing the mean annual temperature and precipitation of the last 30 years and the 2016-2019 four-year study period shows that 2016 and 2018 were much drier than average, receiving 18% and 15% less, respectively, while 2019 was similar to the long-term average, and 2017 received ~11% more precipitation than average. Mean annual temperature varied by less than 2° C for the study period and was similar to the long-term average temperature, though 2016 and 2017 were slightly warmer and 2019 slightly cooler than average.

Wetland Ecosystem Services

Wetlands are some of the most valuable features of the landscape due to the ecosystem services they provide. However, these features are also highly susceptible to degradation. About 50% of the total wetlands in the United States have been either drained, filled, or altered in some form, endangering flora and fauna that depend on wetlands for survival and impairing wetland functions (Fretwell et al., 1996). Mitsch et al. (2015) identified several ecosystem services provided by wetlands through an analysis and summary of available literature. Ecosystem services commonly include food, water, timber, fiber, and genetic resources. Regulating ecosystem services, those that improve the surrounding environment, include air quality regulation, climate amelioration, water purification, disease and pest control, pollination, and flood and other natural hazards reduction. Cultural ecosystem services include benefits that people obtain from wetland, such as spiritual enrichment, recreation, ecotourism, aesthetics, formal and informal education, inspiration, and cultural heritage. Supporting ecosystem services include basic ecosystem processes of nutrient cycling and primary productivity. These ecosystems services, including those provided by High Plains playas, are critically important for people and the environment.

Playas are defined as shallow, depressional recharge wetlands, each existing in their own closed watershed or catchment (Smith, 2003). Playas receive water from precipitation and catchment runoff, and water loss is a product of evapotranspiration and infiltration. The hydrology of these depressional wetlands drives their functional characteristics and services (Smith et al., 2008). One of the primary services of playas is providing a point of recharge to the High Plains/Ogallala Aquifer (Smith, 2003), and playas provide greater recharge than the surrounding uplands (Gurdak and Roe, 2009). Playas also provide water quality improvement services by naturally filtering agricultural inputs such as fertilizers and pesticides from infiltrating water (Smith, 2003). Playas provide some of the only remaining natural habitat supporting biodiversity in the High Plains due to extensive landcover conversion to agriculture fields (Haukos and Smith, 1996). Playa value to biodiversity can be seen at the scale of an individual playa up to continental scale (Smith, 2003). Playas are the only aquatic habitat for vast expanses of the High Plains and a single playa can increase biodiversity by >300% compared to the same area of short-grass prairie without playas (Smith, 2003). Migratory birds depend on playas as a source of water and food, and rest areas along their migratory route; playas support millions of birds as they migrate to and from northern North America to Central and South America each year (Haukos and Smith, 1994). Consequently, this increases biodiversity at the continental to hemisphere scale. Additionally, playas store substantial amounts of organic matter, ranging from 200 to 20,000 kg/ha per playa, leading to carbon sequestration and mitigating the impacts of greenhouse gas emissions on climate change (Smith, 2003).

Groundwater and Surface Water Hydrology

The Ogallala Aquifer is a significant part of the High Plains Aquifer system and functions as a crucial groundwater source for irrigation and municipal use (Hirmas and Mandel, 2017). The High Plains Aquifer underlies ~450,000 km^2 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (McGuire, 2017) and ~90,000 km^2 of 46 counties in western and south-central Kansas. The Ogallala or High Plains Aquifer water level has been declining, particularly since the 1950s (Fig. 5).

McGuire (2017) analyzed groundwater levels from over 3,100 wells throughout the High Plains Aquifer region from predevelopment (i.e., 1950) to 2015. Results show that for the entire High Plains Aquifer, the area-weighted average decline has been ~4.8 m. The most significant decline was recorded in Texas at 12.5 m. At the same time, Kansas ranked second with a decline of 8 m. Overall, ~9% of groundwater storage has been lost in the High Plains Aquifer since predevelopment, and over 23%, or 73 km^3, was lost in Kansas.

The state of Kansas has 13 major river basins, with the Kansas and Arkansas basins being two of the largest (Fig. 5). The Smoky Hill-Saline basin is located within the ten-county study area. The Smoky Hill-Saline Basin is an elongated drainage area extending ~400 km from the Colorado border eastward to Junction City, Kansas, and flows into the Republican River. The Smoky Hill River has a drainage area of about 22,818 km^3. There is only one USGS stream gauge on the Smoky Hill River within the study area (United States Geological Survey, 2021). From 1940 to 2019, discharge has been highly variable, with a general decline in discharge since the 1960s (Fig. 6). Mean annual discharge was ~30 m^3/s, but it has not exceeded 7 m^3/s in the last 20 years.

Vegetation and Wildlife

Land cover of the High Plains is dominated by cropland and grassland. About 73% of the total land has been converted to agriculture or development, leaving only 27% of the natural landscape remaining in the Kansas High Plains.

Short-grass prairie species such as blue grama (*Bouteloua Gracilis*), buffalo grass (*Bouteloua Dactyloides*) are dominate. Other plant species include yucca (Y*ucca spp.*), prickly pear cactus (*Opuntia spp.*), and woody shrubs, including sagebrush (*Artemisia Tridentate*), which frequent areas of Colorado and Wyoming that are close to the Rocky Mountains into Kansas, Nebraska, and South Dakota (Hirmas and Mandel, 2017). Mixed-grass prairies dominated by big bluestem (*Andropogon Gerardi*), little bluestem (*Schizachyrium Scoparium*), blue grama (*Bouteloua Gracilis*), and sideoats grama (*Bouteloua Curtipendula*) are located along the eastern edge of the High Plains (Hirmas and Mandel, 2017). Plants frequently associated with playa wetlands include spike rushes (*Eleocharis Palustris*), toothcup (*Ammannia Coccinea*), umbrella sedge (*Fuirena Rottb.*), and western water clover *(Marsilea Vestita)* (Flowers, 1996).

Playas are the primary source of water for local and migratory biota. Haukos and Smith (1994) estimated at least 340 plants, 185 birds, 37 mammals, 13 amphibians, and 124 types of aquatic invertebrate species are associated with Great Plains playa ecosystems. Typical bird species found in Kansas are the Golden Eagle (*Aquila Chrysaetos*), Great Blue Heron (*Ardea Herodias*), Indigo Bunting (*Passerina Cyanea*) , American Avocet (*Recurvirostra Americana*), Mallard (*Anas Platyrhynchos*), Sandhill Crane (*Antigone Canadensis*), and Canada Geese (*Branta Canadensis*) (Haukos and Smith, 1994). Other wildlife that utilize playa wetlands include dragonflies, toads, turtles, rabbits, raccoons, coyotes, bats, and deer (Haukos and Smith, 1994).

Soils

Playa soils are commonly composed of Epiaquerts and Haplusterts in the Southern and Central High Plains and Argiaquolls and Argialbolls with Vertic subgroups in the Northern High Plains (Gurdak and Roe, 2009). Two soil series commonly found composing playa floors in the study area are Pleasant clay loam or silty clay loam and Ness clay (USDA, 2019) (Table 3). Playa soils are often not differentiated from surrounding upland soils in soil surveys, so playa soils are also mapped as Goshen, Keith, Kuma, and Ulysses silt loams. Organic carbon ranges from 0.5% to over 2% in the upper horizons due to the high decomposition rates from wetting and drying cycles (Hirmas and Mandel, 2017; Smith, 2003).

Ness and Pleasant soils are typically dominated by smectitic clays with high shrink-swell processes, resulting in slickensides and wedge structures (USDA Natural Resources Conservation Service, 2009). When dry, these smectitic clays have large cracks that allow rapid infiltration in the playa floor; when wet, cracks swell shut, infiltration is greatly reduced, and playas store water (Gurdak and Roe, 2009). Redox concentrations in the form of iron-manganese masses and concretions are also common in the upper soil horizons due to repeat cycles of saturation and drying (Hirmas and Mandel, 2017; USDA Natural Resources Conservation Service, 2009). Uplands surrounding playas commonly consist of seven soil series: Colby, Richfield, Ulysses, Harney, Buffalo Park, Manter, and Goshen (USDA, 2019) (Table 3). Uplands soils are silt-rich (Bowen and Johnson, 2012), with little to no smectite clays, so when they get transported to the playa, they fill the cracks and can greatly reduce infiltration.

Chapter 3. Methodology

This study included an initial population of 123 playas distributed throughout a 10-county region in western Kansas; 64 of these playas were included in an analysis of sediment accumulation within playas wetlands by Bowen and Johnson (2017). Of the initial 123 playas, outliers were excluded using the "1.5 times the interquartile range" rule (Hoaglin et al., 1986) based on playa or watershed morphometric variables. Of the 31 playa outliers that were removed from the study, 15 were removed based on playa area exceeding the 1.5 times the interquartile range rule (10 of these also had watersheds that exceeded the rule), and eight playas were removed because watershed area was too large. This resulted in the removal of 31 playas, for a total of 92 playas included in this study.

Weather Data Collection

Monthly total precipitation data were collected from the "Oakley 22S" High Plains Regional Climate Center (HPRCC) weather station (http://climod.unl.edu/) for the 2016 to 2019 study period. Monthly summarized data was obtained by selecting the variable "Precipitation" and "Sum" to obtain total precipitation for each month of the study period. Monthly precipitation for the entire period of record (1989-2020) was also obtained to compare precipitation trends during the study period to long-term precipitation patterns. Collected data were exported to an Excel worksheet to calculate monthly minimum, maximum, and mean precipitation for the study period and period of record; annual precipitation for each year of the study period; and mean annual precipitation for the study period and period of record. Initially, 13 weather stations distributed throughout the study area were examined (Fig. 1). Precipitation data for all weather stations were generally similar, so the Oakley 22S weather station was selected to represent the entire study area since it was located near the center of the study area, had continuous precipitation data for the past 30 years, and there were no missing data for the study period (Table 2).

Playa Hydrology

Playa water status was analyzed using color satellite imagery from Planet Explorer (www.planet.com) from 2016 to 2019. Planet Explorer collects imagery using three different types of satellites (PLANETSCOPE, RAPIDEYE, and SKYSAT). Approximately 130 satellites capture daily images of Earth's entire land surface with 3 to 5-meter resolution.

A shapefile containing the 92 playas was imported into Planet Explorer. The monthly mosaic display was then selected since it provides the best quality imagery that eliminates atmospheric disturbances and corrupted imagery. Navigation to each playa was performed manually to visually inspect the images with and without image enhancement (Fig. 7). Image enhancement is a color correction of three facets: brightness (the overall level of light in an image), contrast (the relative light levels of adjacent areas in an image), and color balancing (adjusting the overall hue of an image). Playa water status was classified as either:

“dry/moist soil” or “standing water”. Dry/moist soil on playas has a characteristic light or dark brown to dark gray surface color with diffuse boundaries. Standing water has a distinct, nearly black color with clear boundaries. Every observation classified as standing water was examined at least twice and reviewed with an expert to confirm classification.

Landcover

Watershed land cover for each playa was mapped using 2016 to 2019 Cropland Data Layers (CDL) available from the National Agricultural Statistics Service (https://nassgeodata.gmu.edu/CropScape/). Land cover was classified as either cropland or grassland. Cropland included all crop types (e.g., corn, winter wheat, sorghum, cotton, soybeans, sunflower, barley, rye, oats, canola, alfalfa, hay, peas) and fallow cropland. Grassland included perennial grassland, shrubland, barren, and pasture classes. Open water and wetland classes contained the playa themselves and were included within grassland. Forest/Deciduous classes, typically fence rows, small patches of trees, or misclassified grassland, were also included within grassland. No researched playa had development within the watershed other than one or two single-family homes, barns, and roads (primarily dirt roads), which were ignored because their impacts were considered minimal. Watershed tilled index (TI) was calculated for each playa's watershed for each year using the equation (Tsai et al., 2007):

Equation 1: $TI = (\text{cropland area} - \text{grassland area}) / (\text{cropland area} + \text{grassland area})$.

Based on watershed TI, playas were divided into three classes: grassland ($TI < -0.5$; i.e., watershed >75% grassland), cropland ($TI > 0.5$; i.e., watershed >75% cropland), and mixed ($-0.5 < TI < 0.5$; i.e., watershed >25% grassland and cropland).

Watershed and Playa Morphometry

Playa watersheds were delineated in ArcGIS by following drainage divides visible on 1:24,000 digital raster graphics (DRGs) and LiDAR-derived digital elevation models (DEMs) (Bowen and Johnson, 2017). Playa boundaries were delineated visually using National Agriculture Imagery Program (NAIP) imagery available from the State of Kansas GIS Data Access and Support Center (www.kansasgis.org), then adjusted to the hydric soil edge for sites in which soils data were available (Bowen et al., 2010; Bowen and Johnson, 2017).

Watershed and playa morphometry were calculated using multiple functions in ArcGIS 10.7. Playa and watershed area and perimeter were calculated using the "Calculate Geometry" tool. "Field Calculator" was used to determine the ratio of watershed area to playa area and playa and watershed circularity. Circularity was calculated using the formula (Bowen and Johnson, 2017):

Equation 2: $\text{Circularity} = 4 * \pi * (\text{Area} / \text{Perimeter}^2)$.

A circularity value closer to 1 indicates a more circular feature, and the lower the value, the more elongated it is (Bowen and Johnson, 2017). Playas were divided into quartile size classes based on 1) playa surface area and 2) watershed area.

Maximum slope and mean slope of watersheds were estimated using National Elevation Dataset DEMs and the "Spatial Analyst Extension." Maximum and mean slope were determined using the "Slope" function, which creates a raster file of the rate of change in elevation for each 10 m^2 grid cell. Maximum slope is the cell value with the highest rate of change in elevation, and mean slope is the average rate of change in elevation for all cells.

Statistical Analysis

Statistical analysis was conducted using SPSS (IBM® SPSS Statistics® Version 25) to assess the impacts of watershed and playa land cover and morphometry, and precipitation on temporal variability of water storage within playas. Bivariate correlation analysis was conducted to assess the degree of correlation between watershed and playa morphometric variables, land cover, precipitation, and playa water status.

One-way analyses of variance (ANOVA) were conducted to compare differences in watershed and playa morphometric variables, watershed TI, and playa water status by county, TI cover class cover (i.e., cropland, grassland, and mixed), playa size class (i.e., playa surface area by quartile), and watershed size class (i.e., watershed area by quartile). Tukey’s honest significant difference test was used to evaluate significant differences among classes. The statistical significance level for bivariate correlations and ANOVA was set at $P < 0.05$. Greeley and Wichita counties and Logan and Gove counties were combined due to the small number of playas in Greeley, Wichita, and Gove counties.

ANOVA assumes that data have a normal distribution; however, the test is robust enough that normality is not necessary if the sample size is sufficiently large (Blanca et al., 2017). Even though the dataset is large (i.e., 92 playas and 48 months of observations = 4,416 observations), all playa and watershed morphometric variables and playa water status observations were tested for normality using the Shapiro-Wilk test. It was determined that none of the variables are normally distributed. To ensure that non-normal distributions did not affect ANOVA results, playa area, watershed area, watershed slope, and two years of playa water status observations were normalized with log transformations. ANOVA was conducted on the original data and transformed data, and there were no differences in statistical outcomes. Thus, non-normal distributions did not impact ANOVA results, so for simplicity all analyses were conducted on the original data.

Chapter 4: Results

Playa and Watershed Morphology

Research sites represent a range of playa and watershed morphologies, though most playas and associated watersheds are relatively small (Table 4). Playa surface area ranges from 0.13 ha to 7.73 ha, with a mean of 2.40 ha and a median value of 1.94 ha. Watershed area ranges from 3.22 ha to 294.86 ha with mean and median values of 58.70 ha and 42.30 ha, respectively. Watershed maximum slope ranges from 0.58% to 10.39%, with a mean for all watersheds of 3.03%. Mean slope ranges from only 0.30% to 1.42%, with a mean for all watersheds of 0.68%. Thus, watersheds included in this study are generally small and nearly level. Playa circularity ranges from 0.57 to 0.97, with a mean of 0.86 and median value of 0.89. Watershed circularity ranges from 0.36 to 0.91, with a mean and median values of 0.66. This indicates that playas are generally very circular, and watersheds are moderately circular.

Playa and watershed morphology are correlated (Table 5). Playa area and perimeter ($r = 0.964$, $P < 0.001$) and watershed area and perimeter ($r = 0.942$, $P < 0.001$) are positively correlated, so perimeter is excluded from further analyses. Playa area is positively correlated with watershed area ($r = 0.624$, $P < 0.001$), so each variable’s impact on playa water status was examined independently. Playa area is also positively correlated with watershed maximum slope (r = 0.326, P <

0.001), which means that larger playas are located in larger and steeper watersheds. Watershed mean and maximum slope are positively correlated ($r = 0.660$, $P < 0.001$), indicating watersheds that are steeper on average also have areas with greater maximum slopes. Playa circularity is negatively correlated with watershed maximum slope ($r = -0.337$, $P < 0.001$) and mean slope ($r = -0.287$, $P = 0.006$), indicating that as watershed slope increases playas become less circular.

Playa and watershed morphology are generally similar among the three TI classes (Tables 4 and 6). Significant differences are only associated with playa circularity ($F(2, 89) = 3.165$; $P = 0.047$), watershed maximum slope ($F(2, 89) = 5.228$; $P = 0.007$), and watershed mean slope ($F(2, 89) = 10.059$; $P < 0.001$) (Table 6). Cropland playa circularity ranges from 0.57 to 0.97 with a mean of 0.88. Grassland playa circularity ranges from 0.58 to 0.97 with a mean of 0.84, and mixed playa circularity ranges from 0.60 to 0.97 with a mean of 0.80. Significant differences in playa circularity only occur between cropland and mixed watersheds, with playas in cropland watersheds being more circular. Cropland watershed maximum slope ranges from 0.58% to 7.68%, with a mean of 2.49%. Grassland maximum slope ranges from 0.82% to 10.39% and a mean of 3.79%. Maximum slope of mixed watershed ranges from 1.43% to 6.66%, with a mean of 3.79%. Cropland mean watershed slope ranges from 0.30% to 1.23%, with a mean of 0.59%. Grassland watershed mean slope ranges from 0.45% to 1.22% and has a mean of 0.78%. Mean slope of mixed watersheds ranges from 0.40% to 1.42%, with a mean of 0.84%. Differences in maximum slope are significant only between cropland and grassland sites, while differences in mean slope are significant between cropland sites and grassland sites and cropland sites and mixed sites. Thus, cropland playas have less steep watersheds, though differences in slope are relatively small among TI classes. TI class average circularity, watershed maximum slope, and watershed mean slope differ by only 0.08, 1.30%, and 0.25%, respectively, indicating playa and watershed morphology are generally similar among TI classes.

Although there are significant differences in most variables, playa and watershed morphology are generally similar among counties (Table 4 and 6). Playas in Finney County are significantly larger than playas in Logan/Gove and Wallace counties. Finney County playa area ranges from 1.82 ha to 7.73 ha with a mean of 4.50 ha. Logan/Gove playa area ranges from 0.23 ha to 4.98 ha with a mean of 1.64 ha, and Wallace playa area ranges from 0.15 ha to 5.69 ha and has a mean of 1.18 ha. Playas in Lane County are significantly larger than playas in all counties except Finney and Thomas counties. Lane County playas range from 3.40 ha to 7.00 ha with a mean of 5.13 ha, and Thomas playas range from 0.78 ha to 7.13 ha and have a mean of 3.16 ha.

Differences in playa circularity were between Gove/Logan and Wallace counties and Greeley/Wichita, Scott, and Sherman counties. Gove/Logan and Wallace counties have the most circular playas of all counties, with average circularity values of 0.92 and 0.93, respectively, and Greeley/Wichita, Scott, and

Sherman counties have the lowest circularity values at 0.77, 0.80, and 0.79, respectively.

Watersheds in Finney County are significantly larger than Gove/Logan watersheds, with averages of 114.60 ha and 33.29 ha, respectively; there are no other significant differences in watershed area by county. Finney County playas have the largest watersheds, while Gove/Logan County playas have the smallest watersheds. Watershed maximum slope is significantly different between Gove/Logan counties and Finney, Greeley/Wichita, and Sherman counties. Logan/Gove county watersheds have the lowest average maximum slope at 1.65%, while Finney (5.43%), Greeley/Wichita (3.93%), and Sherman (4.19%) counties have the three highest average maximum slopes. Watershed mean slope in Sherman County (0.93%) is significantly steeper than watersheds in Scott (0.61%), Lane (0.55%), and Logan/Gove (0.55%) counties.

Although there are differences in playa and watershed morphology are by county, they are relatively small. Thus, playas and watersheds are generally similar among counties. The county average playa area and circularity only differ by 4.12 ha and 0.16 ha, respectively. County average watershed area differs by 81.31 ha, and average maximum slope differs by only 3.78%, while mean slope differs by only 0.38%.

Watershed Land Cover

Of the 92 playas included in this study, 54 have cropland watersheds, 24 have grassland watersheds, and 14 have mixed watersheds. Watershed land cover was relatively constant for the four-year study period among all sites (Table 7). Mean watershed TI is 0.92 for cropland sites, -0.84 for grassland sites, and 0.01 for mixed sites. Of the 54 cropland sites, 32 have watersheds composed of 100% cropland, but only 7 of the 24 grassland sites have watersheds composed of 100% grassland. Differences in mean watershed TI by county are significant (F (7, 84) = 5.531, P < 0.001), but significant differences are limited to Gove/Logan County. All playas in Gove/Logan County are within the cropland cover class with watershed TI ranging from only 0.88 to 1.0 and a mean watershed TI of 0.99, while playas in other counties have a broader range of watershed TI. Thus, other than Gove/Logan County playas, counties have playas with similar watershed TI.

Precipitation

During the 2016-2019 study period, seasonal trends in precipitation were generally similar from year to year, with little to no precipitation during winter and maximum precipitation during late spring and summer, while total annual precipitation was variable during the four-year period (Table 2; Fig. 8). Annual precipitation was 39.3 cm in 2016, 53.2 cm in 2017, 40.6 cm in 2018, and 45.01cm in 2019, while mean annual precipitation for the last 30 years (1989-2019) was 47.9

cm. Three of the four years were drier than the long-term average, with 2016 receiving ~20% less than the long-term average and 2018 receiving ~15% less. Only 2017 exceeded the long-term average and received ~10% more than average. The study period represents a range of climatic conditions, with 2016 and 2018 much drier than average, 2019 precipitation similar to average, and 2017 much wetter than average.

Playa Water Status

During the study period (2016-2019), playas were dry in 87.8% of all observations and had standing water in 12.2% of observations (Table 9; Fig. 8). In 2016, average standing water observations were 2.3%, and only April (7.7%) and June (5.6%) were above the average. While 2017 had 14.5% standing water observations on average, May had 52.2%, June had 25.3%, July had 21.6%, August had 16.5%, and October had 25%, all above average; all other months had standing water observations below the yearly average. Standing water observations averaged 8.6% in 2018, in which June had 12%, July had 10.1%, August and September had 9.8%, October had 27.2%, and November 14.3%; all other months were below the 2018 average. The highest average of standing water observations occurred in 2019 at 23.5%. January had 35.5%, February had 38.9%, March had 70.7%, April had 23.3%, May had 53.3%, and June had 25.3% standing water observations; August, at 15.4%, was the only other month to exceed 7%. Thus, standing water observations were typically greatest during late spring and summer (i.e., May-August) with secondary peaks during fall (i.e., October-November) in some year; standing water observations were relatively low the rest of the year

Playa water status is not consistently significantly correlated with playa or watershed morphometric variables except playa and watershed area (Table 8). Playa area is significantly positively correlated with percent standing water observations in 2016 ($r = 0.227$; $P = 0.030$), 2017 ($r = 0.255$; $P = 0.014$), 2019 ($r = 0.513$; $P < 0.001$), and the four-year mean ($r = 0.452$; $P < 0.001$). Similarly, watershed area is significantly positively correlated with percent standing water observations in 2016 ($r = 0.227$; $P = 0.029$), 2017 ($r = 0.287$; $P = 0.006$), 2019 ($r = 0.327$; $P = 0.001$), and the four-year mean ($r = 0.385$; $P < 0.001$). Playa and watershed circularity were not significantly correlated to water observations for any year or the four-year mean. Lastly, watershed maximum slope ($r = 0.268$; $P =0.010$) and mean slope ($r = 0.300$; $P = 0.004$) were only correlated to percent standing water observations in 2016.

Playa Size Class

Seasonal and annual trends in playa water status are similar among playa size classes (Table 9; Fig. 9). Playas in the smallest size class had a four-year mean of 9.2% standing water observations, yet only 2016 and 2018 were below the average with 0.0% and 8.0% standing water observations (Table 9). For 2017 and 2019, the averages were 11.3% and 14.2% and were above the four-year mean. The next smaller size class (quartile 2) had a four-year mean of 9.6%, in which only 2016 and 2018 were below the average with 0.4% and 7.6% standing water observations. During 2017 and 2019, averages were 10.3% and 20.3% and were above the four-year mean. Quartile 3 had a four-year mean of 13.3%, in which only 2016 and 2018 were below the average with 4.1% and 7.3% standing water observations. For 2017 and 2019, the average was 14.8% and 27.0% and were above the four-year mean. Lastly, the largest size class (quartile 4) had a four-year mean of 16.7%, and 2016 and 2018 were also below average with 4.9% and 11.3% standing water observations, respectively. Similarly, in 2017 and 2019, the averages were 17.6% and 33.1% and were above the four-year mean.

Thus, for all playa size classes, 2016 and 2018 were below average for percent standing water observations, and 2017 and 2019 were above average. Differences in percent standing water by playa size class were significant in 2016 ($F(2, 89) = 3.525$; $P < 0.01$), 2019 ($F(2, 89) = 9.775$; $P < 0.01$) and the four-year mean ($F(2, 89) = 6.763$; $P < 0.01$) (Table 10). Significant differences are between the largest playa size class and the two smallest size classes.

Watershed Size Class

Watershed size class follows a similar pattern as playa size class (Table 9; Fig. 10). The smallest watershed size class had a four-year mean of 8.3%, yet

2016 and 2018 were below the average with 0% and 6.2% standing water observation. For 2017 and 2019, the averages were 11.9% and 14.9% and were above the four-year mean. The next larger size class (quartile 2) had a four-year mean of 11.4%, in which only 2016 and 2018 were below average with 3.2% and 6.7% standing water observations, respectively. During 2017 and 2019, the average was 12.3% and 23.2%, respectively, and both were above the four-year mean. Quartile 3 had a four-year mean of 10.7% standing water observations, in which 2016 and 2018 were below average at 1.1% and 9.1%, respectively. For 2017 and 2019, the averages were 11.5% and 21.2%, respectively, and were above the four-year mean. Lastly, the largest size class (quartile 4) had a four-year mean standing water observation of 18.3%, in which only 2016 and 2018 were below average at 4.8% and 12.0%, respectively. In 2017 and 2019, the averages were 21.9% and 34.3%, respectively, and were above the four-year mean.

As with playa size class, standing water observations for all playas, regardless of watershed size class, were below average in 2016 and 2018 and above average for 2017 and 2019. Differences in percent standing water by watershed size class were significant in 2017 (F (2, 89) = 3.663; P = 0.015), 2019 (F (2, 89) = 6.009; P <0.01) and the four-year mean (F (2, 89) = 6.763; P < 0.01) (Table 10). Significant differences occur between the largest watershed size class and the three other size classes.

Tilled Index Class

Trends in water status are similar among all TI classes for the study period, with few exceptions (Table 9; Fig. 11). In 2016, grassland playas had the greatest mean percent standing water observations at 3.3%, while cropland and mixed playas were 2.0% and 1.8%, respectively. In 2017, the wettest year, grassland playas had 15.4% standing water observations, cropland playas had 14.7%, and mixed playas had 11.3%. Cropland playas had 11.0% standing water observations in 2018, while grassland playas had only 5.2% and mixed playas had only 4.8%. The highest percentage of standing water observations was in 2019, with cropland playas having 25.4%, grassland playas having 23.0%, and mixed playas having 17.8%. Over the four-year period, cropland playas averaged the highest percent standing water observations at 13.3%, followed by grassland playas at 11.7%, and mixed playas at 8.9%. However, ANOVA results indicate no significant differences in percent standing water observations by TI class (Table 10).

County

Seasonal and annual trends in water status were generally similar among counties, though there were notable differences in geographic variability (Table 9; Fig. 12). Percent standing water was significantly different by county for only 2017 (F (2, 89) = 2.666; P = 0.015), 2019 (F (2, 89) = 6.648; P < 0.001) and the four-year mean (F (2, 89) = 2.800; P = 0.011) (Table 10). Playas in the southern half of the study area (Finney, Greeley/Wichita, Lane, and Scott counties) had a higher percentage of standing water observations and a lower percentage of dry/moist soil observations compared to playas in the northern half of the study area (Logan/Gove, Sherman, Thomas, and Wallace counties) (Fig. 12).

In 2016, percent standing water observations for playas in the study area's southern counties ranged from 0.9% to 7.3% by county and averaged 3.4%. Playas in the northern counties ranged from 0.4% to 5.2% by county and averaged 2.6%. In 2017, percent standing water observations for playas in the study area's southern counties ranged from 8.3% to 17.1% by county and averaged 3.4%. Playas in the northern counties standing water observations ranged from 5.8% to 23.8% by county and averaged 14.6%. In 2018, percent standing water observations for playas in the study area's southern counties ranged from 5.0% to 8.1% by county and averaged 6.2%. Playas in the northern counties ranged from 5.6% to 19.8% by county and averaged 10.7%. In 2019, percent standing water observations for playas in the study area's southern counties ranged from 14.4% to 44% by county and averaged 30.8%. Playas in the northern counties ranged from 9.3% to 26.7% by county and averaged 18.2%. Four-year mean percent standing water observations for playas in the study area's southern counties ranged from 7.5% to 17.5% by county and averaged 13.9%. In comparison, four-year mean percent standing water observations for playas in the north ranged from 6.1% to 18.3% by county and averaged 11.5%.

Precipitation and Standing Water Observations

Monthly average precipitation and percent standing water observations are significantly positively correlated regardless of playa size, watershed size class, and TI class (Table 10). All 92 sites, all four playa and watershed size classes, and all three TI classes have distinct peaks in monthly precipitation and percent standing water observations that coincide (Table 11; Figs. 8-12). Percent standing water observations are consistently low in 2016 and are highest in 2019. Standing water observations spiked in April 2016 after receiving 11cm of precipitation, in May 2017 after receiving 14.6 cm of precipitation, in October 2018 after receiving 14.6 cm of precipitation, and in May 2019 after receiving 14.6 cm of precipitation. These patterns were evident in all playa and watershed size classes and TI classes.

Although there are significant differences in percent standing water observations based on playa and watershed size class and county, observation differences are small, and there are no significant differences by TI class. Thus, percent standing water observations by playa size class, watershed size class, TI class, and county are generally similar. Average percent standing water observations by playa size class differ by only 4.9% in 2016, 7.3% in 2017, 4% in 2018, and 19.1% in 2019. Differences by watershed size class are 4.9% in 2016, 10.4% in 2017, 5.5% in 2018, and 19.4% in 2019. County averages differ by 6.9% in 2016, 18.4% in 2017, 14.8% in 2018, and 34.7% in 2019. TI class averages differ by 1.5% in 2016, 4.1% in 2017, 6.2% in 2018, and 7.9% in 2019.

Chapter 5: Discussion

Playa and Watershed Morphology and Playa Water Status

On average, larger playas and playas in larger watersheds store water more frequently. The primary sources of water to playas are runoff and direct precipitation (Smith, 2003). Larger watersheds have a greater land area to capture precipitation and contribute to runoff (Knighton, 2014), and larger playas have a greater capacity to store water. Playas in the two smallest size classes had the highest percentage of dry observations for all four years of the study period, while playas in the largest class had the highest percentage of standing water observations for all four years. Larger playas are more likely to become inundated, and the chance of inundation increases by 15% for every hectare increase in playa area (Cariveau et al., 2011).

The influence of playa and watershed size on hydroperiod is not clear based on previous studies. Tsai et al. (2007) examined the impact of playa size on hydroperiod and water loss rates for playas in the Southern High Plains. Their results show that playa area was not an important factor influencing hydroperiod or water loss rate. However, their study focused only on playas that were currently storing water during site selection and for a single season, lacking interpretation of the impacts of playa and watershed area on hydroperiod and water loss over a prolonged period. Johnson et al. (2011) evaluated and modeled several factors that influence playa inundation for playas on the Texas High Plains. Their results show that playa area was positively correlated with inundation. However, the most influential variables were watershed landcover (i.e., percent grassland) and precipitation patterns, indicating playa and watershed morphology are only subordinate factors influencing playa hydroperiod.

Results of the current research indicate that playa and watershed area exert a moderate influence on a playa's ability to sustain standing water. Other studies confirm that playa and watershed area are not the most important factors influencing playa water status (Johnson et al., 2011; Tsai et al., 2007). For this study, outliers were removed based on playa and watershed morphology. Thus, most "large" playas and watersheds were removed from the dataset, and this study focused on a relatively narrow range of playa and watershed sizes. If these much larger playas and watersheds had not been removed, the influence of playa and watershed area on playa water status may have been more dramatic.

Watershed Land Cover and Playa Water Status

Of the 92 playas included in this study, 54 were classified as cropland, 24 as grasslands, and 14 as mixed. Playas in the three TI classes were approximately equally distributed across the study area and range of playa and watershed sizes. Each county in the study area included playas in all three TI classes, except for Gove/Logan County, which only included playas in the cropland TI class.

Watershed land cover is not significantly correlated with playa water status for any of the four-year study periods (Table 10). From 2016 to 2019, standing water observations for all TI classes reflected the amount of precipitation received. This pattern was apparent at monthly, seasonal, and annual time scales, with standing water observations mimicking precipitation patterns for all TI classes.

Percent standing water observations are similar for the four-year study period for all TI classes. The only difference is the persistence of standing water observations in cropland-dominated watersheds from month to month, especially from the late fall of 2017 to the early summer of 2018. Through this period, standing water observations rapidly declined from month to month for playas in grassland and mixed watersheds but gradually declined for playas in cropland watersheds. During the four-year study period, playas in cropland watersheds had only seven months when there were no standing water observations. Playas in grassland watersheds experienced 17 months with no standing water observations, and playas in the mixed TI class had 27 months with no standing water observations. This pattern may be the result of increased runoff to the playa floor in cropland-dominated watersheds (Tsai et al., 2007). The current study only examined absence/presence of standing water in playas and did not examine the amount of water within playas. Playas in cropland watersheds may receive and store more water than grassland or mixed watersheds during equivalent rain events, allowing them to store water for longer periods.

Results of this study indicate that watershed landcover has only a minor influence on a playa's ability to receive and store water. However, previous research has indicated that watershed land cover is an important factor influencing playa water status. Johnson et al. (2011) evaluated and modeled factors influencing playa inundation for playas on the Texas High Plains and found that watershed landcover (i.e., percent grassland) was a major factor influencing playa hydroperiod. Tsai et al. (2007) monitored the water levels on 33 playas in the southern High Plains during the growing season to examine the influence of land use and playa characteristics on water loss rate and hydroperiod. Their results show that vegetation and soil texture were important factors in water loss rates, and land use was an important factor in playa hydroperiod. However, their research was limited to one season, limiting the temporal effects of landcover on playa hydroperiod. Gray and Smith (2005) noted longer hydroperiods in grassland playas than cropland playas in the southern High Plains. However, their study suggests that landcover plays a minor role in influencing playa hydrology.

Cariveau et al. (2010) studied the effects of landcover on the response of playas in southwestern Nebraska to rain events. Their results show that playas surrounded by rangeland and cropland are more likely to become inundated than playas in watersheds with considerable areas with Conservation Reserve Program (CRP). This program often uses taller and denser grasses than native grasses. In this study, it was not possible to differentiate native grassland from

CRP grassland to investigate non-native grass influence on playa hydrology. Further research is necessary to confirm that playas in cropland watersheds receive and store more water and to examine the influence of native and CRP grasses on playa water status.

Precipitation Patterns and Playa Water Status

Playa water status generally responds to seasonal precipitation patterns, regardless of playa and watershed size class and TI class. Total annual precipitation deviated considerably each year from 2016 to 2019 and from the long-term average annual precipitation for 2016, 2017, and 2018. Overall, percent standing water observations were higher in late spring to early summer and late fall for all playas regardless of playa and watershed size class and TI class, which corresponded to precipitation peaks. Significant snowfall was only observed in 2019 and contributed to early-season water storage within playas and much higher percent standing water observations for the year.

There were a few differences between the playa and watershed size classes and TI classes. The largest playa size class had the greatest increase and most gradual decline of standing water observations month to month for the four-year study period, likely the result of larger playas being able to store more water (Cariveau et al., 2011), but as previously stated, playa area is not a primary factor influencing playa hydrology (Johnson et al., 2011; Tsai et al., 2007). Another difference is the persistence of standing water observations in cropland playas, especially from the late fall of 2017 to the early summer of 2018, when percent standing water observations in cropland playas declined gradually but declined rapidly for grassland and mixed playas, which is likely the result of increased runoff to the playa floor in cropland-dominated watersheds (Tsai et al., 2007).

Russell et al. (2020) studied the effects of hydrologic alterations in playas and their response to droughts in the Great Basin, USA. Their results show that the likelihood and duration of playas being inundated increases or decreases depending on seasonal weather patterns (dry or wet seasons). Their results support my findings that precipitation patterns are the most influential factor on playa hydrology.

Summary

The ability of playa wetlands to store water depends on multiple factors, including playa and watershed morphology, watershed land cover, and precipitation patterns. Results show that playa and watershed morphology exert a moderate influence on playa water status. However, this study and previous studies indicate that playa and watershed morphology are not the most important factors affecting playa hydrology (Johnson et al., 2011; Tsai et al., 2007). Impacts of watershed TI class on playa water status are minimal, with cropland playas retaining water for slightly longer periods than grassland and mixed playas. This may be due to increased runoff to the playa floor in cropland-dominated watersheds or due to differences in evapotranspiration rates (Tsai et al., 2007). Data indicate seasonal precipitation patterns are the most influential factor affecting playa water status.

Chapter 6: Conclusion

Playa wetlands are complex ecosystems, and their ability to store water depends on a host of factors, including playa and watershed morphology, watershed land cover, and precipitation patterns. Playa and watershed area are positively correlated, showing that as playa area increases, watershed area and the ability to store water increases. Larger playas in larger and steeper watersheds can capture more runoff, allowing them to store more water for longer periods than smaller playas with smaller watersheds. However, playa and watershed morphometry had only a moderate impact on playa water status in this study. Playas in cropland watersheds stored water more frequently and for slightly longer durations than playas with grassland and mixed watersheds, though differences in water status among TI classes are not significant. Thus, playa and watershed morphology and watershed land cover are not primary factors influencing playa hydroperiod.

Precipitation patterns and regional climate have the greatest influence on playa water status. Monthly precipitation has a clear relationship with standing water observations within playas, regardless of playa and watershed morphology and watershed land cover. Standing water observations follow the general precipitation trend in which peaks in precipitation result in peaks in standing water observations in a given month, with no clear threshold precipitation amount required to increase standing water observations. Percent dry/moist soil observations follow a similar pattern, with dry periods corresponding to decreases in standing water observations regardless of playa and watershed morphology and watershed land cover. These observations highlight the importance of regional climate and precipitation patterns and trends on playa hydroperiod, as has been observed in playa hydrology studies in the High Plains and Great Basin (Cariveau et al., 2011; Johnson et al., 2011; Russell et al., 2020).

More research is required to understand better the spatial and temporal variability in playa water status driven by precipitation patterns. This project initially included 123 playas, but the population was reduced to 92 by excluding outliers based on playa and watershed morphometric variables (i.e., area, circularity, and slope). The exclusion of large playas and watersheds may have led to a lack of significant difference among size classes. Additionally, research playas were not equally distributed among TI classes, with playas in cropland watersheds comprising nearly 60% of all sites, ~25% with grassland watersheds, and ~15% with mixed watersheds.

Playa water status was only classified qualitatively (i.e., absence/presence of standing water), which limited the ability to assess the influence of watershed landcover on playa water status. Quantifying the playa area inundated rather than determining absence/presence of water could reveal whether or not cropland playas receive more runoff than grassland playas for equivalent precipitation events, allowing them to store water for longer periods. Additionally, in this study we were not able to differentiate between native grassland and CRP grassland. This could be an important factor influencing playa hydrology since it is well known that CRP grasses reduce the amount of runoff that reaches the playa floor compared to native grasses (Cariveau et al., 2011). A more robust dataset, with a more equally distributed TI class, as well including quantification of water status and including very large playas and watersheds, could provide a better understanding of spatial and temporal variability of playa water status and the relative influence of the timing and duration of precipitation patterns.

The primary limitation of expanding this research to examine a longer time period is the lack of high temporal resolution data before 2016. Another limitation of the data is the inability to distinguish between playas that are completely dry and playas with moist soils, especially in smaller playas. This project initially aimed to include three water status classifications (i.e., standing water, moist playa floors, or completely dry). However, due to inconsistently being able to differentiate dry soils and moist soils, it was decided to combine both groups to limit classification errors.

Weather patterns are predicted to change dramatically over the next several decades to century due to anthropogenic climate change. Increased frequency of high-intensity storm events is likely to concentrate more precipitation in shorter periods, which could result in playas storing water more frequently but for shorter durations (Easterling et al., 2017; Shafer et al., 2014). Concentrating major precipitation events in fewer days can be problematic since increased runoff leads to accelerated sediment accumulation within playas, especially cropland playas (Bowen and Johnson, 2017; Luo et al., 1997a). Consequently, increased sediment accumulation decreases playa water storage volume, and combined with predicted temperature increases and shifts in precipitation patterns (Shafer et al., 2014), could result in significant declines in playa water storage.

Playas are critical resources for the High Plains, providing a range of ecosystem services such as surface water storage, groundwater recharge, and wetland habitat that depend on a playa's ability to store water for prolonged periods. Playa functions are declining due to landcover change, climate change, and playa and watershed modifications (Tsai et al., 2007). Playas must continue to receive and store adequate amounts of surface water to maintain biodiversity and provide groundwater recharge. Playas in Kansas are one the most critical ecosystems in the state's landscape. It is essential to increase efforts to protect, improve and preserve these complex ecosystems to sustain playa hydrology and critical ecosystem services.

Conservation practices from multiple programs have been implemented on sites across the High Plains. Programs include the Environmental Quality Incentives Program (EQIP), Wildlife Habitat Incentives Program (WHIP), Wetlands Reserve Program (WRP), and Conservation Reserve Program (CRP) (Smith et al., 2011). These voluntary programs support playas' conservation by providing incentives to farmers or landowners to reduce contamination from agricultural sources. It promotes efficient utilization of nutrients and increases soil health to help mitigate against increasing weather volatility and prevent soil erosion. As well, increasing habitat for the local and migratory wildlife.

References Cited

Blanca, M.J., Alarcón, R., Arnau, J., Bono, R. and Bendayan, R., 2017. Non-normal data: Is ANOVA still a valid option?. Psicothema, 29(4), pp.552-557.

Bowen, M.W., 2011. Spatial distribution and geomorphic evolution of playa-lunette systems on the central High Plains of Kansas (Ph.D.). University of Kansas.

Bowen, M.W., Johnson, W.C., 2019. Sediment accumulation and sedimentation rates in playas on the High Plains of western Kansas, USA. Geomorphology 342, 117–126. https://doi.org/10.1016/j.geomorph.2019.06.014

Bowen, M.W., Johnson, W.C., 2017. Anthropogenically accelerated sediment accumulation within playa wetlands as a result of land cover change on the High Plains of the central United States. Geomorphology 294, 135–145. https://doi.org/10.1016/j.geomorph.2017.02.017

Bowen, M.W., Johnson, W.C., Egbert, S.L., Klopfenstein, S.T., 2010. A GIS-based Approach to Identify and Map Playa Wetlands on the High Plains, Kansas, USA. Wetlands 30, 675–684. https://doi.org/10.1007/s13157-010-0077-z

Buchanan, R., Wilson, B., Buddemeier, R., Butler, J., 2015. The High Plains Aquifer. Kansas Geological Survey, Public Information Circular 18.

Burris, L., Skagen, S.K., 2013. Modeling sediment accumulation in North American playa wetlands in response to climate change, 1940–2100. Climatic Change 117, 69–83.

Cariveau, A.B., Pavlacky, D.C., Bishop, A.A., LaGrange, T.G., 2011. Effects of Surrounding Land use on Playa Inundation following Intense Rainfall. Wetlands 31, 65–73. https://doi.org/10.1007/s13157-010-0129-4

Dennehy, K.F., Litke, D.W., McMahon, P.B., 2002. The High Plains Aquifer, USA: Groundwater development and sustainability. Geological Society, London, Special Publications 193, 99–119.

Easterling, D.R., Kunkel, K., Arnold, J., Knutson, T., LeGrande, A., Leung, L.R., Vose, R., Waliser, D., Wehner, M., 2017. Precipitation change in the

United States, in: Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC, USA, pp. 207–230.

Flowers, T.L., 1996. Classification and Occurrence of the Birds of the Playa Lakes of Meade County, Kansas. Kansas Ornithological Society Bulletin 47, 21–28.

Fretwell, J.D., Williams, J.S., Redman, P.J., 1996. National Water Summary on Wetland Resources. U.S. Department of the Interior, Geological Survey, Washington, DC, USA.

Gray, M.J., Smith, L.M., 2005. Influence of Land Use on Postmetamorphic Body Size of Playa Lake Amphibians. Journal of Wildlife Management 69, 515–524. https://doi.org/10.2193/0022-541X(2005)069[0515:IOLUOP]2.0.CO;2

Gurdak, J.J., Roe, C.D., 2009. Recharge rates and chemistry beneath playas of the High Plains Aquifer - A literature review and synthesis. U.S. Department of the Interior, Geological Survey, Reston, VA, USA.

Haukos, D.A., Smith, L.M., 1996. Effects of Moist-Soil Management on Playa Wetland Soils. Wetlands 16, 143–149.

Haukos, D.A., Smith, L.M., 1994. The Importance of Playa Wetlands to Biodiversity of the Southern High Plains. Landscape and Urban Planning 28, 83–98.

High Plains Regional Climate Center, 2020. High Plains Regional Climate Center. [Online] [WWW Document]. URL http://www.hprcc.unl.edu (accessed 11.2.20).

Hirmas, D.R., Mandel, R.D., 2017. Soils of the Great Plains, in: West. The Soils of the USA. 131–163. https://doi.org/10.1007/978-3-319-41870-4_8

Hoaglin, D.C., Iglewicz, B., Tukey, J.W., 1986. Performance of Some Resistant Rules for Outlier Labeling. Journal of the American Statistical Association 81, 991–999. https://doi.org/10.1080/01621459.1986.10478363

Johnson, W.P., Rice, M.B., Haukos, D.A., Thorpe, P.P., 2011. Factors Influencing the Occurrence of Inundated Playa Wetlands During Winter on the Texas High Plains. Wetlands 31, 1287–1296. https://doi.org/10.1007/s13157-011-0243-y

Knighton, D., 2014. Fluvial forms and processes: a new perspective. Routledge.

Luo, H.-R., Smith, L.M., Allen, B.L., Haukos, D.A., 1997a. Effects of Sedimentation on Playa Wetland Volume. Ecological Applications 7, 247–252.

Luo, H.-R., Smith, L.M., Haukos, D.A., Allen, B.L., 1999. Sources of Recently Deposited Sediments in Playa Wetlands. Wetlands 19, 176–181.

McGuire, V.L., 2017. Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2015 and 2013–15 (Scientific Investigations Report No. 2017–5040), Scientific Investigations Report. Geological Survey Scientific Investigations Report.

Mitsch, W.J., Bernal, B., Hernandez, M.E., 2015. Ecosystem services of wetlands. International Journal of Biodiversity Science, Ecosystem Services & Management 11, 1–4. https://doi.org/10.1080/21513732.2015.1006250

National Ocean and Atmospheric Administration, 2020. Average Wind Speed by Month. Live Monitoring [Online] [WWW Document]. URL https://www.weather.gov/ddc/avewind (accessed 3.2.20).

Romero-Lankao, P., Gurney, K.R., Seto, K.C., Chester, M., Duren, R.M., Hughes, S., Hutyra, L.R., Marcotullio, P., Baker, L., Grimm, N.B., Kennedy, C., Larson, E., Pincetl, S., Runfola, D., Sanchez, L., Shrestha, G., Feddema, J., Sarzynski, A., Sperling, J., Stokes, E., 2014. A critical knowledge pathway to low-carbon, sustainable futures: Integrated understanding of urbanization, urban areas, and carbon. Earth’s Future 2, 515–532. https://doi.org/10.1002/2014EF000258

Russell, M.T., Cartwright, J.M., Collins, G.H., Long, R.A., Eitel, J.H., 2020. Legacy Effects of Hydrologic Alteration in Playa Wetland Responses to Droughts. Wetlands 40, 2011–2024. https://doi.org/10.1007/s13157-020-01334-0

Shafer, M., Ojima, D., Antle, J.M., Kluck, D., McPherson, R.A., Petersen, S., Scanlon, B., Sherman, K., 2014. Ch. 19: Great Plains. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. https://doi.org/10.7930/J0D798BC

Skagen, S.K., Melcher, C.P., Haukos, D.A., 2008. Reducing sedimentation of depressional wetlands in agricultural landscapes. Wetlands 28, 594–604.

Smith, L.M., 2003. Playas of the Great Plains. University of Texas Press, Austin, TX, USA.

Smith, L.M., Euliss, N.H., Wilcox, D.A., Brinson, M.M., 2008. Application of a geomorphic and temporal perspective to wetland management in North America. Wetlands 28, 563–577.

Smith, L.M., Haukos, D.A., McMurry, S.T., LaGrange, T., Willis, D., 2011. Ecosystem services provided by playas in the High Plains: potential influences of USDA conservation programs. Ecological Applications 21, 82–92.

Steward, D.R., Bruss, P.J., Yang, X., Staggenborg, S.A., Welch, S.M., Apley, M.D., 2013. Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. Proceedings of the National Academy of Sciences 110, E3477–E3486. https://doi.org/10.1073/pnas.1220351110

Tsai, J.-S., Venne, L.S., McMurry, S.T., Smith, L.M., 2007. Influences of land use and wetland characteristics on water loss rates and hydroperiods of playas in the Southern High Plains, USA. Wetlands 27, 683–692.

United States Department of Agriculture, 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin, in: Natural Resources Conservation Service. p. 296.

University of Kansas, 2020. High Plains-GeoKansas. URL http://geokansas.ku.edu/high-plains (accessed 1.15.20).

Evans, C.J., 2010. Playas in Kansas and the High Plains. Kansas Geological Survey.URL http://www.kgs.ku.edu/Publications/PIC/PIC30.pdf (accessed 4.6.21).

U.S. Department of Agriculture Farm Service Agency, 2010. The Conservation Reserve Program: 39th signup results. URL https://www.fsa.usda.gov/Internet/FSA_File/su39book.pdf (accessed 2.7.20).

USDA, 2019. Soil map survey. URL https://www.nrcs.usda.gov/wps/portal/nrcs/site/soils/home/ (accessed 5.5.20).

USDA Natural Resources Conservation Service, 2009. Soil Survey Geographic (SSURGO) Database Description - NRCS Soils [Online] [WWW Document]. URL http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627 (accessed 7.9.20).

United States Geological Survey, 2021. National Water Information System: Web Interface. URL https://waterdata.usgs.gov/usa/nwis/uv?site_no=06877600 (accessed 4.6.20).

Veregin, H., 2005. Goode's World Atlas, 21st Edition, 21st ed. Rand McNally, USA.

Tables and Figures

Table 1. Distribution of playas in the ten-county study region of western Kansas (n=92).

County	Playa ID
Finney (n= 7)	FI-B3, FI-B4, FI-C1, FI-C4, FI-G2, FI-G3, FI-G4
Greeley (n= 4)	GL-B2, GL-B3, GL-11, GL-12
Wichita (n= 4)	WH-B1, WH-B2, WH-B3, WH-B5
Lane (n= 7)	LE-C2old, LE-C3, LE-G2, LE-C1, LE-C2, LE-C4, LE-B3
Gove (n= 2)	GO-11, GO-12
Logan (n= 20)	LG-11, LG-12, LG-13, LG-14, LG-15, LG-16, LG-17, LG-18, LG-19, LG-20, LG-21, LG-22, LG-23, LG-24, LG-25, LG-26, LG-27, LG-28
Scott (n= 16)	SC-B2, SC-B3, SC-B4, SC-B5, SC-B6, SC-B7, SC-B8, SC-C1, SC-C2, SC-C3, SC-C4, SC-C5, SC-G1, SC-G2, SC-G3, SC-G4
Sherman (n= 9)	SH-11, SH-12, SH-13, SH-16, SH-18, SH-19, SH-21, SH-23
Thomas (n= 8)	TH-12, TH-13, TH-14, TH-16, TH-18, TH-19, TH-21, TH-23
Wallace (n= 17)	WA-11, WA-12, WA-13, WA-14, WA-15, WA-16, WA-17, WA-18, WA-19, WA-20, WA-21, WA-22, WA-23, WA-24, WA-25, WA-26, WA-31

Table 2. Oakley 22S precipitation and Oakley 4W temperature data for 2016-2019.

Year		**Month**											
		Jan	**Feb**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2016	Precip (cm)	0.01	0.42	0.66	5.16	1.89	1.59	4.11	1.46	1.97	0.1	0.09	0.23
	Temp (C)	-0.67	2.67	7.28	10.44	14.17	23.67	25.17	22.61	19.83	14.00	7.11	-3.83
2017	Precip (cm)	0.92	0.09	2.06	3.32	7.57	3.63	2.67	2.9	3.98	3.01	0.13	0.02
	Temp (C)	-2.06	3.89	7.33	10.78	14.06	22.44	25.17	21.39	18.89	11.78	5.78	-1.83
2018	Precip (cm)	0.43	0.27	0.33	0.84	3.82	3.34	2.11	2.91	1.2	2.97	0.6	1.25
	Temp (C)	-1.94	-2.67	5.28	6.89	18.56	24.06	24.61	22.11	19.78	9.17	2.11	-0.50
2019	Precip (cm)	0.4	0.86	1.88	0.32	6.63	2.38	1.34	5.91	1.9	0.4	0.32	0.51
	Temp (C)	-1.78	-7.50	-0.06	9.83	15.17	21.33	25.56	24.11	22.72	8.50	2.61	1.00

Table 3. Soil series mapped in research playas and the surrounding uplands in western Kansas (USDA Natural Resources Conservation Service, 2009).

Soil Series	Texture	Taxonomic Class	USDA Official Soil Series Description
Keith	Silty loam	Fine-silty, mixed, superactive, mesic Aridic Argiustoll	Very deep, well-drained soils that formed in calcareous loess. Keith soils are on upland hillslopes, tableland plains, and valley terraces. Slopes range from 0 to 6 percent.
Pleasant	Loam	Fine, smectitic, mesic Torrertic Argiustolls	Deep, well to moderately well drained soils formed in thick, noncalcareous, silty to clayey materials derived as local alluvium from eolian deposits, silty sedimentary rocks, or adjacent soils. These soils are on drains, depressions on uplands and fans, and outwash sediments. Slopes are about 0 to 6 percent.
Ness	Silty clay	Fine, smectitic, mesic Ustic Epiaquerts	Deep poorly drained soils that formed in clayey alluvium and eolian sediments. These nearly level soils are in depressions on uplands or valley floors. Slopes range from 0 to 1 percent.
Colby	Silt Loam	Fine-silty, mixed, superactive, calcareous, mesic Aridic Ustorthents	Very deep, well-drained, and somewhat excessively drained, moderately permeable soils that formed in loess. These soils are on plains and hillslopes on tableland in the Central High. Slopes range from 0 to 60 percent.

Table 3 continued.

Soil Series	Texture	Taxonomic Class	USDA Official Soil Series Description
Richfield	Silt Loam	Fine, smectitic, mesic Aridic Argiustolls	Very deep, well-drained soils that formed in calcareous loess. Richfield soils are on tableland plains. Slopes range from 0 to 6 percent.
Ulysses	Silt loam	Fine-silty, mixed, superactive, mesic Torriorthentic Haplustolls	Very deep, well-drained soils that formed in loess. These soils are on plains, rises, and hillslopes on tableland in the Central High. Slopes range from 0 to 20 percent.
Harney	Silt loam	Fine, smectitic, mesic Typic Argiustolls	Deep, well-drained, moderately slowly permeable soils that formed in loess. These soils are on uplands on slopes that range from 0 to 8 percent.
Manter	Sandy loam	Coarse-loamy, mixed, superactive, mesic Aridic Argiustolls	Deep, well to somewhat excessively drained soils formed in thick, calcareous, eolian, or outwash material. Manter soils are on hills and plains. Slopes are 0 to 30 percent.
Goshen	Loam	Fine-silty, mixed, superactive, mesic Pachic Argiustolls	Very deep, well-drained soils that formed in silty alluvium derived mainly from loess. These soils are in swales and narrow drainage ways of uplands and have slopes ranging from 0 to 3 percent.

Table 4. Summary of playa and watershed morphometric variables for all 92 research playas, by playa size class, watershed size class, tilled index class, and county.

		Playa Area (ha)	**Playa Perimeter (m)**	**Playa Circularity**	**Watershed Area (ha)**	**Watershed Perimeter (m)**	**Watershed Circularity**	**Watershed Max Slope (%)**	**Watershed Mean Slope (%)**
All sites (n=92)	Min	0.13	131.18	0.57	3.22	1053.19	0.36	0.58	0.30
	Max	7.73	1134.29	0.97	294.86	7575.67	0.91	10.39	1.42
	Mean	2.40	553.42	0.86	58.70	3145.61	0.66	3.03	0.68
	Median	1.94	531.35	0.89	42.30	2940.88	0.66	2.28	0.63
Playa Size Class									
Quartile 1 (n=23)	Min	0.13	131.18	0.62	3.22	1053.19	0.37	0.58	0.32
	Max	0.87	347.11	0.97	70.54	4462.29	0.85	4.72	1.42
	Mean	0.51	261.17	0.91	25.76	2153.44	0.66	1.76	0.62
	Median	0.51	260.56	0.94	17.16	1664.41	0.67	1.53	0.59
Quartile 2 (n=23)	Min	0.92	353.15	0.60	7.50	1078.19	0.36	0.70	0.39
	Max	1.87	526.30	0.97	89.66	5129.18	0.91	9.47	0.97
	Mean	1.35	442.85	0.86	33.03	2493.99	0.65	3.01	0.67
	Median	1.33	448.34	0.87	28.42	2364.71	0.62	2.02	0.67
Quartile 3 (n=23)	Min	2.01	536.40	0.57	11.43	1568.86	0.36	1.21	0.33
	Max	3.45	795.48	0.97	141.14	5681.79	0.88	7.68	1.31
	Mean	2.60	631.21	0.83	62.33	3411.87	0.65	3.30	0.73
	Median	2.56	618.73	0.88	58.21	3422.37	0.64	3.08	0.70
Quartile 4 (n=23)	Min	3.52	744.60	0.62	32.89	2276.05	0.51	1.49	0.30
	Max	7.73	1134.29	0.96	294.86	7575.67	0.83	10.39	1.27
	Mean	5.19	886.38	0.83	114.00	4537.93	0.67	4.09	0.70
	Median	4.98	898.18	0.84	108.78	4492.01	0.67	3.15	0.61

Table 4 continued.

		Playa Area (ha)	**Playa Perimeter (m)**	**Playa Circularity**	**Watershed Area (ha)**	**Watershed Perimeter (m)**	**Watershed Circularity**	**Watershed Max Slope (%)**	**Watershed Mean Slope (%)**
Watershed Size Class									
Quartile 1 (n=23)	Min	0.13	131.18	0.62	3.22	1053.19	0.36	0.82	0.40
	Max	2.44	566.93	0.97	20.90	2346.13	0.91	6.12	1.42
	Mean	0.96	346.07	0.88	12.89	1515.00	0.70	2.06	0.65
	Median	0.82	340.23	0.93	11.89	1504.90	0.75	1.77	0.63
Quartile 2 (n=23)	Min	0.23	174.77	0.60	20.99	1824.68	0.38	0.58	0.32
	Max	7.00	1067.37	0.97	42.23	3648.90	0.91	6.66	1.04
	Mean	2.01	503.76	0.87	30.93	2507.49	0.64	2.54	0.63
	Median	1.55	483.69	0.92	30.61	2470.83	0.61	1.91	0.63
Quartile 3 (n=23)	Min	0.23	174.77	0.57	20.99	1824.68	0.36	0.58	0.32
	Max	7.73	1067.37	0.97	76.27	4881.75	0.91	6.66	1.31
	Mean	2.54	577.48	0.84	52.76	3239.75	0.66	3.16	0.71
	Median	2.08	561.54	0.87	52.73	3184.53	0.64	2.74	0.65
Quartile 4 (n=23)	Min	1.09	400.45	0.70	79.63	3703.92	0.42	1.29	0.30
	Max	7.13	1134.29	0.95	294.86	7575.67	0.85	10.39	1.23
	Mean	4.28	790.28	0.84	132.03	5125.28	0.64	4.21	0.69
	Median	4.46	786.44	0.85	119.23	5107.88	0.65	3.21	0.61
Tilled Index Class									
Cropland (n=54)	Min	0.13	131.18	0.57	3.22	1053.19	0.37	0.58	0.30
	Max	7.13	1134.29	0.97	161.82	6293.90	0.91	7.68	1.23
	Mean	2.49	558.65	0.88	61.87	3277.00	0.64	2.49	0.59
	Median	2.15	540.37	0.91	44.54	3048.77	0.63	2.01	0.54
Grassland (n=24)	Min	0.15	137.40	0.58	7.50	1077.37	0.36	0.82	0.45
	Max	6.72	987.91	0.97	294.86	7575.67	0.88	10.39	1.22
	Mean	2.02	506.76	0.84	51.10	2820.00	0.68	3.79	0.78
	Median	1.32	440.45	0.86	30.48	2204.23	0.69	3.11	0.74
Mixed (n=14)	Min	0.38	222.09	0.60	14.42	1494.05	0.53	1.43	0.40
	Max	7.73	1067.37	0.97	212.34	7025.22	0.86	6.66	1.42
	Mean	2.75	613.24	0.80	59.51	3196.97	0.70	3.79	0.84
	Median	2.04	561.38	0.84	49.80	3114.84	0.70	3.55	0.80

Table 4 continued.

		Playa Area (ha)	Playa Perimeter (m)	Playa Circularity	Watershed Area (ha)	Watershed Perimeter (m)	Watershed Circularity	Watershed Max Slope (%)	Watershed Mean Slope (%)
County									
Finney (n=7)	Min	1.82	519.06	0.79	32.89	2276.05	0.59	1.49	0.40
	Max	7.73	1065.89	0.87	294.86	7575.67	0.82	10.39	1.17
	Mean	4.50	799.72	0.83	114.60	4309.63	0.71	5.43	0.89
	Median	3.64	753.73	0.84	89.90	3713.97	0.65	4.99	1.05
Greeley/ Wichita (n=8)	Min	0.78	344.64	0.57	7.50	1077.37	0.36	1.98	0.48
	Max	4.90	940.43	0.89	212.34	7025.22	0.87	6.66	0.93
	Mean	2.08	562.12	0.77	65.74	3099.91	0.70	3.93	0.72
	Median	1.68	492.71	0.80	33.65	2227.48	0.80	2.92	0.73
Lane(n=7)	Min	3.40	683.20	0.77	23.44	1824.68	0.66	1.44	0.33
	Max	7.00	1067.37	0.96	139.17	5123.37	0.88	6.14	0.99
	Mean	5.13	857.10	0.87	79.18	3548.90	0.75	3.34	0.55
	Median	5.18	859.94	0.88	95.54	4054.74	0.73	3.12	0.48
Logan/ Gove (n=20)	Min	0.23	174.77	0.81	9.13	1384.94	0.42	0.58	0.32
	Max	4.98	829.47	0.97	102.57	5568.92	0.91	4.24	0.78
	Mean	1.64	448.72	0.93	33.29	2537.10	0.61	1.65	0.55
	Median	1.48	461.42	0.95	24.97	2363.06	0.57	1.47	0.54
Scott (n=16)	Min	0.13	131.18	0.60	3.22	1053.19	0.36	1.07	0.35
	Max	5.60	909.08	0.97	143.94	5750.99	0.85	6.04	1.04
	Mean	2.33	567.19	0.80	60.45	3332.05	0.61	3.02	0.61
	Median	2.40	605.25	0.82	43.54	3079.93	0.60	3.11	0.54
Sherman (n=9)	Min	0.47	256.22	0.58	10.01	1234.60	0.63	1.28	0.43
	Max	4.60	898.18	0.94	113.47	4529.92	0.88	6.44	1.42
	Mean	2.43	592.36	0.79	49.91	2695.76	0.76	4.19	0.93
	Median	2.23	544.04	0.83	47.20	2867.54	0.81	4.23	0.92
Thomas (n=8)	Min	0.78	327.19	0.62	26.14	2676.40	0.38	1.03	0.30
	Max	7.13	1134.29	0.96	154.59	5107.88	0.83	5.93	1.31
	Mean	3.16	681.15	0.82	73.55	3756.23	0.61	2.94	0.79
	Median	2.57	591.47	0.85	66.17	3647.04	0.61	2.02	0.68
Wallace (n=17)	Min	0.15	137.40	0.84	9.44	1189.94	0.40	0.82	0.49
	Max	5.69	898.51	0.97	135.96	5489.73	0.91	9.47	0.90
	Mean	1.18	352.39	0.92	49.87	3012.96	0.66	2.54	0.66
	Median	0.54	264.91	0.93	42.23	3069.94	0.63	1.79	0.63

Table 5. Bivariate correlation matrix of playa and watershed morphometric variables.

		Playa Area (ha)	**Playa Perimeter (m)**	**Playa Circularity**	**Watershed Area (ha)**	**Watershed Perimeter (m)**	**Watershed Circularity**	**Watershed Max Slope (%)**
Playa Primeter (m)	r	0.964						
	P	0.000						
Playa Circularity	r	-0.246	-0.424					
	P	0.018	0.000					
Watershed Area (ha)	r	0.624	0.623	-0.166				
	P	0.000	0.000	0.113				
Watershed Perimeter (m)	r	0.568	0.582	-0.134	0.942			
	P	0.000	0.000	0.203	0.000			
Watershed Circularity	r	0.093	0.098	-0.172	-0.146	-0.367		
	P	0.377	0.352	0.102	0.165	0.000		
Watershed Max Slope (%)	r	0.326	0.395	-0.337	0.442	0.380	0.128	
	P	0.001	0.000	0.001	0.000	0.000	0.225	
Watershed Mean Slope (%)	r	-0.014	0.081	-0.287	0.099	0.052	0.197	0.660
	P	0.898	0.445	0.006	0.346	0.622	0.060	0.000

Table 6. One-way ANOVA comparing mean differences in playa and watershed morphometric variables by tilled index (TI) class and county.

	TI Class		**County**	
Morphometric variable	**F value**	**P value**	**F value**	**P value**
Playa Area (ha)	0.767	0.467	7.383	0.000
Playa Perimeter (m)	0.846	0.433	7.404	0.000
Playa Circularity	3.165	0.047	6.313	0.000
Watershed Area (ha)	0.360	0.698	2.528	0.021
Watershed Perimeter (m)	0.812	0.447	1.650	0.133
Watershed Circularity	1.094	0.339	2.031	0.060
Watershed Max Slope (%)	5.228	0.007	4.756	0.000
Watershed Mean Slope (%)	10.059	0.000	4.222	0.000

Table 7. Summary of watershed tilled index for 2016-2019 and the four-year mean by tilled index class.

		Tilled Index 2016	**Tilled Index 2017**	**Tilled Index 2018**	**Tilled Index 2019**	**Mean Tilled Index**
Cropland (n=54)	Min	0.53	0.55	0.55	0.55	0.55
	Max	1.00	1.00	1.00	1.00	1.00
	Mean	0.92	0.93	0.93	0.94	0.93
	Median	1.00	1.00	1.00	1.00	1.00
Grassland (n=24)	Min	-1.00	-1.00	-1.00	-1.00	-1.00
	Max	-0.55	-0.55	-0.55	-0.55	-0.55
	Mean	-0.84	-0.84	-0.84	-0.84	-0.84
	Median	-0.87	-0.87	-0.87	-0.87	-0.87
Mixed (n=14)	Min	-0.38	-0.38	-0.38	-0.39	-0.38
	Max	0.39	0.39	0.39	0.39	0.39
	Mean	0.01	0.01	0.01	0.01	0.01
	Median	0.01	-0.01	-0.01	0.03	0.00

Table 8. Bivariate correlation of playa water status for 2016-2019 and the four-year mean to playa and watershed morphometric variables.

% Standing Water		Playa Area (ha)	Playa Perimeter (m)	Playa Circularity	Watershed Area (ha)	Watershed Perimeter (m)	Watershed Circularity	Watershed Max Slope (%)	Watershed Mean Slope (%)
2016	r	0.227	0.263	-0.133	0.227	0.204	-0.006	0.268	0.300
	P	0.030	0.011	0.207	0.029	0.051	0.953	0.010	0.004
2017	r	0.255	0.217	0.025	0.287	0.269	-0.005	0.061	-0.051
	P	0.014	0.038	0.815	0.006	0.009	0.964	0.562	0.627
2018	r	0.160	0.113	0.204	0.202	0.219	-0.096	-0.023	0.004
	P	0.127	0.282	0.051	0.053	0.036	0.363	0.828	0.973
2019	r	0.513	0.495	-0.041	0.327	0.313	-0.007	0.163	-0.061
	P	0.000	0.000	0.696	0.001	0.002	0.950	0.120	0.561
4-year mean	r	0.452	0.419	0.038	0.385	0.374	-0.039	0.149	0.013
	P	0.000	0.000	0.716	0.000	0.000	0.710	0.156	0.902

Table 9. Summary of playa water status for 2016-2019 and four-year mean for all 92 research playas, by playa size class, watershed size class, tilled index class, and county.

		2016	**2017**	**2018**	**2019**	**Mean**
All sites	% Dry/moist soil	97.7	85.5	91.4	76.5	87.8
(N=92)	% Standing water	2.3	14.5	8.6	23.5	12.2
Playa Size Class						
Quartile 1	% Dry/moist soil	100.0	88.7	92.0	85.8	90.8
(n=23)	% Standing water	0.0	11.3	8.0	14.2	9.2
Quartile 2	% Dry/moist soil	99.6	89.7	92.4	79.7	90.4
(n=23)	% Standing water	0.4	10.3	7.6	20.3	9.6
Quartile 3	% Dry/moist soil	95.9	85.2	92.7	73.0	86.7
(n=23)	% Standing water	4.1	14.8	7.3	27.0	13.3
Quartile 4	% Dry/moist soil	95.1	82.4	88.7	66.9	83.3
(n=23)	% Standing water	4.9	17.6	11.3	33.1	16.7
Watershed Size Class						
Quartile 1	% Dry/moist soil	100.0	88.1	93.8	85.1	91.7
(n=23)	% Standing water	0.0	11.9	6.2	14.9	8.3
Quartile 2	% Dry/moist soil	96.8	87.7	93.3	76.8	88.7
(n=23)	% Standing water	3.2	12.3	6.7	23.2	11.4
Quartile 3	% Dry/moist soil	98.9	88.5	90.9	78.8	89.3
(n=23)	% Standing water	1.1	11.5	9.1	21.2	10.7
Quartile 4	% Dry/moist soil	95.2	78.1	88.0	65.7	81.8
(n=23)	% Standing water	4.8	21.9	12.0	34.3	18.3
Tilled Index Class						
Cropland	% Dry/moist soil	98.0	85.3	89.0	74.6	86.7
(n=54)	% Standing water	2.0	14.7	11.0	25.4	13.3
Grassland	% Dry/moist soil	96.7	84.6	94.8	77.0	88.3
(n=24)	% Standing water	3.3	15.4	5.2	23.0	11.7
Mixed	% Dry/moist soil	98.2	88.7	95.2	82.2	91.1
(n=14)	% Standing water	1.8	11.3	4.8	17.8	8.9
County						
Finney	% Dry/moist soil	92.7	83.3	92.9	68.5	84.4
(n=7)	% Standing water	7.3	16.7	7.1	31.5	15.7
Greeley/Wich-	% Dry/moist soil	100.0	92.7	92.7	86.3	92.9
ita (n=8)	% Standing water	0.0	7.3	7.3	13.7	7.1
Lane	% Dry/moist soil	97.4	82.9	95.0	56.0	82.8
(n=7)	% Standing water	2.6	17.1	5.0	44.0	17.2
Logan/Gove	% Dry/moist soil	99.6	90.3	93.3	73.3	89.1
(n=20)	% Standing water	0.4	9.7	6.7	26.7	10.9
Scott	% Dry/moist soil	97.4	83.3	91.9	66.8	84.9
(n=16)	% Standing water	2.6	16.7	8.1	33.2	15.2
Sherman	% Dry/moist soil	96.2	94.2	94.4	90.7	93.9
(n=9)	% Standing water	3.8	5.8	5.6	9.3	6.1
Thomas	% Dry/moist soil	94.8	76.3	80.2	75.7	81.8
(n=8)	% Standing water	5.2	23.8	19.8	24.3	18.3
Wallace	% Dry/moist soil	99.0	80.9	89.2	87.3	89.1
(n=17)	% Standing water	1.0	19.1	10.8	12.7	10.9

Table 10. One-way analysis of variance (ANOVA) results comparing mean differences in playa water status and mean watershed tilled index class, county, playa size class, watershed size class.

	Tilled Index Class		**County**		**Playa Size class**		**Watershed Size class**	
Water status observations	**F value**	**P value**	**F value**	**P value**	**F value**	**P value**	**F value**	**P value**
% Standing water 2016	0.287	0.751	1.433	0.203	3.525	0.018	2.405	0.073
% Standing water 2017	0.421	0.658	2.666	0.015	2.069	0.110	3.663	0.015
% Standing water 2018	2.761	0.069	1.410	0.212	0.459	0.712	1.050	0.375
% Standing water 2019	1.236	0.296	6.648	0.000	9.775	0.000	6.009	0.001
% Standing water four-year mean	1.580	0.212	2.800	0.011	6.763	0.000	6.692	0.000

Table 11. Bivariate correlation of monthly precipitation and monthly average percent standing water observations for all 92 research playas, by playa size class, watershed size class, and tilled index class.

	% Standing Water	
All sites (N=92)	r	0.453
	P	0.001
Playa Size Class		
Quartile 1 (n=23)	r	0.376
	P	0.009
Quartile 2 (n=23)	r	0.456
	P	0.001
Quartile 3 (n=23)	r	0.491
	P	0.000
Quartile 4 (n=23)	r	0.379
	P	0.008
Watershed Size Class		
Quartile 1 (n=23)	r	0.389
	P	0.006
Quartile 2 (n=23)	r	0.438
	P	0.002
Quartile 3 (n=23)	r	0.484
	P	0.000
Quartile 4 (n=23)	r	0.414
	P	0.003
Tilled Index Class		
Cropland (n=54)	r	0.436
	P	0.002
Grassland (n=24)	r	0.418
	P	0.003
Mixed (n=14)	r	0.453
	P	0.001

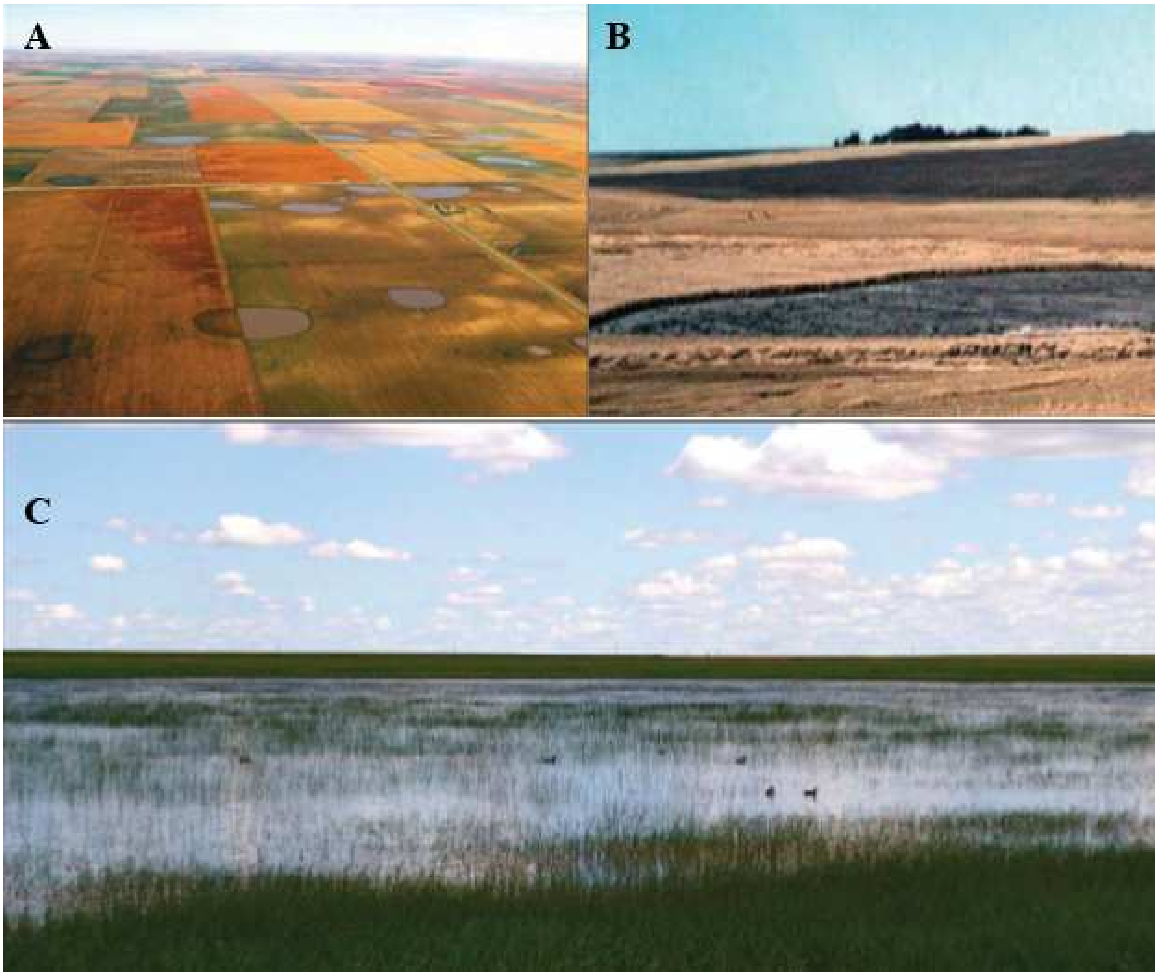


Figure 1. A) Oblique aerial view of typical distribution of playas in western Kansas; B) dry cropland playa; C) playa utilized by waterfowl with aquatic vegetation during a wet period (Evans, 2010)

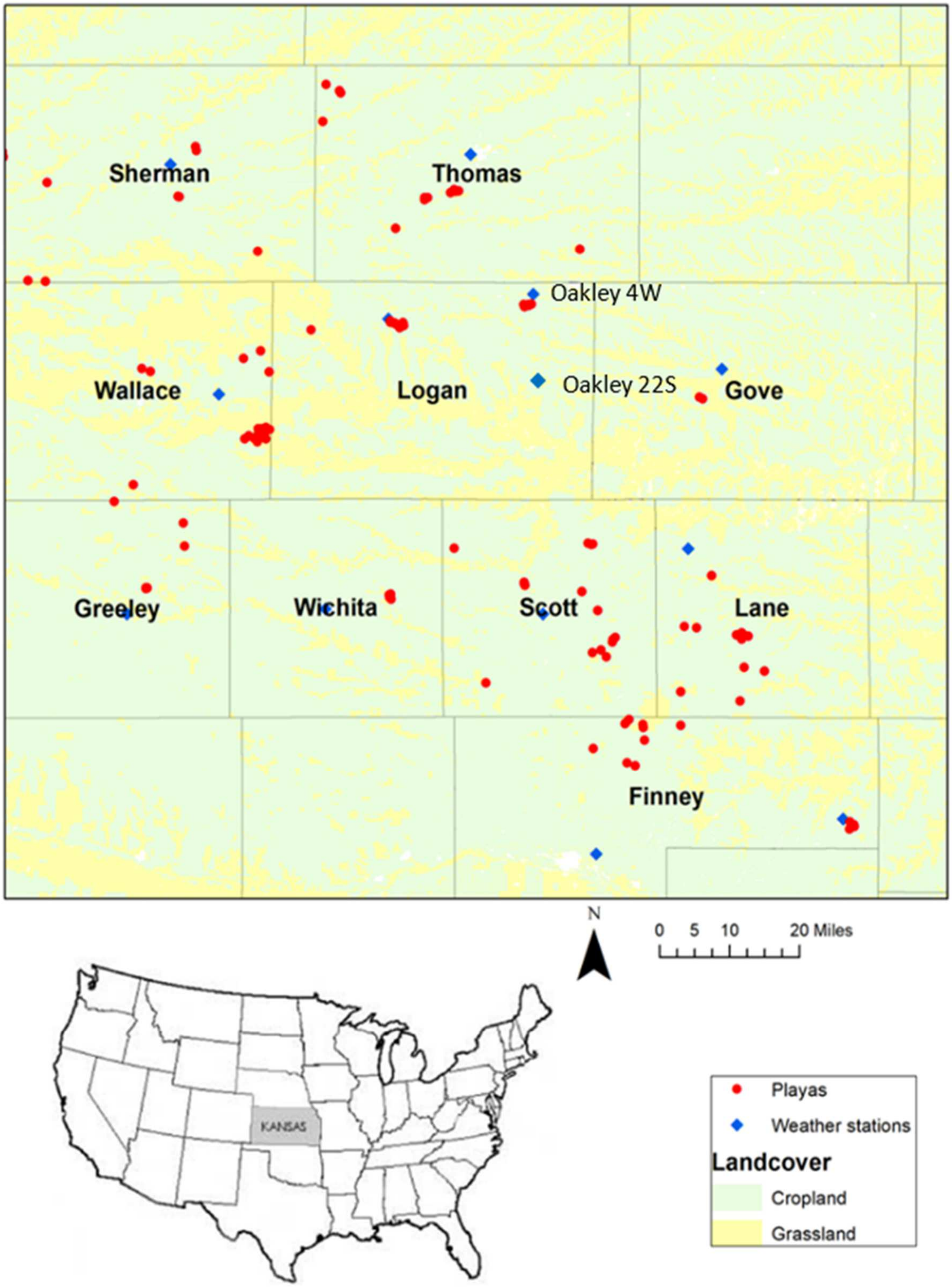


Figure 2. Distribution of research playas (n = 92) and weather stations in western Kansas.

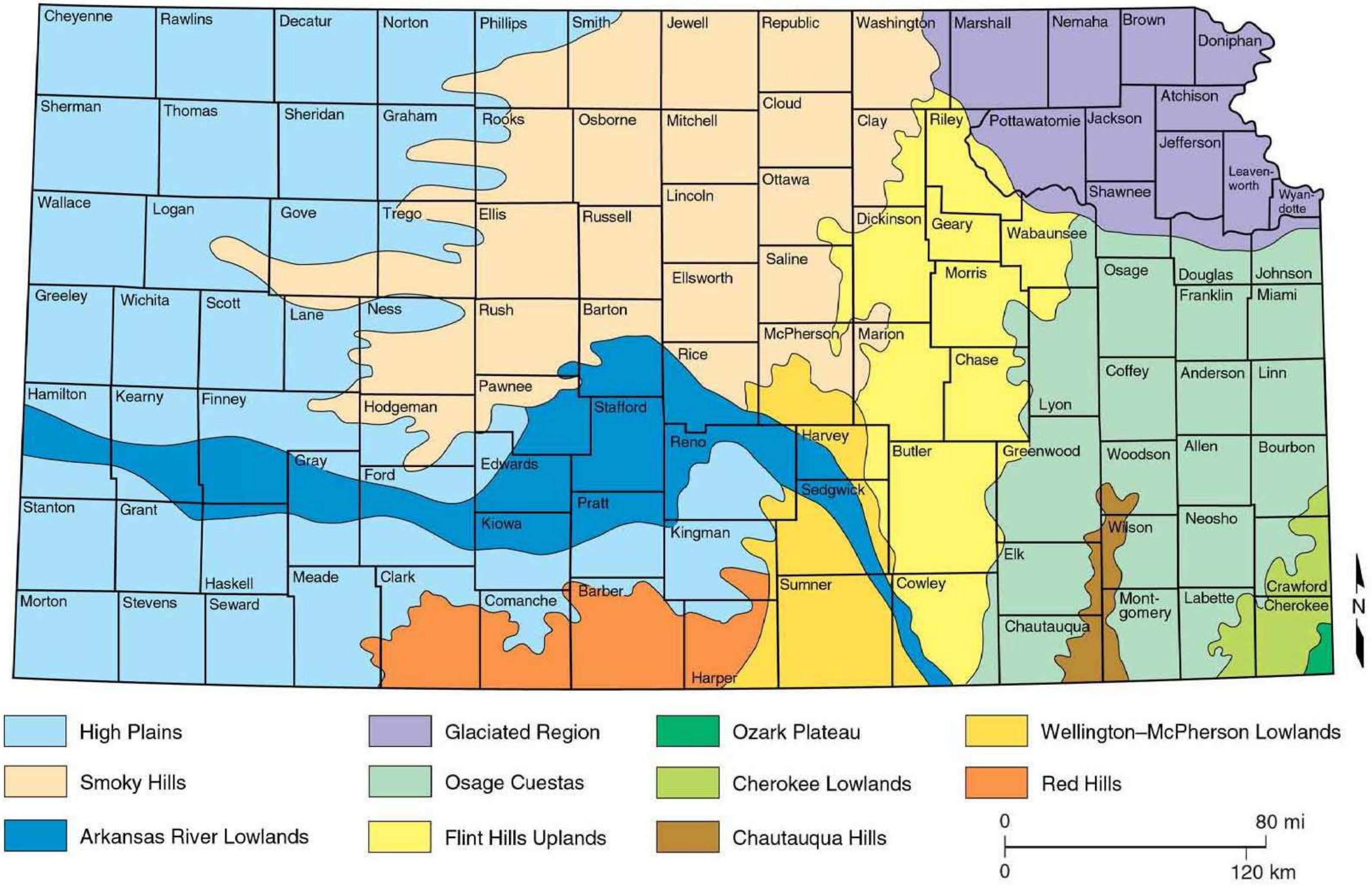
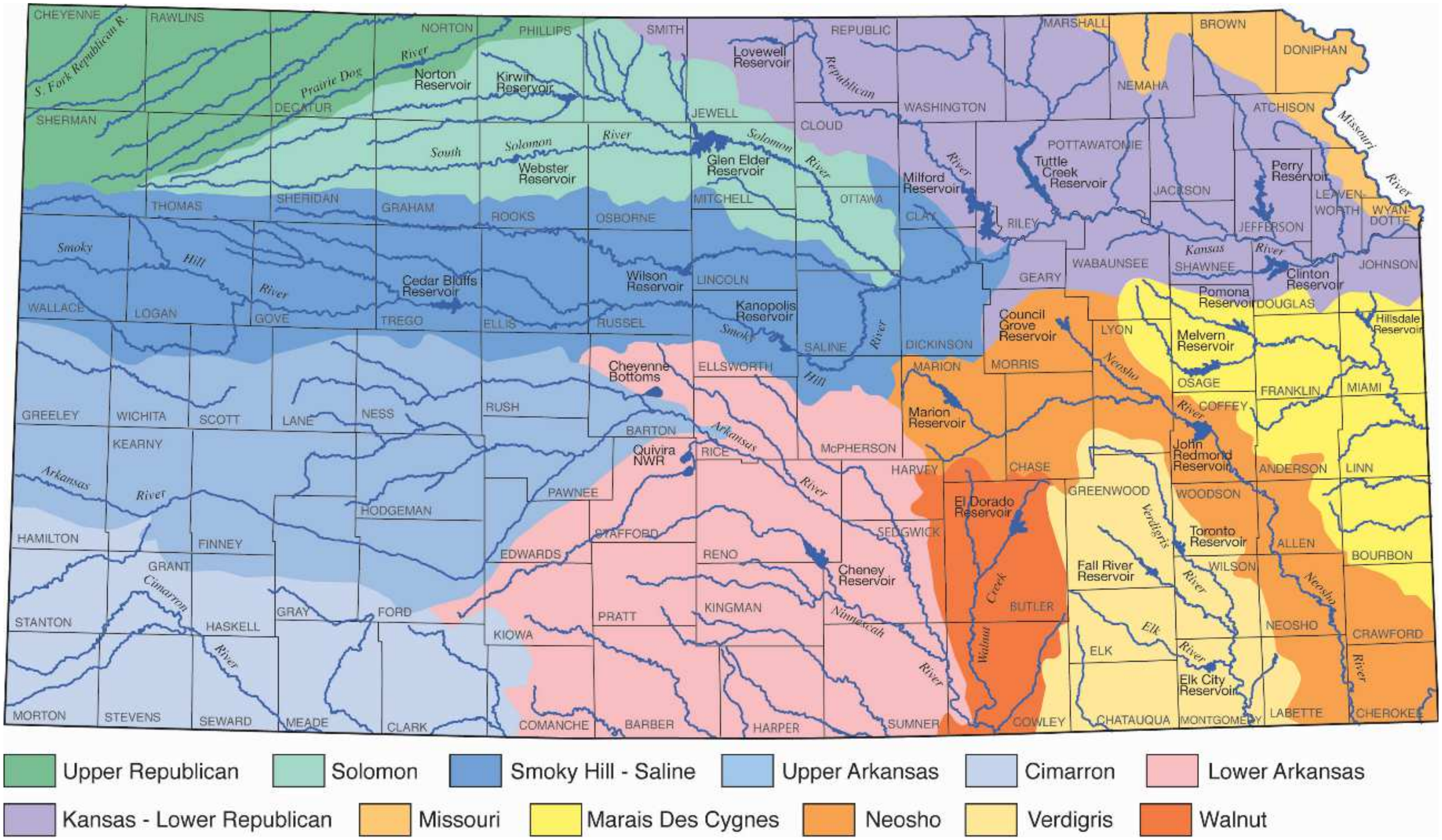


Figure 3. Physiography of the State of Kansas (University of Kansas, 2020).



🟩 Upper Republican
🟩 Solomon
🟦 Smoky Hill - Saline
🟦 Upper Arkansas
🟦 Cimarron
🟥 Lower Arkansas
🟪 Kansas - Lower Republican
🟧 Missouri
🟨 Marais Des Cygnes
🟧 Neosho
🟨 Verdigris
🟧 Walnut

Figure 4. Major river basins in Kansas (University of Kansas, 2020).

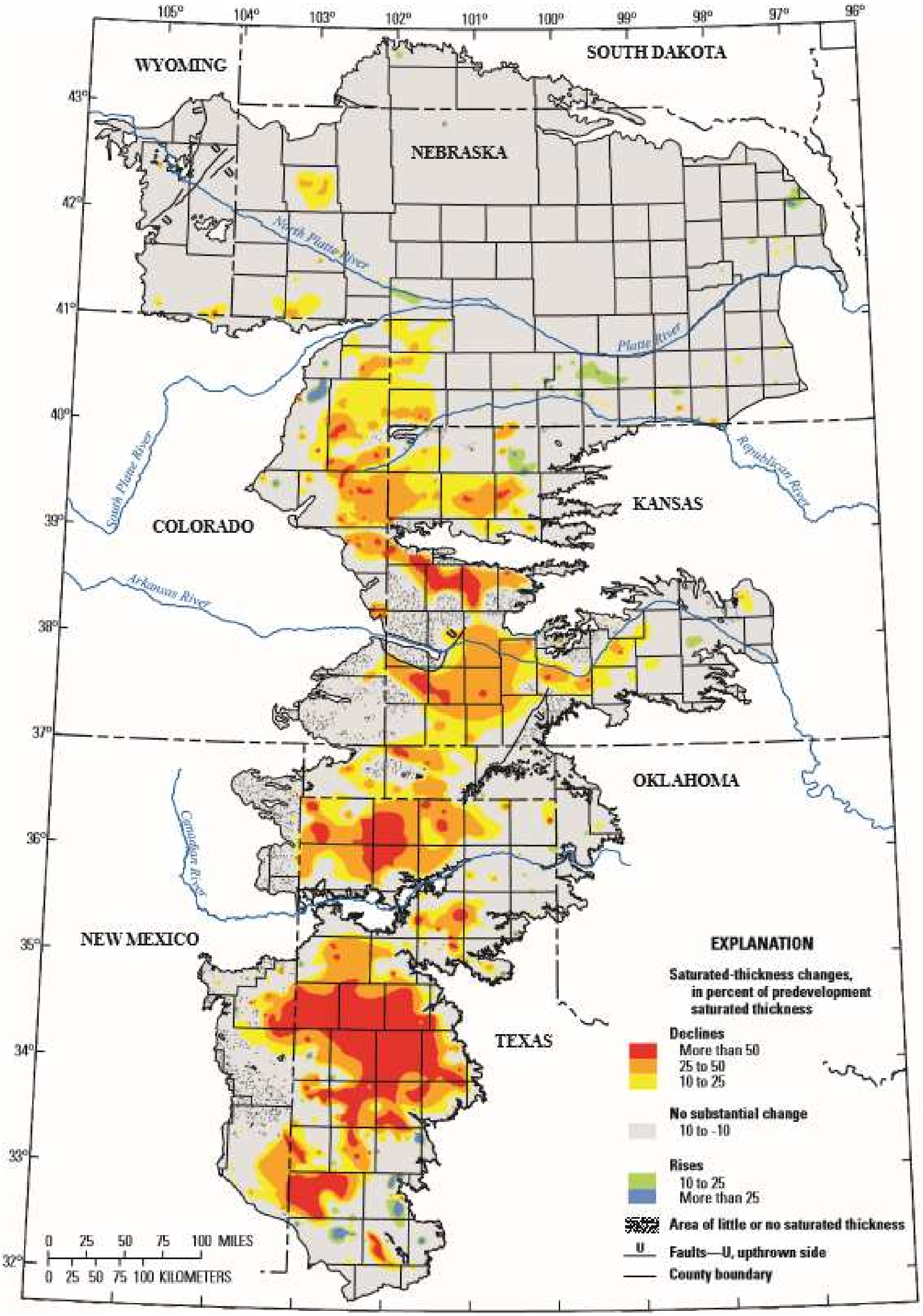


Figure 5. Change in saturation thickness of the High Plains Aquifer from predevelopment (1950) to 2015 (McGuire, 2017).

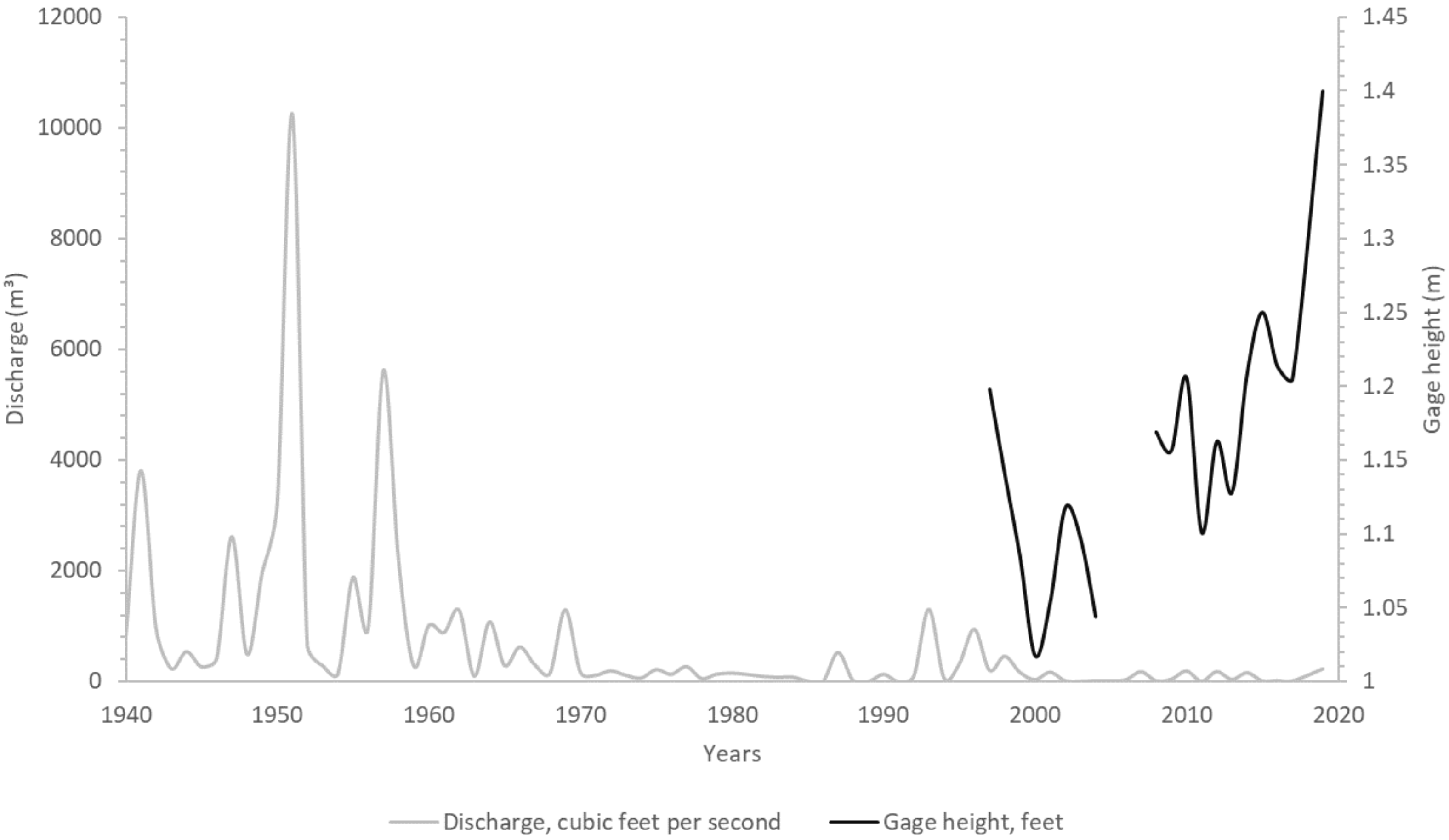


Figure 6. Discharge of Smoky Hill River at Elkader, Kansas (USGS 06860000) from 1940 to 2019 and water level from 1997 to 2019.

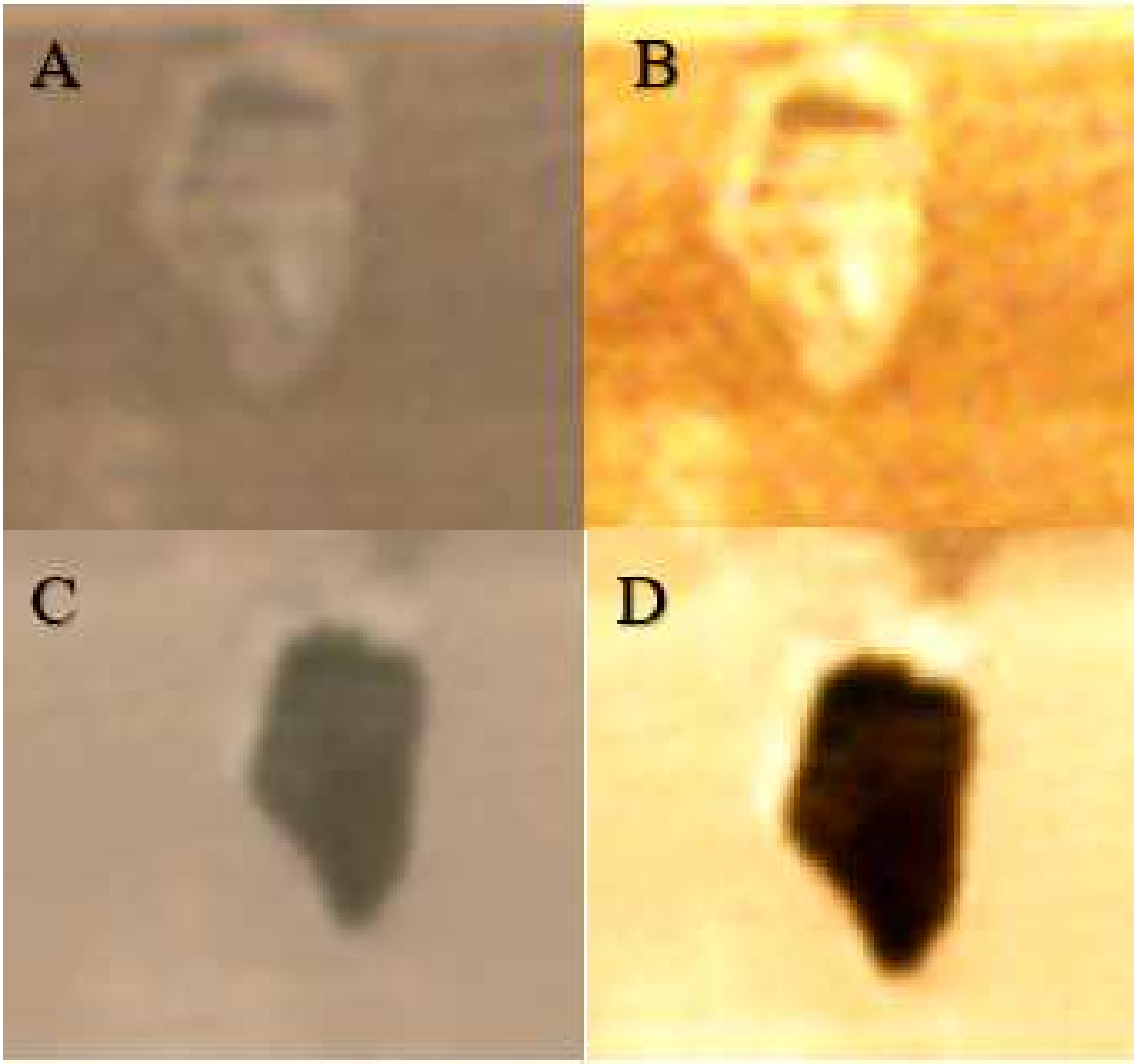


Figure 7. Planet Explorer (www.planet.com) monthly mosaic satellite imagery of playa water status categories: (a) dry/moist soil; (b) dry/moist soil playa with image enhancement; (c) playa with standing water; and (d) playa with standing water with image enhancement.

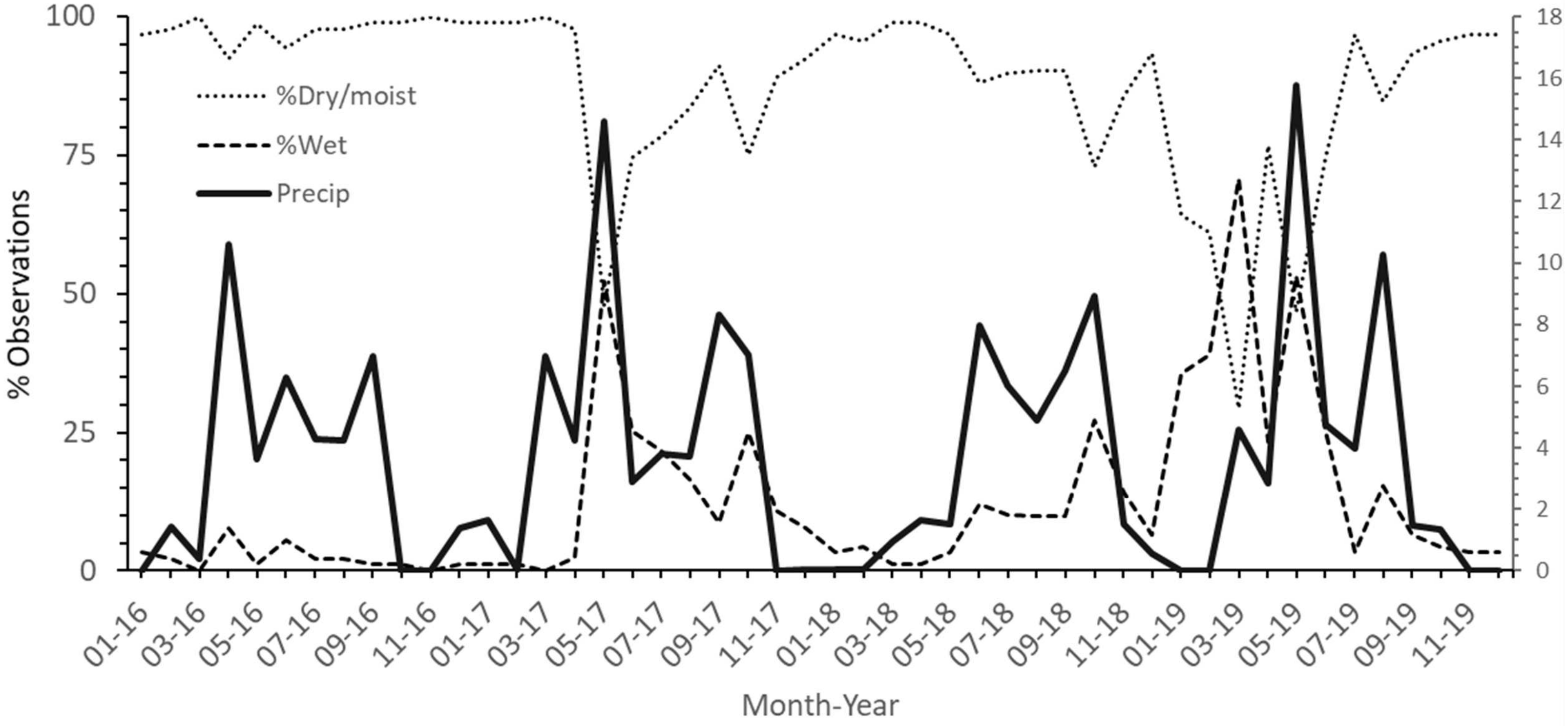


Figure 8. Percent dry and standing water observations of playa water status for 92 playas distributed throughout western Kansas and monthly precipitation at Oakley 22S High Plains Regional Climate Center weather station from 2016-2019.

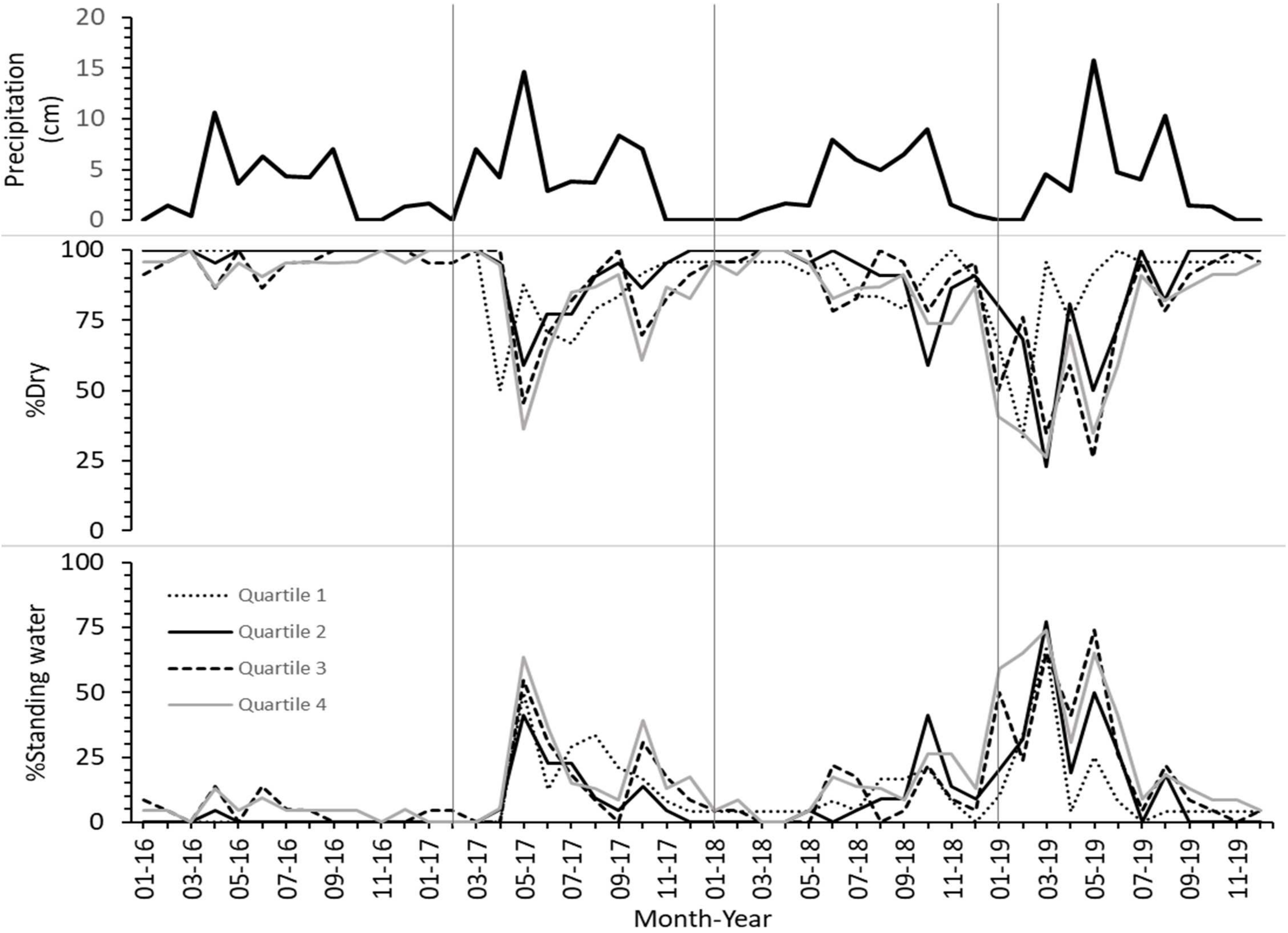


Figure 9. Precipitation recorded at Oakley 22S weather station and percent of playa water status observations by playa size class quartiles for 92 playas distributed throughout western Kansas from 2016-2019.

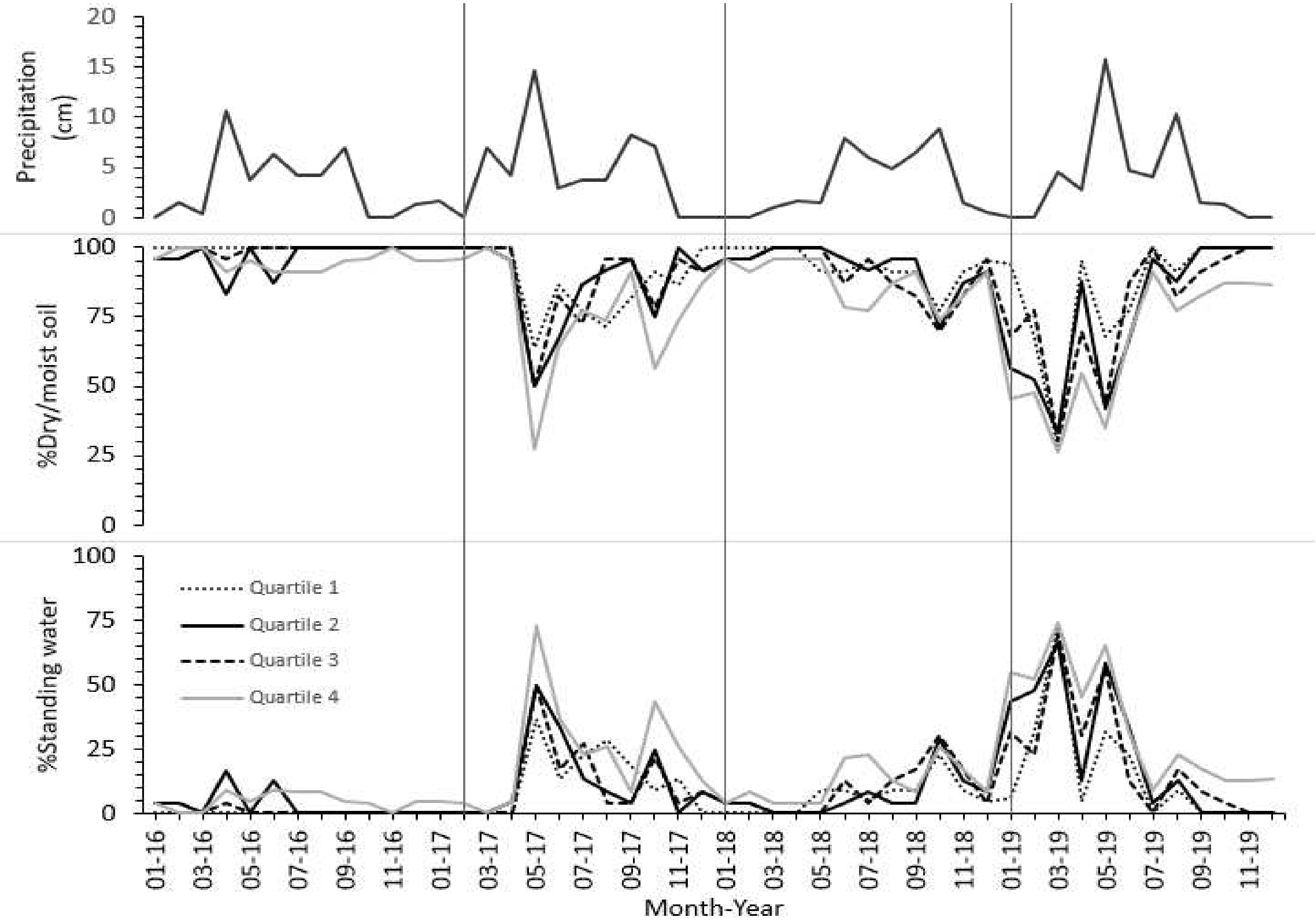


Figure 10. Precipitation recorded at Oakley 22S weather station and percent of playa water status observations by watershed size class quartiles for 92 playas distributed throughout western Kansas from 2016-2019.

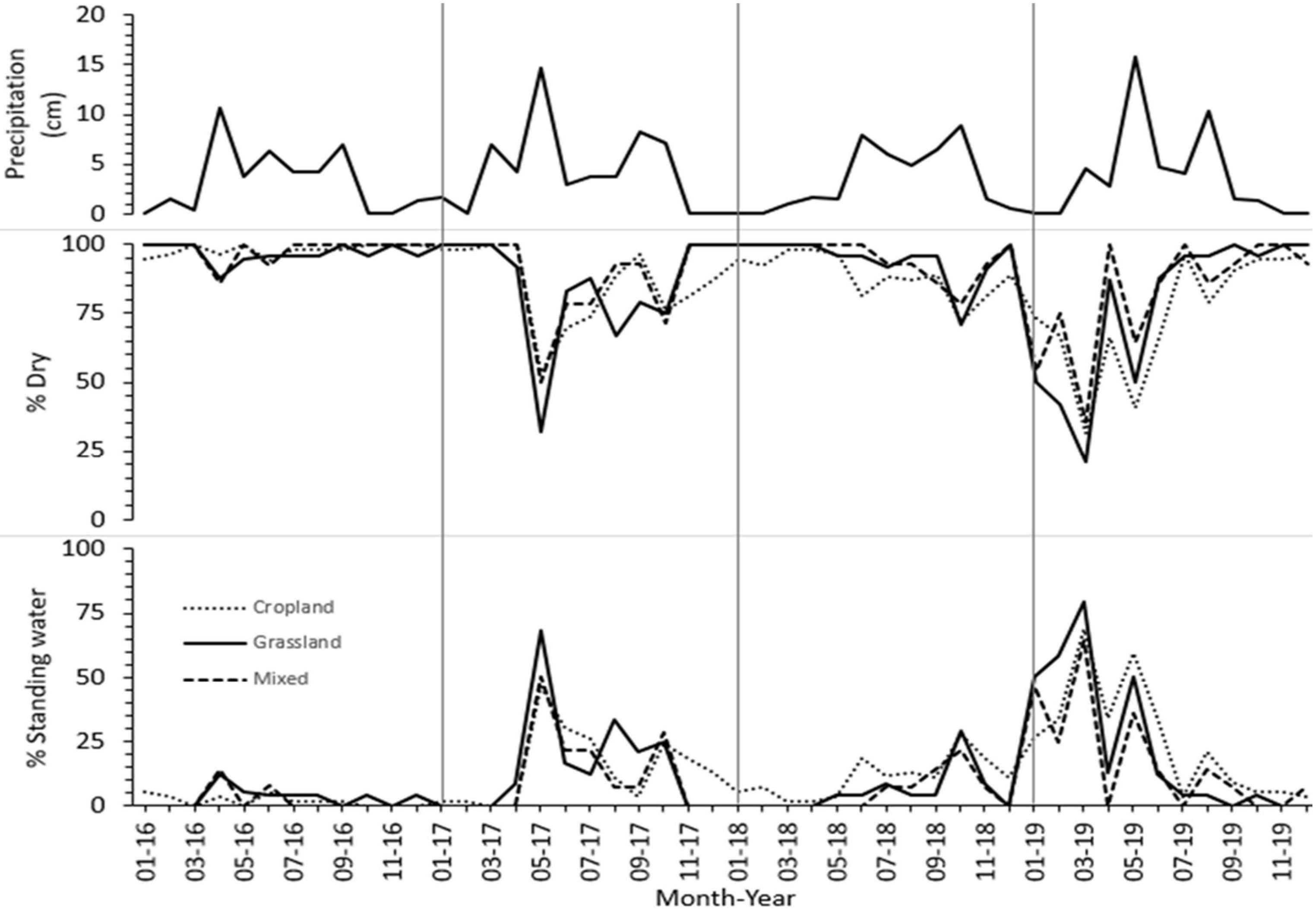


Figure 11. Precipitation recorded at Oakley 22S weather station and percent of playa water status observations by TI class for 92 playas distributed throughout western Kansas from 2016-2019.

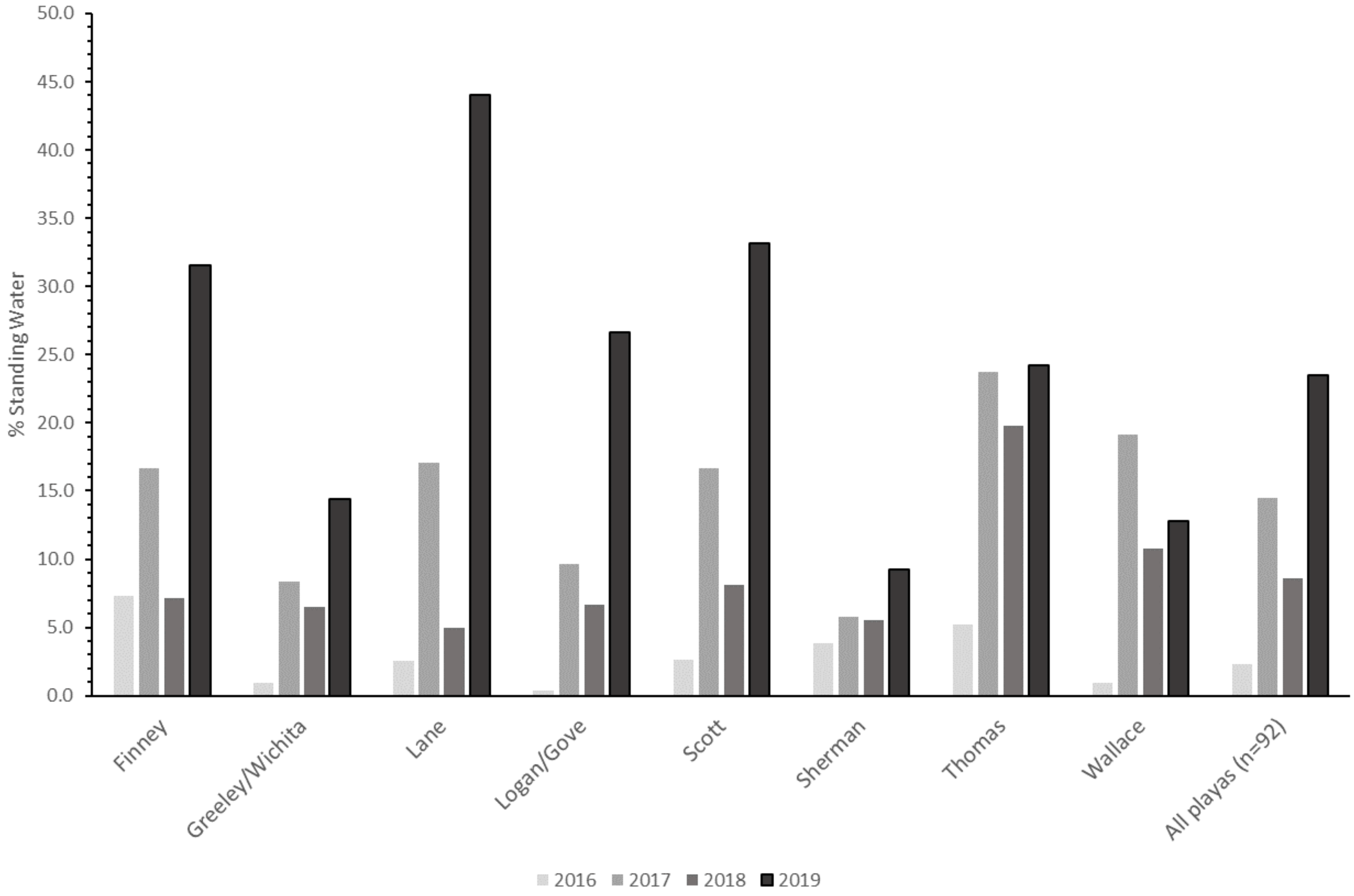


Figure 12. Percent of playa water status observations by county for 92 playas distributed throughout western Kansas from 2016-2019.