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Cover photo: Lake Austin Dam on the Colorado River, June 15, 1935. Photo CO8484, Austin History Center, Austin Public Library.

Comparison of infiltration flux in playa lakes in grassland and cropland basins, Southern High Plains of Texas

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Abstract: Playas are the dominant wetland type on the Southern High Plains of Texas and capture runoff during periods of heavy rainfall. Observing the hydrologic functions of playas is important to evaluate their ecological services, which include encouragement of species biodiversity and recharge of the underlying High Plains (Ogallala) Aquifer. Ten pairs of playas were chosen in 10 counties on the Texas Southern High Plains. Each pair included 1 playa surrounded by natural grassland (not in the Natural Resources Conservation Service's Conservation Reserve Program) and 1 playa surrounded by cultivated cropland. Instrumentation at each playa allowed calculation of changes in free water evaporation and water stored over time during the hydroperiods, defined as continuous durations of surface water storage in the playa basins, caused by one or more rainfall events that generated sufficient runoff flows to reach and fill the playas. A water budget model calculated daily infiltration flux through the playa bottoms. Six cropland playas and 3 grassland playas had significant hydroperiods with associated consistent instrumentation operation during the 6-year study across the years 2005 to 2011. The average observed infiltration flux rates were approximately 10 millimeters/day (range 2 to 20 millimeters/day) and 3 millimeters/day (range 1 to 5 millimeters/day) for the cropland and grassland playas, respectively. The preliminary results may be influenced by the presence of eroded sediments from the surrounding cropland, but more runoff events are needed to differentiate between the impacts of playa floor soils and variations in rainfall and playa watershed characteristics that contribute to the hydroperiods.

Keywords: playas, infiltration, Ogallala Aquifer, evaporation

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Terms used in paper

Short name or acronym	Descriptive name
ARS	Agricultural Research Service
CRP	Conservation Reserve Program
NRCS	Natural Resources Conservation Service
SHP	Southern High Plains
USDA	U.S. Department of Agriculture

INTRODUCTION

Playas are the dominant wetland systems on the Southern High Plains (SHP) of Texas and New Mexico, which is one of the world's most intensely cultivated areas (Bolen et al. 1989). Playas are ephemeral depressional recharge basins that function as stormwater runoff catchments during periods of significant rainfall. Understanding the ecological factors that are shaping the playa's ecosystem is necessary for conservation of these wetlands because playas are becoming the only remaining sites of natural biodiversity within the SHP (Haukos and Smith 1994). These playas support wildlife and plant life species, as well as a variety of invertebrates (Bolen et al. 1989). These wetlands also function as areas of water storage, providing a principal flood control mechanism in the SHP. In addition, playas serve as the primary source of recharge to the underlying High Plains Aquifer system, which is a main source of water for irrigation, livestock, and many municipalities (Reeves 1996). Land use surrounding the playa, either grassland or cultivated land for crop production, controls quantity and quality of runoff and thereby recharge volume through the playas. Besides recharge, water stored in playas can be lost to either free water evaporation or evapotranspiration through vegetation.

Quantifying infiltration flux through playas is necessary to estimate the portion of surface runoff that potentially recharges the groundwater system. As part of the U.S. Department of Agriculture (USDA)-Agricultural Research Service (ARS) Ogallala Aquifer Program and the Natural Resources Conservation Service (NRCS) Conservation Effects Assessment Program, a long-term study of infiltration flux observation began in 2005. This study focused on a pair of playas each surrounded by cropland and natural grassland in 10 selected Texas counties in the SHP. The natural grassland areas were sometimes used by the landowners for grazing cattle. The word "natural" primarily means that those grassland areas were not enrolled in the Conservation Reserve Program (CRP), which normally prevents grazing. All 20 playas were instrumented to measure required weather variables for calculation of free-water evaporation as well as changes in water stored in the playas when inundated. The primary objective of this study was to evaluate the hypothesis that playas surrounded by cropland have faster infiltration flux losses than playas surrounded by grassland. This objective was addressed through field data collection and application of a water budget model to estimate infiltration flux losses through playas surrounded by cropland or natural grassland based on the data collected.

BACKGROUND

High Plains Aquifer

The High Plains (Ogallala) Aquifer encompasses groundwater beneath 450,000 square kilometers in Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, Wyoming, and South Dakota (Opie 2000). The Ogallala Aquifer represents the principal source of domestic and irrigation for the region, which provides much of the nation's livestock, corn, cotton, sorghum, and wheat production (Reeves 1996). The SHP encompasses the southernmost part of the aquifer and includes over 77,700 square kilometers of West Texas and eastern New Mexico (Reeves 1996). Irrigation and other withdrawals exceed recharge in much of the SHP, causing declining water levels in many locations (Mulligan et al. 2005). The areas of the aquifer without withdrawal, however, show increasing groundwater storage.

Playas

More than 20,000 playas have been mapped in the High Plains of Texas based on the presence of hydric soils in historical soil surveys (Fish et al. 1998, PLJV 2009). Figure 1 displays the distribution of playas in Floyd County (PLJV 2009) as an example. A playa wetland is defined as a shallow depression with a relatively flat bottom, sometimes called the lakebed or
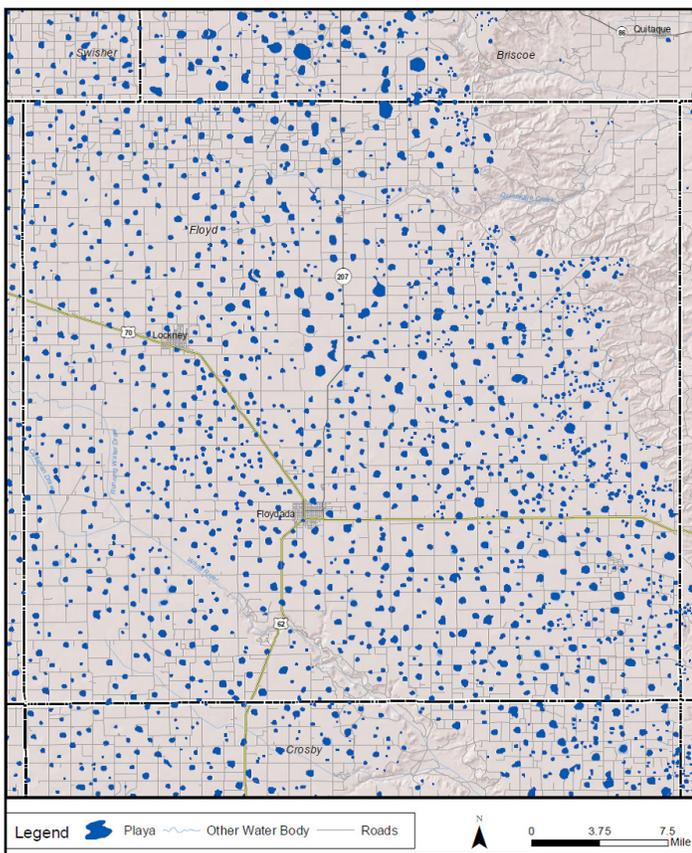
Figure 1. Playa wetlands in Floyd County, Texas (PLJV 2009).

playa floor. Playa bottoms are comprised of 0.3 to 1.5 meters of hydric soils and vertisol clays, usually Randall or Ranco clays (fine, smectitic, thermic Ustic Epiaquerts) in the SHP. Vertisol clays swell when wet and shrink when dry, forming large desiccation cracks (Hovorka 1997). The playa edge sloping upward from the lakebed is referred to as the annulus, which leads to the surrounding watershed, or upland region. The shallow soil texture in the annulus is typically coarser than the playa bottom clays. The Playa Lakes Joint Venture (2009) release notes for Figure 1 stated that the playas in Texas were mapped using the combination of SSURGO soils data, LANDSAT imagery to establish the "wettest image" from 1986 to 2000, and the National Agricultural Imagery Program of the USDA. This approach did not limit the playa shapes to the hydric soil boundaries but allowed for inundated areas in the playas beyond the hydric soils. As our project was also concerned with the water held within the basins, this representation was useful.

It was previously hypothesized by some observers that recharge through the playas was prevented by the playas' clay bottoms (Reddell 1994). Evidence suggests otherwise. First, playas are freshwater systems. If all the water loss within the playas occurred through evaporation, then all playas should be more saline than the rainfall and runoff. Only 40

to 50 large saline lake basins exist as local topographic lows correlated with bedrock highs in the southwestern portion of the SHP (Wood et al. 1992), and their high salinities are due to long-term evaporation of groundwater. Chaudhuri and Ale (2014) noted that the total dissolved solids levels in the SHP groundwater tend to be larger in the southern counties in the SHP, but their study did not tie the ephemeral playa lake water qualities to the aquifer beneath. Infiltrating water from the playas can dissolve materials during movement through the unsaturated and saturated zones. Second, calcrete or caliche layers that typically top the Ogallala formation generally are thin or missing beneath the playas (Reeves 1996). Calcrete is a hardened deposit of calcium carbonate and forms in arid regions when infiltrating rainfall dissolves minerals and redeposits them lower in the soil profile, forming a caliche layer. Since caliche layers are thin or missing beneath the playas, the dissolved minerals must be passing through the bottom of the playa. Finally, tritium in rainwater and runoff from above-ground nuclear testing has been detected at much greater depths beneath playas than in the surrounding upland areas (Nativ 1992; Wood and Sanford 1995; Wood et al. 1997).

Some researchers (Wood and Osterkamp 1984a, b; Claborn et al. 1985; Reed 1994) have proposed that infiltration flux through the annulus may exceed that through the playa bottoms. If the water depth is high enough to inundate the coarser soils along the edge of the playa, infiltration rates in those soils can be faster than those in the playa floor (Wood and Osterkamp 1984; Claborn et al. 1985). The behavior of the expansive clay soil in the playa bottom further complicates the infiltration process. When the playa has been dry for several weeks or longer, the bottom clays form large desiccation cracks (Figure 2a). Coarser sediments carried by runoff from the surrounding cropland can fill the cracks. Grassland playas receive less sediment because the vegetation limits soil erosion. Rainfall intensity must exceed 1.2 to 3 centimeters/day, depending on antecedent moisture conditions, to cause runoff events that inundate or flood the playa (Reed 1994).

Infiltration in the playa floor follows 3 distinct stages (Zartman et al. 1994.). Immediately after inundation, stage I flooding, or macropore infiltration, takes place, in which the cracks in the lakebed allow infiltration at a high rate (Figure 2b). As infiltration progresses, the clay swells and becomes less permeable, resulting in a sharp decrease of infiltration rate during Stage II, as micropore infiltration becomes dominant. Playas surrounded by cultivated cropland may receive coarse sediments in runoff that can fill the desiccation cracks and increase the overall permeability of the playa bottoms sediments. Stage III of infiltration occurs when the soil becomes saturated, resulting in a constant infiltration rate (Figure 2c). Zartman et al. (1994) performed 14 infil-

(a)

(b)

(c)
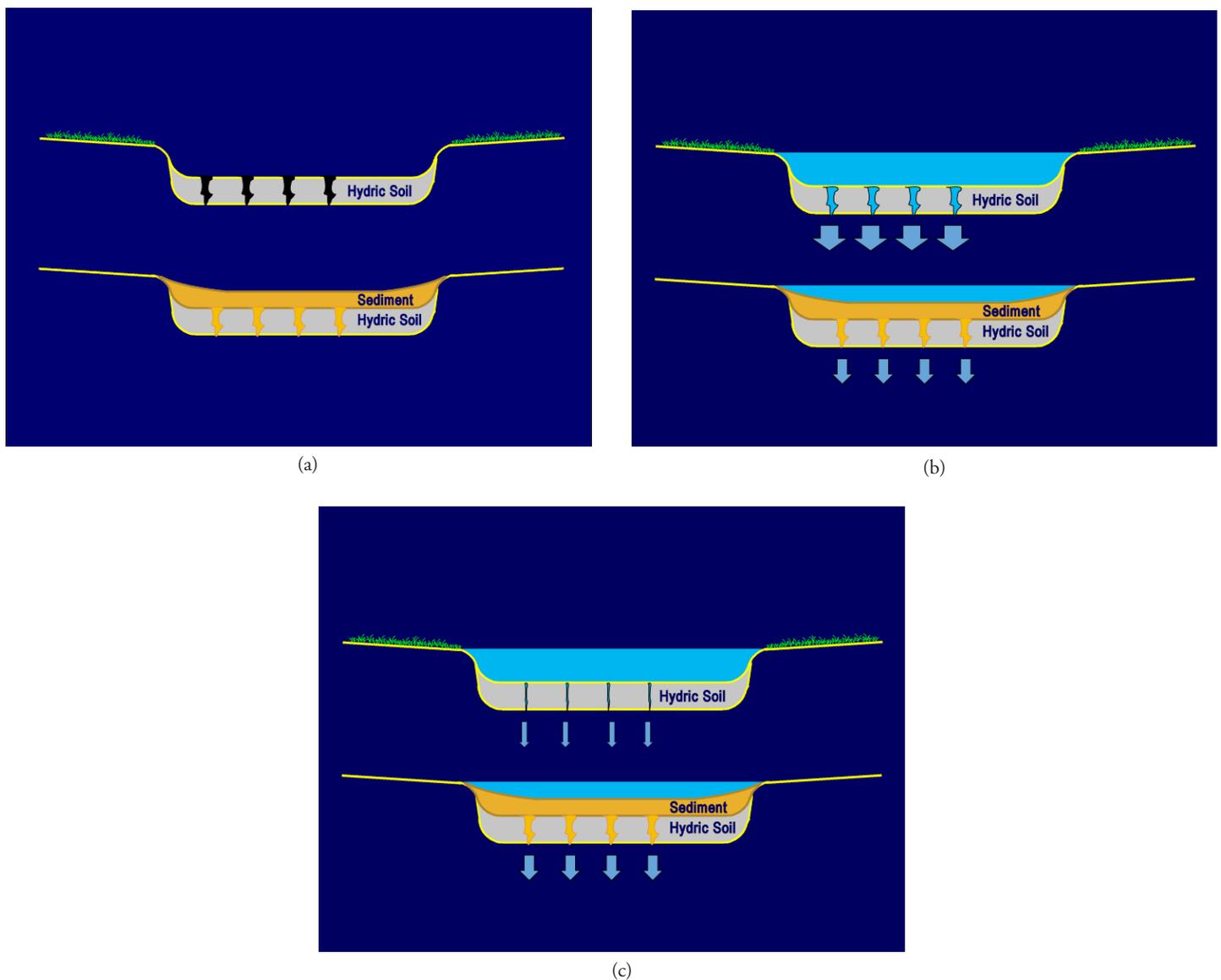
Figure 2. General schematic descriptions of hydrologic conditions near a playa lake, and comparison of conditions in grassland (upper) and cultivated (lower) playas (a) when dry, (b) during the first flush of early inundation, and (c) after days of inundation allowing floor clays to swell.

trometer tests at each of 3 different relative elevations in each of 3 playas. Large Stage I and Stage III rates were noted in infiltrometers that included desiccation cracks. Stage I infiltration rates ranged from 10 to 2490 millimeters/minute with average values between 100 and 200 millimeters/minute. Stage III infiltration rates ranged from 0.004 to 996 millimeters/minute, with average values near 5 millimeters/minute.

Water loss through evaporation from the free water surface occurs also during the hydroperiod, which is the duration when the playa wetland continuously holds water due to one or more sequential rainfall events (Tsai et al. 2007; Gaff et al. 2000), at rates controlled by the temperature, wind speed, and solar radiation. Vegetation can also transpire water from the root zone to the atmosphere at rates depending on the available water content and the growth stage of the individual plants.

Land use in playa watersheds

Land use adjacent to and surrounding a playa can influence its hydrologic function. Upland sites surrounding playas generally consist of cropland or native (or CRP) grassland. In a playa surrounded by grassland, the Randall clay is exposed as hydric soil. In playas surrounded by cropland, however, coarser sediments can accumulate in the basin during runoff events, thereby changing the shape of the basin and reducing the hydric soil-defined volume available for ponding. Luo et al. (1997) compared the effects of sediment accumulation

between 20 cropland playas and 20 grassland playas in 11 SHP counties and reported that cropland playas contained 8.5 times more sediment than grassland playas. Their interpretation was that 18 of the 20 cropland playas had lost most of their original basin hydric soil-defined volumes, while grassland playas lost only about one-third of their volumes. Villarreal et al. (2012) compared the sediment depth and grain-size distributions above the hydric soils in pairs of cropland and grassland playa basins in Briscoe, Floyd, and Swisher counties that were also included in the field observations in our project. Their work noted non-uniform distributions of sediment depth and clay/sand fractions. Quantitative sediment depths for playas in Briscoe, Floyd, and Swisher counties from Villarreal et al. (2012) are presented with our results for interpretation of this project's findings.

Alteration of the playa basin due to sediment accumulation also leads to an increase in the amount of surface area per unit volume, thereby increasing the evaporative component of water loss from the playa. Increased evaporation also results in a shortened hydroperiod. Tsai et al. (2007) studied the influences of land use on water loss and hydroperiods of 40 SHP playas. They formulated a tilled index, which is the fraction of tilled or untilled area within a watershed. A tilled index value of 1 indicated that 100% of the land within the watershed was tilled, while an index value of -1 indicated that 100% of the land was untilled. Their results showed that higher tilled index values resulted in a greater water volume loss, demonstrating that a playa with more surrounding grassland will have longer hydroperiods. The ability of wetlands to store water has ecological, environmental, and economic implications (Luo et al. 1997). Maintaining natural and therefore longer hydroperiods is necessary for persistence of plants and animals that use the playa wetland. The CRP serves to replace cultivation with grasses to reduce erosive losses within the playa. These grasses may also benefit the playa hydrologic behaviors.

Field observations

Analysis of recharge from the playas began in the 1930s. It was originally believed that evaporation from the playas was more common than infiltration, as indicated by Schwiesow (1965), who estimated that less than 10% of runoff water reaches the aquifer by infiltration through the soil, and more than 90% of this water is lost through evaporation. Water budget studies in several master's thesis projects at Texas Tech University, however, demonstrated otherwise and have shown that more recharge takes place than previously thought. Koenig (1990) studied the effects of macropores on infiltration patterns in the basin soils of a cultivated playa in Lubbock County using a 7.6-meter diameter basin infiltrometer. Three trials were conducted at 3 sites in the playa during April and May of 1990. Results indicated that infiltration

rates were 418, 225 and 349 millimeters/hour during the first 28 minutes. Initial soil moisture contents were 15.6%, 28.4%, and 18.8%, respectively, for the 3 trials, indicating that the higher initial soil moisture contents resulted in lower initial infiltration rates.

Evans (1990) investigated the bimodal infiltration patterns in 3 playas in Lubbock County. The 3 playa watersheds were in cropland, grassland, and CRP. For each playa, stage I and stage III infiltration rates were determined at 90 different sampling points via a double-ring infiltrometer method. The inner and outer rings were 128 and 205 millimeters in diameter, respectively. Stage III infiltration rates were 720, 900, and 2000 millimeters/hour for cropland, grassland, and CRP playas, respectively. Stage III determinations were made at the end of 3 days for 2 of the wetlands and at the end of 2 days for the third playa due to unexpected flooding. Stage III infiltration rates were high because steady-state flow had not yet been achieved in all infiltrometers within the 3-day test period — much shorter than natural playa hydroperiods of weeks to months.

Reed (1994) conducted a water budget study of 3 playas in Carson County at the Pantex Plant. Playa 1 received discharge from the site's wastewater treatment plant, and, as a result, retained water continuously, along with runoff from surrounding industrial and grassland areas. Playas 2 (cropland and grassland) and 3 (grassland only) only received storm runoff. A water budget model was developed specifically to calculate infiltration rates through Playas 2 and 3. Daily meteorological data from the National Weather Service station at the Amarillo airport were used to compute evapotranspiration rates by the Penman equation. Typical infiltration rates ranged from 3.1 to 7.5 millimeters/day (totaling 1930 millimeters/year) for Playa 2 and 2.1 to 4.4 millimeters/day (totaling 1185 millimeters/year) for Playa 3. Wood et al. (1997) later expanded the study to specifically relate recharge amounts of macropore recharge within the playa floors to micropore recharge in the upland areas surrounding the playas. Based on the combination of the water budget results with geochemical chloride and tritium tracer calculations, they estimated that macropore flow was 25 to 50 times faster than interstitial flow through the playa bottom sediments.

James (1998) reported a hydrologic budget analysis on 5 urban playa lakes that were permanently wet due to urban storm runoff from Lubbock, Texas, over a 2-month period in the summer of 1995. In urban settings, urban playas collect stormwater volumes that have been increased by land development and urbanization. During the residential and commercial development of these neighborhoods, these playas were deepened by removing some of the natural hydric soils to increase the storage volume for the increased runoff from the increased impervious areas, but the bulk of the playa

floor soils were still the Randall clay found in the rural playas. Water surface elevations were measured using pressure trans-ducers. Meteorological data were obtained from the National Climatic Data Center for evapotranspiration calculation, and topographic data were obtained from bathymetric and land surveys. The water budget analysis yielded infiltration fluxes that ranged from 3 to 48 millimeters/day and hydroperiods of 18 to 49 days. West (1998) performed a companion water budget analysis on 6 urban playa lakes in Lubbock, Texas, including 5 of the same lakes observed by James (1998). Six lakes were observed during the summer of 1995, and 2 lakes were also monitored during the summer and fall of 1997. West (1998) noted that the infiltration rates varied from 1.5 to 14 millimeters/day, with hydroperiods varying from 11 to 142 days.

METHODS

Study area

For this study, 10 pairs of playas, 1 surrounded by cultivated cropland and 1 by grassland, were chosen in 10 SHP counties as shown in Figure 3 and Table 1. The study sites were selected as pairs of similarly sized playas, each relatively close to the other to minimize differences in rainfall and surrounding soils. The watershed area contributing to each playa was carefully delineated considering both local topographic maps and the influence of roadways and ditches; the watershed areas are also listed in Table 1.

Table 1. Location and land use of playas.

Station	County	Land use	Latitude (decimal degrees)	Longitude (decimal degrees)	Watershed area (hectare)
1	Floyd	Grass	34.095	-101.117	145
2	Floyd	Crop	34.073	-101.315	244
3	Briscoe	Crop	34.487	-101.279	391
4	Briscoe	Grass	34.499	-101.398	161
5	Swisher	Crop	34.542	-101.571	125
6	Swisher	Grass	34.486	-101.548	83
7	Hockley	Grass	33.401	-102.485	129
8	Hockley	Crop	33.494	-102.408	109
9	Bailey	Grass	34.021	-103.018	244
10	Bailey	Crop	34.033	-102.676	103
12[1]	Lubbock	Grass	33.491	-101.591	18
13	Lubbock	Crop	33.807	-102.056	187
14	Crosby	Crop	33.541	-101.298	203
15	Crosby	Grass	33.512	-101.260	169
16	Castro	Crop	34.544	-102.231	557
17	Castro	Grass	34.665	-102.221	566
18	Carson	Crop	35.358	-101.321	586
19	Carson	Grass	35.461	-101.280	364
20	Gray	Crop	35.266	-100.951	51
21	Gray	Grass	35.268	-100.922	21

[1]Station 11 was assigned to the Lubbock data collection site.
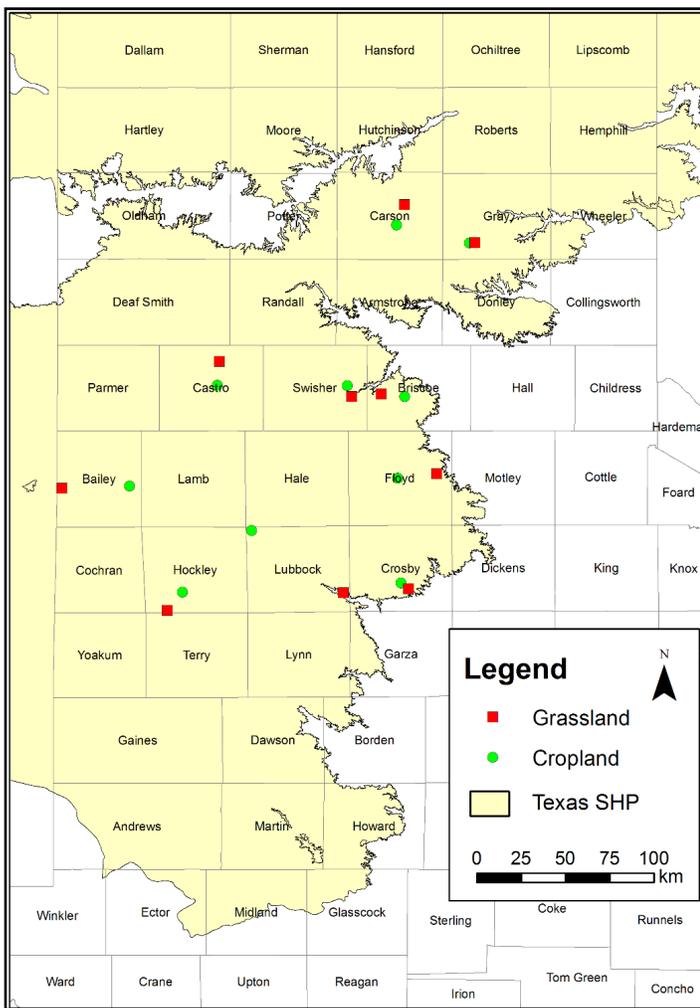
Figure 3. Study area showing playa locations in the Southern High Plains (SHP) in Texas.

Basic water budget

The hydrologic budget model is an application of the law of conservation of mass for the playa lake for a given time period, as expressed by the continuity equation denoted by equation 1

$$\Delta S = PA + R - EA - IA \qquad (1)$$

where P = precipitation (meters), R = runoff into the playa (meters^3), E = free water evaporation (meters), A = free water surface area (meter^2), I = infiltration flux (meters), and ΔS = change in storage (meters^3). Transpiration losses by vegetation type and season within the inundated playa were not considered separately as collection of that data was beyond the scope and budget of the project. The research team chose to emphasize collecting similar data in as many playa locations and land uses as financially feasible, which limited the types of data that could be quantified. The free water evaporation loss from the

playa water surface to the atmosphere was assumed to be much greater than transpiration because of the large water surface area of the playa relative to the coincident vegetation. Movement of runoff into the playas was primarily overland flow that could not be measured directly, and some playas were also influenced by roadway ditches or subtle flow channels that drained part of their watersheds.

The project team defined an inundation period as the time between consecutive significant precipitation events during which the playa held standing water. In dry periods of no rainfall, the water depth in the playa was constant at zero. Inundation began when runoff from rain events initially flooded the playa. Following significant rainfall events and subsequent inundation, the water depth in the playa increased due to runoff and then declined due to infiltration flux and evaporation.

Precipitation and runoff were considered inputs to the playa system, whereas evaporation and infiltration were considered outputs. Change in storage represented the quantity of water left in the playa after accounting for losses due to evaporation and infiltration. Between precipitation and runoff events, runoff and precipitation were zero, leaving

$$I = -\left(\frac{\Delta S}{A}\right) - E \qquad (2)$$

for a given time period. Free water evaporation can only be estimated using calculations based on multiple weather data measurements as shown in the next section, each with its own uncertainty caused by instrument and maintenance limitations. The change in storage for the playa contains approximations based on the water level measurement approach and movement of the water surface caused by winds as well as the surveyed topography of the playa bottom. All of these uncertainties are then lumped into the overall estimate of infiltration through the playa floor as the final unknown in the water budget. The total error in the infiltration calculation could be similar in magnitude to the calculated values, which encouraged great care in all instrument maintenance, data processing, and evaluation of the numerical results.

Evaporation model

For this study, the Penman-Monteith equation was used to model evaporative losses from the playa basin and is denoted by equation 3 below (Maidment 1993).

$$E_p = \frac{\Delta}{(\Delta + \gamma)} \frac{R_n}{\rho_w \lambda} + \left(\frac{\gamma}{\Delta + \gamma}\right)\left(\frac{6.43(1 + 0.536U_2)D}{\lambda}\right) \qquad (3)$$

where E_p = potential evaporation (millimeters/day), R_n = net radiation exchange for the free water surface (millimeters/day), U_2 = wind speed, measured at 2 meters (meters/day), D = vapor pressure deficit (kilopascals), λ= latent heat of vaporization (megajoules/kilogram, Δ = gradient of vapor pressure (kilopascals/degree Celsius), γ = psychrometric constant (kilopascals/degree Celsius, and ρ_w = density of water (kilogram/meter³). The vapor pressure deficit (D) is calculated as

$$D = e_s - e \tag{4}$$

where e = vapor pressure (kilopascals) and

$$e_s = 0.6108\,exp\left(\frac{17.27T_a}{237.3 + T_a}\right) \tag{5}$$

where T_a = observed air temperature (degree Celsius).The latent heat of vaporization (γ) is calculated by

$$\lambda = 2.501 - 0.00236T_s \tag{6}$$

where T_s = observed water surface temperature (degree Celsius). The gradient of vapor pressure is found as

$$\Delta = \frac{4098e_s}{(237.3 + T_a\,)^2} \tag{7}$$

The psychrometric constant (γ) is calculated by

$$\gamma = 0.0016286\,\frac{P}{\lambda} \tag{8}$$

where P = atmospheric pressure (kilopascals). A wind speed correction factor of 1.0082 was recommended by the manufacturer for the instrumentation (Campbell Scientific, Logan Utah, 1998) to scale up the wind speed, U_2 (meters/second), observed at the sensor level.

It should be noted that true values of free water evaporation are not available, as all equations or field observations in evaporation pans or other devices are estimates at best. The Penman-Monteith equation was selected as a model to calculate evaporation rates because of its success in 2 previous regional studies. The complex nature of equations 3 through 8 makes it difficult to quantify the uncertainty in the daily evaporation calculations based on the uncertainties in the multiple observed weather data. Acceptance of the calculated estimates is typically supported by comparing them with other reported estimates from nearby locations. Dean (1993) confirmed that evaporation rate estimates from the Penman-Monteith equation agreed with corrected pan evaporation measurements

from a local research station in Lynn County in 1990-91. The average daily evaporation rates for the Penman-Monteith and corrected pan evaporation methods were 5.5 and 5.6 millimeters/day, respectively. Rainwater et al. (2005) used a Penman-type equation to calculate evapotranspiration (ET) rates in a study dealing with septic tanks and their drainfield capacities. During the year 2000, the total ET was 1820 millimeters, which compared well to the average uptake of 1830 millimeters from the ET trenches. In the current study, the calculated free water evaporation estimates were measured to the Texas Water Development Board's monthly lake evaporation data reports for appropriate locations across the state (TWDB 2014). These data were provided as monthly totals in each year, so seasonality and precipitation impacts were included, even though the daily values were not provided. Weighted average evaporation rates were calculated for the hydroperiods.

Weather stations and device information

Instrumentation units were assembled and placed within the playa basins to track precipitation and water level, and provide variables for calculation of free water evaporation. Sensors for measuring wind speed (014A Anemometer*, Met One Instruments, Grants Pass, Oregon), air temperature and relative humidity (HMP50-L Temperature and Relative Humidity Sensor, Campbell Scientific Inc.), precipitation (TR-525M tipping bucket rainfall sensor, Texas Electronics Inc. Dallas, Texas), and water depth (260-700 Ultrasonic Snow Depth Sensor, NovaLynx Corp. Grass Valley, California) were mounted on a horizontal boom at 2 meters above the playa bottom. A 1 meter by 1 meter steel plate placed directly below the ultrasonic depth sensor prevented weed growth and provided a clean echo reflection surface. Radiation as both global down-welling solar radiation (LI-200 solid state pyranometer, LiCor Inc. Lincoln, Nebraska) and net solar radiation (NR-Lite2 thermopile radiometer, Kipp & Zonen USA Inc., Bohemia, New York) were measured with sensors placed on the primary tripod or on a remotely mounted 2-meter mast. A thermocouple mounted on the lower surface of an expanded Styrofoam float measured the water surface temperature. Another thermocouple placed at a depth of 5 centimeters below the soil surface measured the temperature of the playa basin. All data were recorded as 15-minute averages. With the exception of wind speed and precipitation, all variables were logged at 1-second intervals averaged over 15 minute and were recorded with a programmable datalogger (CR-1000, Campbell Scientific Inc.). Because precipitation and wind speed transducers deliver discrete pulses rather than continuous voltages, these data were

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totaled over 15-min periods and recorded. A digital cellular modem provided internet connectivity to each datalogger so that data could be downloaded weekly for cursory inspection and plotted monthly for visual inspection and comparison in an attempt to ensure data integrity.

Equations 3 through 8 were used to calculate the evaporation for each 15-minute time interval in each day, then those values were summed to get a daily evaporation amount. The average water surface elevations for each day were used to estimate the water surface area and storage volume for each day.

Elevation-area and elevation-volume relationships

As shown in equation 2, the water budget components for this study, storage, evaporation, and infiltration flux were calculated on a volumetric basis. The Penman-Monteith procedure in equations 3 through 8 yielded potential evaporation rate in millimeters/day. Therefore, a method was required to determine the changes in playa water storage on a volumetric basis, as well as playa water surface area to convert the evaporation rates to a volumetric basis. Elevation-volume and elevation-area curves were developed from topographic data determined through GPS surveys and Surfer® (Golden Software 2009). Polynomial equations were fitted to the data points to calculate each elevation-volume and elevation-area curve. For some of the playas, single smooth trend lines sufficiently fit the data. In some instances, several polynomial lines were required for different segments of the data, thereby completely representing the surveyed topography. The playa bottom shapes varied from near circular to rectangular when viewed from above, the playa bottoms were not completely flat, and the upward slopes at the edge of the hydric soils into the coarser annulus upland soils were not consistent. The goal was to honor the data points calculated by Surfer® rather than produce smooth curves.

Water budget calculation

The water surface elevation values for the playas after each rainfall event were used as the independent variables in the volume and area curves. The volume of water stored and the surface area of water at the exact water surface elevation were computed using the polynomial equations from the volume and area curves. The change in storage was computed and the daily evaporation, multiplied by that day's surface area, resulted in evaporation values on a volumetric basis. Adhering to the water budget model in equation 2, subtraction of evaporation from storage resulted in the estimate of infiltration volume through the playa bottom, which was then divided by that day's water surface area to obtain the daily infiltration flux. Daily infiltration flux values were averaged for each inundation period. Sequential inundation periods were summed for the lengths of the hydroperiods.

Uncertainties in the free water evaporation calculations and the water level measurements were both lumped into the final estimate of the daily infiltration flux. Quantitative analysis of errors is possible for the results of simple equations that combine variables that can be assumed to be normally distributed, or at least have simple error distributions within the range of observed values. In our case, the observed weather variables varied both within each day as well as across seasons of the year, so comparison of mean or median values with associated variations about those values was problematic. The challenge of calculating small amounts of infiltration flux by comparing small changes in water levels and daily evaporation amounts was still well worth pursuing, but precise quantification of errors in infiltration flux was not pursued. The hypothesis considered the potential difference in infiltration fluxes between playas with different surrounding land use, so the means and standard deviations for the inundation events observed in each playa were compared.

RESULTS

Deployment of instrumentation began in 2005, and data collection continued into 2011. Occasional instrument problems were encountered and repaired, but unfortunately some rainfall and inundation events were not captured completely. During that time period (2005–2011), the Floyd grassland (station 1), Floyd cropland (2), Briscoe cropland (3), Swisher cropland (5), Hockley cropland (8), Bailey grassland (9), Bailey cropland (10), Castro grassland (17), and Gray cropland (20) playas received sufficient rainfall for significant inundation while all instruments were operational. Examples of the relationship between rainfall and water depth in playas during their hydroperiods are shown in Figures 4 to 10. The figures emphasize long-term observations while the playas were inundated, so the time scales differ between playas, and the infiltration conditions are Stage III.

Typical calculated daily evaporation rates are shown in Figure 11 for the Briscoe cropland playa (3). The evaporation rates adhered to normal seasonal weather patterns (higher in summer, lower in winter), as well as day and night diurnal variations. The relationship between infiltration rates across the playas varied over time based on the differences in rainfall/runoff events that affected the depth of water in the playas (providing hydraulic head for infiltration), the season of the year (higher evaporation during the summer and lower evaporation in the winter), and the land use differences. For example, both playas in Floyd County held water during 3/10/2007 to 1/20/2008. The grassland playa infiltration rates for different inundation periods varied from 0.2 millimeters/day during 6/12/2007 to 7/12/2007 (depth fell from 68 to 50 centimeters) to 2.4 millimeters/day during 12/27/2007 to
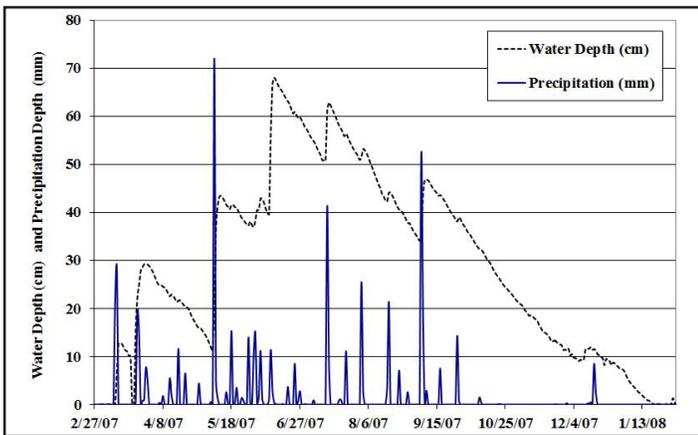
Figure 4. Water depth and precipitation during significant inundation periods at Station 1, Floyd grassland playa.
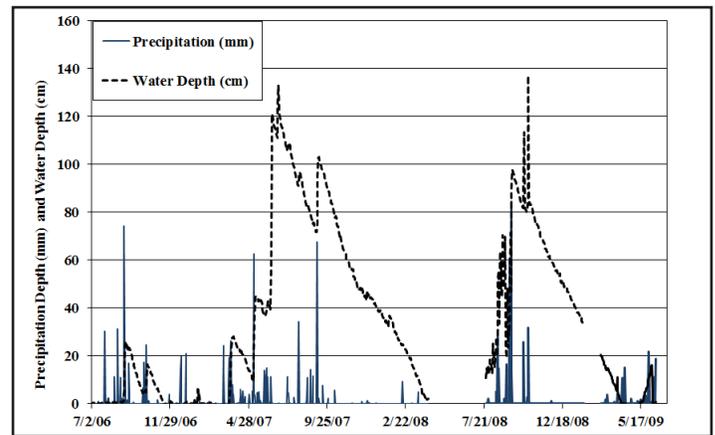
Figure 5. Water depth and precipitation during significant inundation periods at Station 2, Floyd cropland playa.
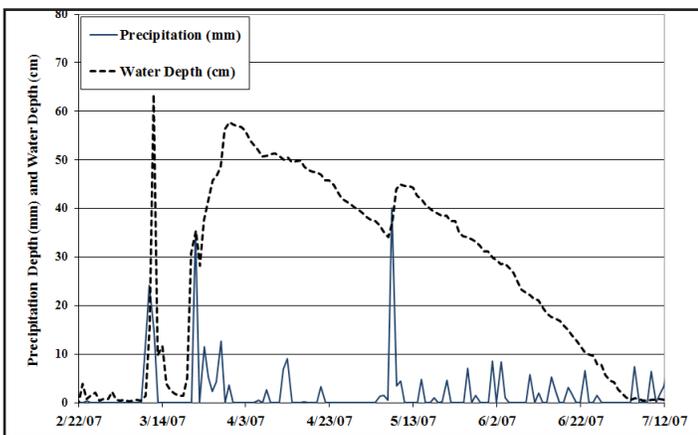
Figure 6. Water depth and precipitation during significant inundation periods at Station 3, Briscoe cropland playa.
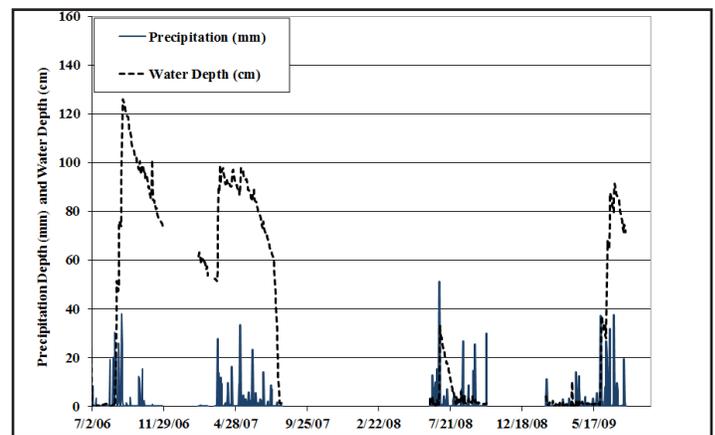
Figure 7. Water depth and precipitation during significant inundation periods at Station 5, Swisher cropland playa.

1/20/2008 (depth fell from 8 to 0 centimeters). The cropland playa infiltration rates for similar inundation periods were 7.0 millimeters/day during 6/24/2007 to 7/10/2007 (depth fell from 132 to 105 centimeters) and 1.7 millimeters/day during 12/11/2007 to 1/14/2008 (depth fell from 47 to 33 centimeters). These incremental values from Ganesan (2010) demonstrated the complexity of the comparisons.

An example of the elevation-volume and elevation-area curves is shown in Figure 12 for the Floyd grassland playa (1). The shape of the elevation-area curve shows that the area of the water surface increases by 100% within the first 10 centimeters of elevation change, then by another 50% over the next 70 centimeters. Complete sets of all observations and measurements are available from the corresponding author upon request.

Hydroperiods varied with location and rainfall amount (Table 2, Figure 13). Based on our definition of inundation period as time with water stored in the playa between rainfall events, it should be noted that multiple inundation periods

were often included in 1 hydroperiod. The TWDB (2014) ranges of lake evaporation rates for the different counties and time periods are also listed for subsequent comparison to our calculated values. Seven of the 25 hydroperiods lasted through at least part of the winter months (Bailey grassland once, Floyd grassland once, Floyd cropland 3 times, and Swisher cropland twice), which were historically the months with the least rainfall and runoff. The prolonged hydroperiods were caused by sequential storm frequency and intensity, with the time between rainfall events insufficient for complete drainage. The other 18 hydroperiods ranged from less than 2 weeks to over 5 months. The shortest hydroperiods were associated with the cropland playas in Swisher, Hockley, Gray, and Bailey counties. The shortest hydroperiods were greatly affected by their relatively small amounts of rainfall. The 2 grassland playas with observed hydroperiods received relatively large amounts of rainfall during those hydroperiods. The relationship between hydroperiod length and precipitation is shown in Figure 13. The total hydroperiod in days, H, versus total rainfall in milli-
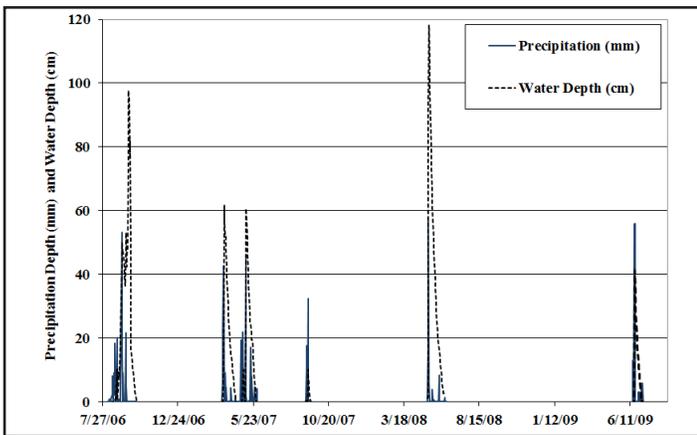
Figure 8. Water depth and precipitation during significant inundation periods at Station 8, Hockley cropland playa.
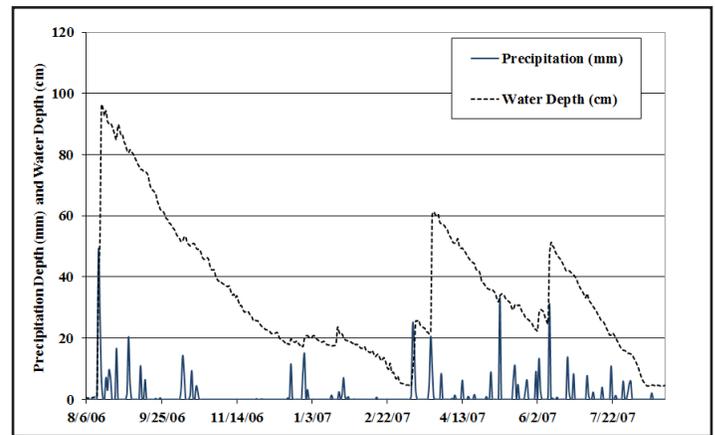
Figure 9. Water depth and precipitation during significant inundation periods at Station 9, Bailey grassland playa.
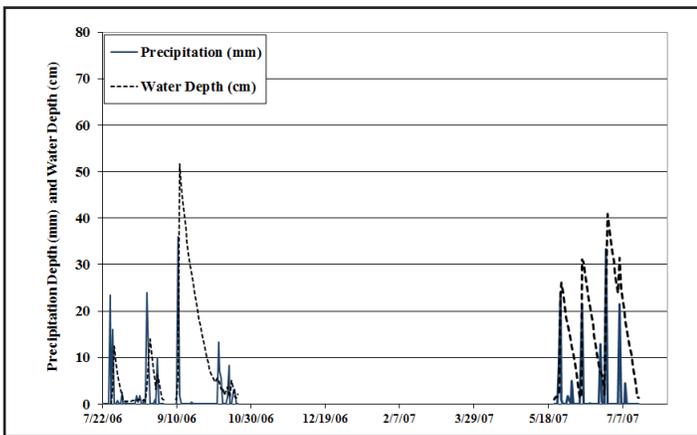
Figure 10. Water depth and precipitation during significant inundation periods at Station 10, Bailey cropland playa.
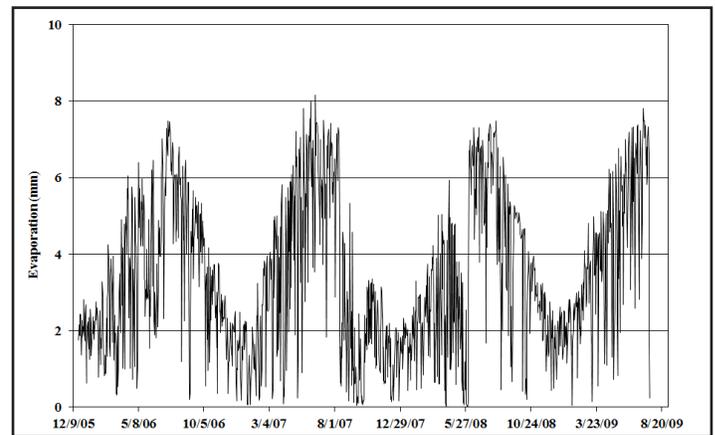
Figure 11. Daily evaporation values at Station 3, Briscoe cropland playa.

meters during the hydroperiods, P_H, was fitted with a power law equation as

$$H = 0.13\, P_H^{1.23} \qquad (9)$$

with R^2 of 0.91. The fitted equation is interesting but simplistic, as it does not include any other variables that describe the rainfall events or hydrologic characteristics of the playas or their watersheds. It should also be noted that the smallest P_H value included in Table 2 was 43 millimeters in the Bailey cropland playa, of which almost 24 millimeters fell on the first day of inundation, similar to other observations of threshold precipitation amounts for runoff to playas (Reed 1994). Future progress by the research team with more observations in more playas should improve understanding of the characteristic behaviors of the playas in different locations and land use.

Water budget results are displayed in Table 3. Among the playas surrounded by cultivation, the number of inundation periods varied from only 1 for the Gray cropland playa to 42 for

the Briscoe and Swisher cropland playas. The Floyd, Bailey, and Castro grassland playas had inundation periods of 12 , 15, and 5 days, respectively. Average inundation period lengths, which represented the time between significant rainfall events during hydroperiods, ranged from 12 days for the Bailey and Swisher cropland playas to 29 days for the Briscoe cropland playa. Of course, the frequency of rainfall events did not depend on the location or land use but was more subject to random meteorological conditions. The calculated average evaporation rates shown in Table 3 appeared reasonable as compared to the weighted average evaporation rates from the TWDB (2014) database for the hydroperiods. Daily evaporation and infiltration volumes were found by multiplying the daily evaporation rates by that day's average water surface area.

Figure 14 allows visual comparison of the average infiltration flux rates for each playa, along with their standard deviations. It is noted that these datasets may not be large enough for proof of normal distributions, but the mean and standard deviations are useful for this preliminary comparison. In Floyd and Bailey

Table 2. Summary of hydroperiod data.

Station	County	Land use	Hydroperiod dates	Hydroperiod duration (day)	Rainfall (millimeters)	TWDB evaporation (millimeters/day)
1	Floyd	Grass	3/10/07–1/20/08	254	557	4.6
2	Floyd	Crop	9/1/06–11/17/06	78	210	4.3
			3/21/07–4/3/08	378	472	4.5
			7/13/08–4/10/09	269	332	4.5
			4/16/10-1/5/11	254	520	5.6
3	Briscoe	Crop	3/18/07–7/4/07	109	216	4.0
5	Swisher	Crop	8/18/06–7/31/07	254	479	3.9
			6/22/08–8/2/08	42	93	7.4
			5/22/09–7/23/09	63	238	7.2
			6/5/09–11/17/09	166	378	6.3
			4/16/10–1/18/11	275	608	5.5
8	Hockley	Crop	8/19/06–10/3/06	45	197	4.7
			3/20/07–4/21/07	33	94	4.8
			4/28/07–5/30/07	33	124	3.7
			9/4/07–9/16/07	13	62	4.6
			5/4/08–6/13/08	41	97	6.9
			6/16/09–7/7/09	22	82	7.4
9	Bailey	Grass	8/12/06–3/9/07	210	273	3.5
			3/10/07–8/20/07	164	311	4.8
10	Bailey	Crop	7/26/06–8/8/06	15	43	6.4
			8/12/06–9/1/06	21	50	5.7
			9/9/06–10/20/06	32	80	4.1
			5/22/07–7/18/07	58	149	4.6
17	Castro	Grass	5/16/10–8/5/10	82	124	6.0
20	Gray	Crop	7/2/11–8/2/11	22	70	9.2

Table 3. Water budget results (rates in millimeters/day).

Station	County	Land use	Number of inundation Events	Average inundation duration (days)	Average daily evaporation (meters³)	Average evaporation rate	Average infiltration flux volume (meters³)	Average infiltration flux rate	Infiltration flux standard deviation
1	Floyd	Grass	12	20	651	4.9	114	0.9	1.0
2	Floyd	Crop	36	21	613	5.7	345	2.8	1.5
3	Briscoe	Crop	42	29	490	5.1	199	2.0	0.3
5	Swisher	Crop	42	12	517	5.3	453	4.7	2.6
8	Hockley	Crop	6	17	74	5.2	342	19.8	4.7
9	Bailey	Grass	15	15	431	5.2	221	2.6	1.5
10	Bailey	Crop	7	12	91	6.0	271	17.4	3.2
17	Castro	Grass	5	13	95	6.2	99	4.7	1.5
20	Gray	Crop	1	13	260	8.9	106	3.8	na
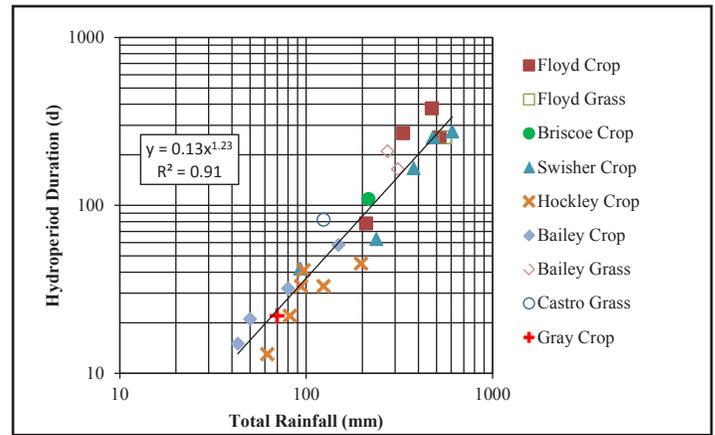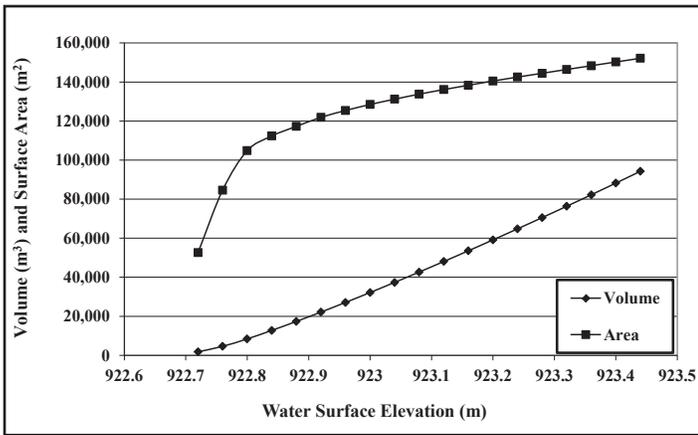
Figure 12. Playa volume and area versus elevation for Station 1, Floyd grassland playa.

Figure 13. Hydroperiod length versus total rainfall during hydroperiod.
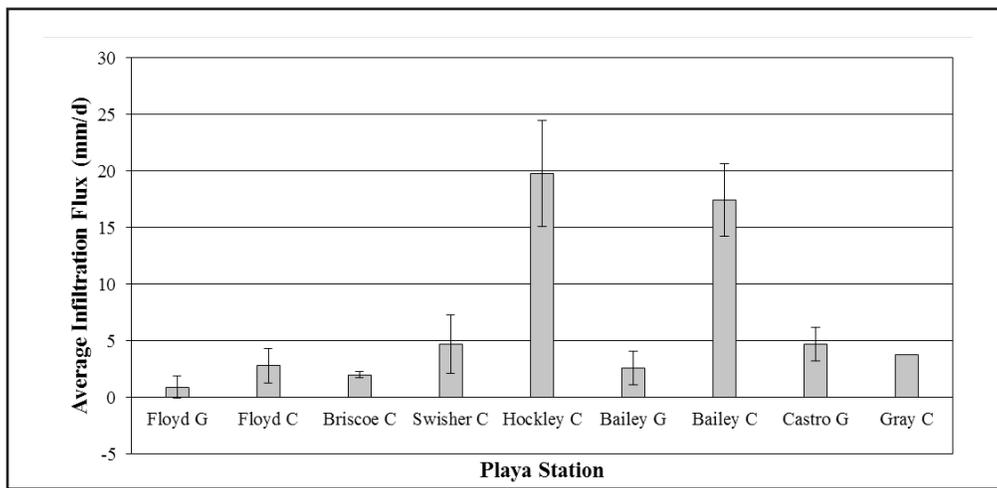
Figure 14. Comparison of average infiltration flux rates across playas.

counties, we were able to compare the average infiltration flux rates estimated for both the cropland and grassland playas. The Floyd cropland playa average infiltration flux rate was 2.8 ± 1.5 millimeters/day, while the Floyd grassland playa average infiltration flux rate was 0.9 millimeters/day ± 1.0 millimeters/day, indicating more infiltration on average in the cropland playa, but the difference between the 2 land uses was not large as both flux rates were relatively small. The Bailey cropland playa average infiltration flux rate was 17.4 ± 3.2 millimeters/day, while the Bailey grassland playa average infiltration flux rate was 2.6 ± 1.5 millimeters/day, which appeared to be a significant difference. Comparison of the 7 cropland playa results showed large differences in the average infiltration flux rates. The Bailey and Hockley cropland playa infiltration flux rates were significantly higher than those for the other 5.

The findings by Villarreal et al. (2012) provided useful insights for the playas in Briscoe, Floyd, and Swisher counties.

In all 6 playas, they found non-uniform distributions of the erosional sediments across the hydric soils in the playa bottoms, affected by both the runoff inflow systems and windblown movement of sediments. The average sediment depths in the Floyd cropland and grassland playas were both 18 centimeters. The clay and sand fractions were 61±12% and 17±13%, respectively, in the cropland playa and 65±11% and 11±8% in the grassland playa, which appeared to relate to the greater infiltration flux in the cropland playa. The Briscoe cropland playa had average sediment depth of 23 centimeters, with 57±10% and 6±6% clay and sand fractions, respectively. The Swisher cropland playa had a much higher average sediment depth of 29 centimeters, with 60±10% and 9±5% clay and sand fractions, respectively. These 2 playas had relatively low infiltration flux rates among the cropland playas, but they exceeded average rates for 2 of the 3 grassland playas. Overall, these analyses do not cause rejection of the study's hypothesis,

but the hypothesis is not yet confirmed. Complete determination of the mechanisms of the potentially enhanced infiltration and the associated reduction in hydroperiods length in playas filling with cropland sediments has not yet been achieved, but the research team is continuing the monitoring of these 10 and additional SHP playas in pursuit of that understanding.

Our preliminary average infiltration flux rates did follow other published results. James (1998) reported infiltration rates of 5 urban playas in Lubbock County ranging from 3.0-48 millimeters/day, while West (1998) observed infiltration rates ranging from 1.5-14 millimeters/day in the same playas. Hydroperiods in the 2 studies lasted from 18 to 49 days and 11 to 142 days, respectively. Their infiltration rates were similar to the results of this study, although the period of observation in this study was much longer. Reed (1994) found typical infiltration flux rates in more rural playas at the Pantex Plant that ranged from 3.1 to 7.5 millimeters/day for Playa 2 and 2.1 to 4.4 millimeters/day for Playa 3.

CONCLUSIONS

This study incorporated a water budget model to calculate infiltration rates through pairs of playas in 10 northwest Texas counties during 5 years of observations. Inundation periods with consistent data collection were observed in 9 of the playas. Two cropland playas had mean infiltration fluxes 3 to 6 times higher than their grassland counterparts in the same counties, tending towards shorter hydroperiods of 3 months or less if rainfall events were widely distributed in time. The presence of sediments in the cropland playa clays may contribute to the higher infiltration flux rates. The timing and intensity of rainfall events appeared to have great control over which playas caught and held runoff, and those conditions can vary greatly over short distances in the SHP, even within a county. The ongoing plan for this long-term project is to observe the hydroperiod behaviors at each playa over many years. A longer dataset will hopefully allow more statistical significance to determining land use effects on playa hydroperiods and infiltration losses as, they might be separated from other hydrologic factors.

Sustainability of the Ogallala Aquifer is an open question because of a declining water table in locations of groundwater withdrawal. It is known that recharge to the aquifer occurs via infiltration of water through playas, though the actual amount has rarely been quantified. Playa watershed land use affects the structure of and recharge through playas. Therefore, understanding recharge and the conditions that affect recharge to the playas is imperative in preserving the Ogallala Aquifer that serves so many important needs. Conservation of these important wetlands is necessary for future replenishment of the Ogallala, as well as for maintenance of the region's vital ecosystems.

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