Wetlands
DOI 10.1007/s13157-017-0940-2

ORIGINAL RESEARCH

Using Satellite Imagery to Examine the Relationship between Surface-Water Dynamics of the Salt Lakes of Western Texas and Ogallala Aquifer Depletion

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Received: 15 February 2017 / Accepted: 2 August 2017

Abstract We used Landsat imagery to examine surface-water dynamics over the past 27 years in 39 salt lakes (salinas) of the Southern High Plains of the U.S. These groundwater- and precipitation-fed wetlands are regionally unique habitats with high salt concentrations and halophytic biota that may be vulnerable to hydrological changes from groundwater extraction for agriculture coupled with drought. We documented amounts and occurrences of water within the 39 salinas, comparing summer and winter (representing periods of high and low groundwater demand, respectively) in 1986–2013. During this span in our study area, total and irrigated cropland acreage increased, and the saturated thickness of the Ogallala Aquifer decreased by ~18.3%. There was variation in inundation frequency by salina, with two never holding water during our study. A third of the salinas went dry at least once, slightly more in summer than winter. Occurrence of water was not simply a function of basin size or to depth to the aquifer. These wetlands are being impacted by human changes to the landscape that are diminishing groundwater inputs, effectively creating novel wetlands that are now primarily supplied by precipitation rather than groundwater, with altered hydrological and ecological traits that may exacerbate regional vulnerability to climate change.

Keywords Agriculture · Groundwater · High Plains Aquifer · Irrigation · Ogallala Aquifer · Salina · Salt playa

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Introduction

Groundwater-fed wetlands are critically important and often scarce habitat resources in arid and semi-arid areas throughout the world. Within hydrologically closed basins, salts in the groundwater accumulate over time, creating a unique ecosystem of brackish water and halophytic biota that may be quite different (hydrologically, geologically, and ecologically) from nearby precipitation-fed or groundwater-recharge freshwater wetlands (Fig. 1a). There are many terms used for these wetlands, including sabkhas, saline lakes, salt lakes, salt pans, salt playas, and salinas (the term we use in this paper). Such wetlands occur throughout the world, including Australia, the Middle East, central Asia, and western North America, where they often occur in conjunction with playas. Although the term "playa" is often used to refer to a desert pan in arid areas around the world, in North America the term is primarily used to refer to shallow, precipitation-fed wetlands in the Great Plains (Bolen et al. 1989; Smith 2003) (Fig. 1b). In the southern and central Great Plains, there are tens of thousands of these wetlands, which are ecologically important at a continental scale as habitat for migratory birds, as well as for regional populations of amphibians, aquatic invertebrates, and wetland plants (Smith 2003). In contrast, there is only a very small number of wetlands in this region that are spring-fed (i.e., salinas) (Wood et al. 1992), occurring at their highest density in the Southern High Plains (SHP) of western Texas and eastern New Mexico (Smith 2003). Salinas have received far less attention than have playas, which are ~500 times more numerous in this region (Rosen et al. 2013).

As wetlands in an otherwise dry region, salinas and playas are critically important wildlife habitat (Smith 2003). With regional groundwater containing >200 g/L dissolved solids (Osterkamp and Wood 1987), salinas become more saline over time via evaporation, thereby supporting a regionally

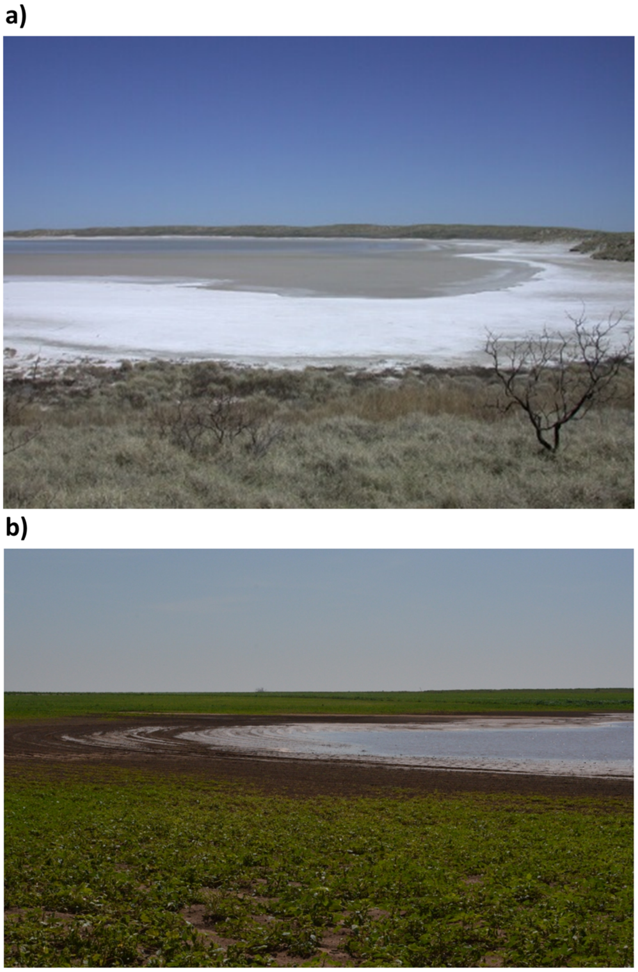


Fig. 1 **a** Photograph of a salina with extensive white salt "beach" in Texas, 2014. Photo by NEM. **b** Photograph of a playa surrounded by a cotton field in Texas, 2013. Notice the tilled furrows within the playa. Photo by NEM

unique halophytic biotic community that warrants conservation attention (Texas Parks and Wildlife Department 2005). Few members of the biotic community of salinas have been studied, primarily birds and plants (e.g. Saalfeld et al. 2011; Conway et al. 2005a, b; Andrei et al. 2008; Rosen et al. 2013), but other taxa are essentially unknown, indicating a pressing need for biotic inventories (Matthews 2008).

The SHP is semi-arid, with decreasing precipitation/ increasing evaporative demand from east to west (Nativ and Smith 1987). The rainy season is April through September, when approximately 73% of the annual 450–550 mm of precipitation occurs (NOAA National Weather Service: http://www.srh.noaa.gov/). Regional climate projections indicate that precipitation is expected to decrease by 20–30% by 2090, and precipitation events are expected to be reduced in frequency but increased in intensity (Matthews 2008; Karl et al. 2009). Despite its aridity, the region is extensively cultivated due to groundwater extraction from the Ogallala (High Plains) Aquifer, which intensified in the mid-twentieth century (Musick et al. 1990). The region accounts for most of the nation's cotton production (USDA 2007) as well as substantial production of wheat, sorghum, and corn, most of which is subsidized with irrigation (Dennehy et al. 2002). Agriculture has been implicated in the losses of playas, both directly (plowing through the hydric soil basin compromises its ability to hold water) and indirectly (sediment accrual from erosional deposits) (Johnson 2011; Collins et al. 2014; Starr et al. 2016). Because salinas are typically larger, saltier, and within deeper watersheds, however, they have not been subject to within-basin cultivation (Fig. 1). Even so, their hydrology may be affected by agriculture effectively competing with salinas for groundwater.

Salina hydroperiod should thus reflect both surface and groundwater inputs. Those salinas that retain their direct hydraulic contacts with the groundwater table (i.e., flowing springs) should contain water more often than those that no longer contact the top of the aquifer due to the water table dropping. Salina hydroperiod should also be associated with geomorphological features that influence surface water capture and retention, such as surface area and basin depth. The fact that the SHP is a flat tableland with topographic relief at a finer scale than Digital Elevation Model resolution (30 m), with basins that are shallower than DEM resolution, makes watershed delineation for salinas and playas problematic. Salina basin area can serve as a proxy of watershed area, however, and thus should be positively associated with frequency of water being present. Similarly, salina basin depth should be associated with water-retention frequency since deeper basins should not dry out as quickly.

Surface water presence and persistence are key ecological drivers in wetlands, including salinas (Conway et al. 2005a, b; Andrei et al. 2008). Salinas are generally larger in surface area than are playas, with a more consistent presence of water, but increased irrigation combined with drought has lowered groundwater tables, causing many formerly productive springs to experience reduced flow or even go dry (Brune 1981). This has led to a reduction in the number of salinas on the SHP with functional springs from ~40 to <10 (Rosen et al. 2013). Because the water table is not static throughout the course of a year, and given the seasonal nature of agriculture in the SHP, there should be a difference in surface water presence and amount in salinas between summer and winter due to differences in groundwater demand (with higher demand during the summer growing season, lower during the winter). Furthermore, salina basin area and depth should be positively associated with water-retention frequency, and those basins that hold water more frequently should be closer to or in direct contact with the groundwater table. Thus, the surface water dynamics of salinas should be intimately tied to anthropogenic land use as well as to their geomorphological traits, but there have been no studies that have quantified these patterns (Rosen et al. 2013). Therefore, our objectives were to conduct a longitudinal study of surface water dynamics in these poorly studied and imperiled wetlands to compare water availability between seasons (summer, winter) within as well as across years, and associate these with land-use change/ groundwater pumping rates. We predicted that: (1) more salinas would be dry in summer than winter due to differences in groundwater demand; (2) changes in surface water availability in salinas over time would be associated with changes in agriculture and irrigation over the past few decades; (3) water-retention frequency would be positively associated with salina basin area, depth, and sub-surface distance to the water table of the Ogallala Aquifer.

Methods

Our focus was on the salinas confirmed as present within the Playas and Wetlands Database (PWD; http://gis.ttu.edu/pwd, accessed 16 December 2015), which mapped the location of 64,726 waterbodies in a ~ 149,810 km^2 area encompassing the SHP of western Texas and eastern New Mexico, as well as the Oklahoma panhandle (Mulligan et al. 2014). The PWD was created from three data sources: (1) county soil surveys conducted by the Soil Conservation Service/National Resource Conservation Service from 1959 to 1998 (Fish et al. 1998) and from the Soil Survey Geographic Database that identified wetlands ≥0.11 ha based on presence of hydric soils; (2) aerial images with 0.0001 ha (1 m × 1 m) resolution from the 2004 National Aerial Imagery Program; and (3) aerial imagery from the 2004 U.S. Fish and Wildlife Service's National Wetlands Inventory, with wetlands delineated at a resolution of ~0.04 ha. The waterbodies of the PWD include saline lakes (i.e., salinas), impoundments, lakes, manmade waters, playas, riparian areas, scrub/other, and unclassified wetlands (see Mulligan et al. 2014 for descriptions). Thirty-nine salinas are present in the PWD, all within the Texas portion of the PWD area. There is some disparity across references in how salinas are identified and, thus, in their number and location. For example, some of the wetlands identified as salinas by Rosen et al. (2013) were not salinas in the PWD (e.g. Tahoka Lake, Grulla Lake). In the PWD, both of these waterbodies are identified as permanent lakes, although Grulla no longer has any spring flow (Rosen et al. 2013). Likewise, one assessment (unpublished data from D.A. Haukos, pers. comm., 2015) identified 43 salinas in eastern New Mexico (*n* = 10) and western Texas (*n* = 33) that included our focal area; our 39 focal basins included 24 of theirs and 15 that they did not identify as salinas. There are thus other waterbodies called salinas present in the U.S.; our analyses focused on those within the ~149,810 km^2 digitally mapped extent of the PWD.

Our workflow is illustrated in Fig. 2. We examined Landsat remotely sensed imagery from four satellite scenes to map the water within the 39 salina basins over seven dates (comparing summer and winter, representing periods of high and low groundwater demand, respectively) from 1986 to 2013. We obtained Landsat imagery from the USGS Global Visualization Viewer (GloVis, http://glovis.usgs.gov). We examined all summer (June and July) and winter (December and January) dates from scenes (path/row) 30/37, 30/38, 31/35, and 31/36. These scenes were chosen based on occurrence of salinas in the PWD (Fig. 3).

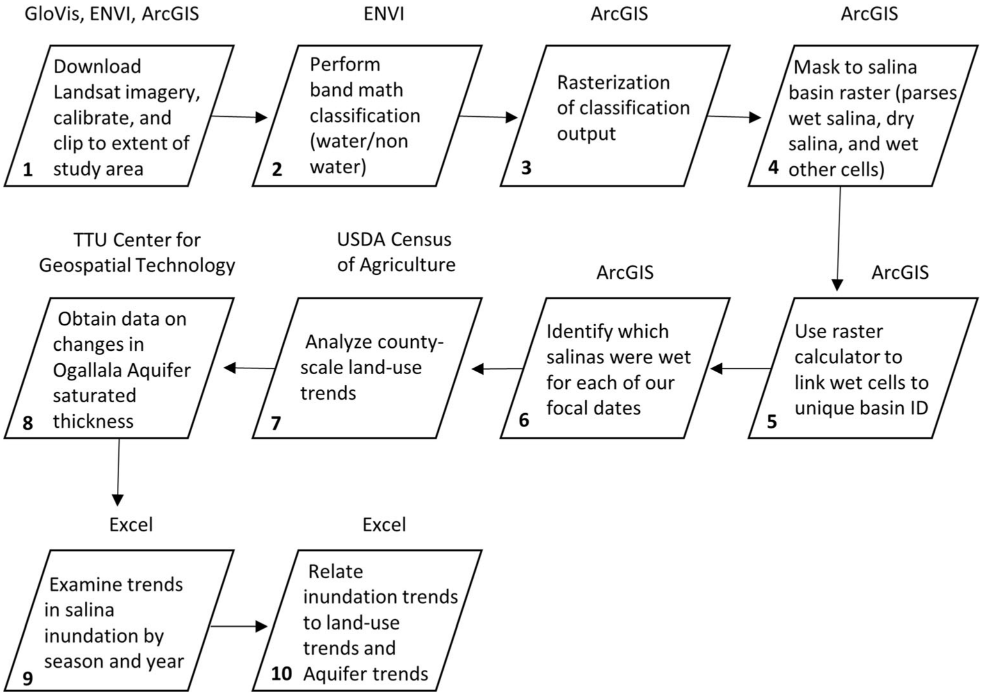
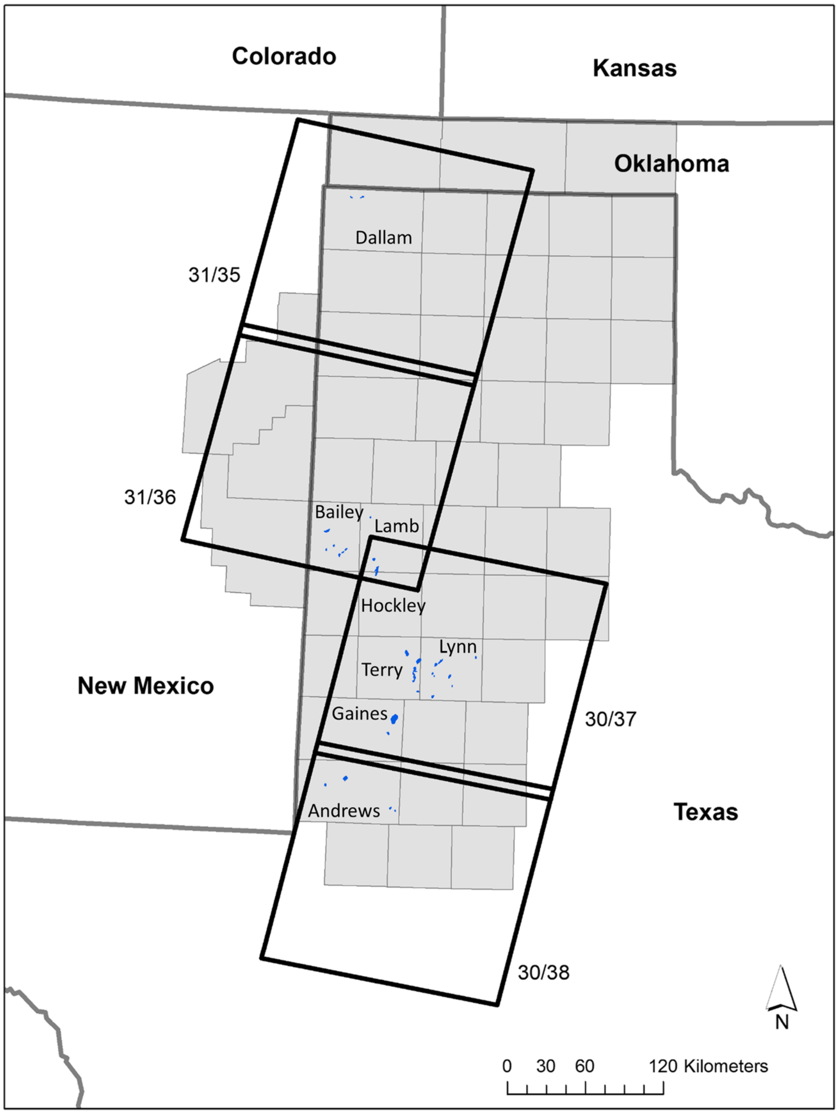


Fig. 2 Conceptual diagram of our workflow methodology. Actions are within boxes, and data sources and software used are listed on top of boxes

Fig. 3 Locations of salinas (blue polygons) within the extent of the PWD (shaded counties), and our four focal Landsat scenes (bold parallelograms; Landsat 8 OLI scenes depicted) in the south-central United States. Scene path/row numbers are adjacent to each scene. Names are included for the counties in Texas that contained salinas



Images from the four scenes during our two focal seasons were examined from December 1982 to August 2015. Each scene is flown at a 16-day interval, meaning that the two 30/x images were taken on the same date, and the two 31/x images were flown on the same date, but all four scenes were not flown on the same date. The intervals between 30/x and 31/x images were 7–9 days. We used only those images that were cloud-free (0% cloud cover) and of maximal quality (GloVis ranking of 9). After this filtering, we were able to obtain seven "consecutive" image dates for all four scenes ("consecutive" meaning 31/35 and 31/36 images came from the same date, and 30/37 and 30/38 images came from the same date but 7–9 days later at the first occurrence of the satellite in that flight path) (see Table 1). These images were fairly evenly distributed between summer and winter dates and across the 27-year span, and comprised all of the cloud-free data available simultaneously for all four scenes. Images from two satellites were used: Landsat 5 Thematic Mapper (TM; for dates prior to November 2011, when that satellite stopped functioning) and Landsat 8 Operational Land Imager (OLI; for dates after April 2013, when that satellite became functional). Whereas the Landsat 5 images were approximately 185 km × 185 km, Landsat 8 images were approximately 170 km × 185 km. All of the images for a given scene were clipped to a common extent covered by both satellites on all seven dates (115,851 km^2). Because scenes 30/37 and 31/36 overlapped substantially in one corner (Fig. 3) but were flown only 7–9 days apart, this allowed for a finer-resolution temporal examination for four salinas.

Image processing was done in ENVI 5.2 (Exelis Visual Information Solutions, Inc.; Boulder, CO) and followed the protocols in Collins et al. (2014), using a band math classification rule to distinguish water from non-water by comparing visible red to shortwave infrared bands. This method is a common way of identifying water in remotely sensed images (e.g. Kloiber et al. 2002; Ozesmi and Bauer 2002; Cariveau et al.

Table 1 Satellite images used in analyses, and numbers of wet and dry salina basins present per scene on each date. Scenes 31/36 and 30/37 shared four salinas (see Methods for explanation); these four are included for each scene/date. Summer images are from June and July, winter are from December and January

Season	Landsat satellite	Scene			
		31/35 *n* = 4	31/36 *n* = 11	30/37 *n* = 24	30/38 *n* = 4
Summer	5 TM	16 July 1986 3 wet, 1 dry	16 July 1986 10 wet, 1 dry	25 July 1986 23 wet, 1 dry	25 July 1986 3 wet, 1 dry
Winter	5 TM	14 Jan. 1995 2 wet, 2 dry	14 Jan. 1995 9 wet, 2 dry	7 Jan. 1995 21 wet, 3 dry	7 Jan. 1995 3 wet, 1 dry
Summer	5 TM	6 July 2000 4 wet, 0 dry	6 July 2000 10 wet, 1 dry	15 July 2000 21 wet, 3 dry	15 July 2000 3 wet, 1 dry
Summer	5 TM	10 June 2002 0 wet, 4 dry	10 June 2002 9 wet, 2 dry	19 June 2002 20 wet, 4 dry	19 June 2002 2 wet, 2 dry
Summer	5 TM	10 June 2008 0 wet, 4 dry	10 June 2008 9 wet, 2 dry	3 June 2008 22 wet, 2 dry	3 June 2008 2 wet, 2 dry
Winter	5 TM	20 Jan. 2009 3 wet, 1 dry	20 Jan. 2009 10 wet, 1 dry	13 Jan. 2009 21 wet, 3 dry	13 Jan. 2009 2 wet, 2 dry
Winter	8 OLI	17 Dec. 2013 1 wet, 3 dry	17 Dec. 2013 10 wet, 1 dry	26 Dec. 2013 20 wet, 4 dry	26 Dec. 2013 3 wet, 1 dry

2011; Ruiz et al. 2014; Starr et al. 2016). The 28 processed images were then converted to shapefiles projected to UTM zone 13 N (geographic coordinate system NAD 1983, datum WGS 1984) in ArcMap 10.2.2 (Esri; Redlands, CA) that were then rasterized to Landsat's native 30 m resolution. Non-salina waterbodies were removed from these images by using a rasterized mask of salina locations from the PWD. We extracted the 39 salinas from the PWD (separating them from the 64,687 other wetlands in the PWD) and used them to remove non-salina portions of the satellite images. By comparing the satellite images to the PWD data, we could quantify the surface water area present within each salina basin on each date with the Raster Calculator function in the Spatial Analyst extension in ArcMap, which generated a binary layer where wet areas within salinas were coded with each basin's unique identification number and other cells (dry salina basins or wet areas outside salinas) were coded as no data. These Raster Calculator products were then overlaid onto the Landsat images to extract data from only the water-covered areas within the salina basins on each date. From these data, we could determine how much surface water was present within each salina basin on each date. From these assessments, we were able to assign salinas to one of three mutually exclusive "wet status" categories: those that had water present on every date examined (always wet), those that had water present on only some but not all dates (sometimes wet/sometimes dry), and those that had no water present on any date examined (always dry).

Minimum depth to the water table (top of the Ogallala Aquifer) (Fig. 4) was derived from 30-m depth to water (DTW) rasters of the Ogallala Aquifer (Mulligan and Barbato 2016). The DTW rasters were also used to extract the maximum depth to the water table for each salina (Fig. 4). DTW rasters were created by subtracting a series of water table elevation rasters for 1990 to 2013 from a land surface elevation raster. Water table elevation (WTE) rasters were developed using a Baysian kriging of observation wells measured at the end of each pumping season (usually December to March) from 1990 to 2013. These wells are spaced many kilometers apart, with a density on average of about one every 23 square km. Although it is unknown what the aquifer is like in between these wells, interpolated WTE values produced rasters representing a reasonable estimate of aquifer surface. Minimum and maximum depth to water values for each salina were obtained by performing a zonal statistics process in ArcMap. This process evaluated DTW raster cell values within each salina (zone) and output the minimum and maximum DTW values by salina for all years

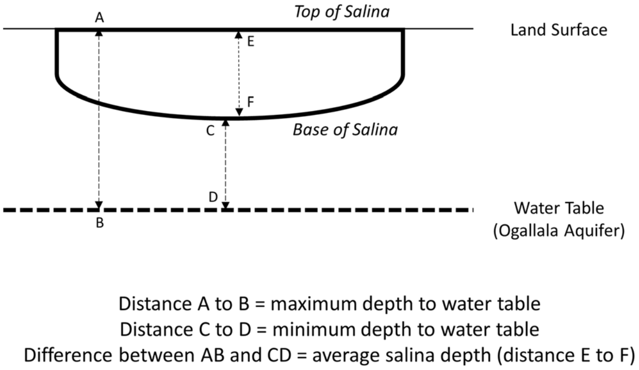


Fig. 4 Schematic of how salina depth was determined based on minimum and maximum depths to the Ogallala Aquifer

in the study period. The difference between maximum and minimum values provided the average depth of each salina basin (Fig. 4). Whereas salina basin area and depth did not change with date (being static geomorphological properties), wet surface area and depth to the aquifer could and did fluctuate.

We used SAS 9.4 (SAS Institute, Cary, NC) to conduct general linear model analyses of variance (ANOVA) with Tukey's post-hoc tests of means of basin area, basin depth, summer wet area, winter wet area, and minimum depth to top of the aquifer by wet status. Because of differences in the temporal properties of the response variables, three separate ANOVAs had to be conducted for (1) basin area and depth (which are static) by wet status, (2) minimum depth to top of aquifer each year by wet status, and (3) summer and winter wet areas by wet status (which have variable numbers of dates each year).

We used the USDA's Census of Agriculture (http://www.agcensus.usda.gov, accessed 22 October 2015) to examine changes in agricultural land use over time. The Census of Agriculture is conducted every five years and reports data at the county level. We obtained data on amount of total cropland and irrigated cropland present from the two censuses closest in time to our two temporal endpoints (the 1987 and 2012 censuses) for the eight counties (all in Texas) where our 39 salinas were located. As these data are reported by county, they provide a landscape-scaled assessment of land use.

We obtained data on the county-level change in saturated thickness of the Ogallala Aquifer from the period 1990–2008 from the Center for Geospatial Technology at Texas Tech University (http://www.gis.ttu.edu/center/Ogallala/OgallalaData.html). Saturated thickness raster surfaces (ST) were created by subtracting a base of aquifer raster containing elevation values from the WTE rasters for 1990 and 2008 (Mulligan and Barbato 2016). A change in saturated thickness raster for the study period was developed by subtracting the 1990 ST surface from the 2008 ST surface. Finally, the ST change in cell values for each county were obtained by summing for areas overlying the aquifer divided by the aquifer area of each county.

If salinas are becoming more reliant on precipitation as the water table drops, then there should be a significant relationship between the number of dry basins and the Palmer Drought Severity Index (PDSI) (i.e., salinas being increasingly dry during droughts). PDSI is calculated on a monthly basis on a scale from −10.0 to 10.0 (usually reported as "-4.0 and below" to "4.0 and above," with more negative values indicating more severe drought) over large "climate divisions." Our focal region was encompassed entirely within climate division "Texas 1" (NOAA National Weather Service Climate Prediction Center, http://www.cpc.ncep.noaa.gov, accessed 3 May 2017). Because the monthly value for each climate division is reported as a category (e.g. "-2.99 to −2.50"), we used the midpoint of this range for each of the seven months that we examined (see Table 1) as our predictor variable (data obtained from NOAA National Centers for Environmental Information, https://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/psi/201312-201312, accessed 3 May 2017), and number of salina basins that were dry (out of the 13 salinas that fluctuated in wet status) as our response variable in a Spearman (i.e., non-parametric) correlation analysis in SAS 9.4.

Results

We examined surface water occurrence in 39 salina basins over four summer dates and three winter dates from 1986 to 2013. The 39 salina basins present in our study area ranged in size from 3.7 to 2255.0 ha, averaging 211.2 ha in basin area, with basin depths ranging from 0.4 to 29.8 m, averaging 9.0 m. Seventeen of the salinas had been named by the USGS. The surface waters of salinas were dynamic through time, varying as much or more among years as between seasons. Furthermore, each salina had unique dynamics. There was individual variation in surface water area per salina, with two salina basins never holding water at all during the dates of the study and 24 basins that held water on every date examined (and 13 that contained water on only some dates) (Fig. 5). One-third (13/39, 33.3%) of the salinas went dry at least once, slightly more frequently during the summer (23 occurrences) than in winter (18) (Table 2). For the 13 salinas that did not exhibit temporal stationarity in wet status, there was a significant, positive relationship between drought severity and number of dry salinas present (Spearman's $\rho = -0.87$, $p = 0.0117$; recall that more negative Palmer Drought Severity Index values indicate more severe drought, so the negative correlation coefficient indicates a positive relationship between drought and number of salinas not containing water) (Fig. 6).

There were no statistically significant differences in average basin surface area among those salinas that were always wet, always dry, and those that fluctuated between wet and dry, primarily because of the very wide range of basin sizes in the always wet category (ANOVA $F_{2,\ 36} = 1.72$, $p = 0.1929$; Table 3). There were significant differences in basin depth among those salinas that differed in wet status, however, with basins that held water on all dates examined being deeper than salinas that went dry at least once or were always dry (ANOVA $F_{2,\ 36} = 5.47$, $p = 0.0084$, Tukey $p < 0.05$; Table 3). Furthermore, water surface areas (summer and winter) varied by wet status between always wet and sometimes wet salinas (ANOVA $F_{1,\ 283} = 22.06$, $p < 0.0001$, Tukey $p < 0.05$; Table 3).

Not surprisingly, those salinas that never held water were on average the smallest and most shallow, those that held water on every date examined were the largest and deepest,

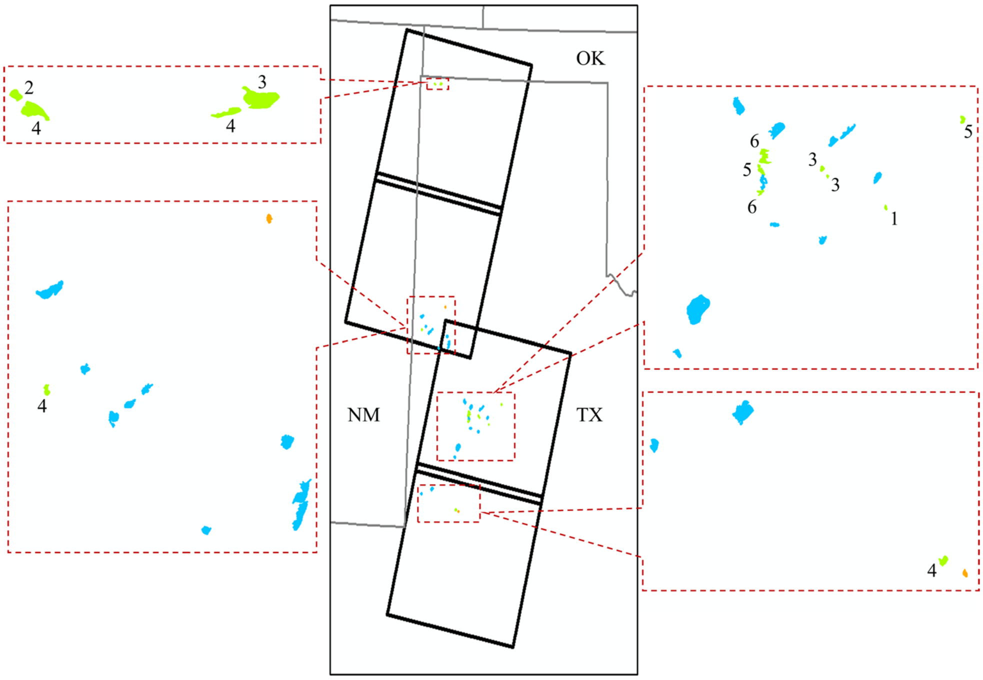


Fig. 5 Map of salinas, color-coded according to wet status. Salinas that contained water on all seven dates examined are in blue, those that were dry on all dates are orange, and those that were sometimes wet/sometimes dry are in green (with numbers denoting the number of dates out of seven where each of these fluctuating basins contained water). Landsat scene outlines (bold parallelograms) are depicted as in Fig. 3

and those that fluctuated between wet and dry were in between (Table 3). What was surprising, however, was that both the largest *and* the smallest basins were always wet, which indicates that hydroperiod of salinas is not simply a function of size. Furthermore, those salinas that were wet more often were not closer to the top of the Ogallala Aquifer, as we had

Table 2 Temporal dynamics of the 39 salinas by wet status. Each row represents a single salina. All dates covered are across the top, but not all Landsat scenes were available on each date (see Table 1); black cells represent dates not covered in satellite imagery for that salina. Cell values indicate proportion basin filled with water, pictorially denoted with horizontal bars within cells

Wet Status	16-Jul-1986	25-Jul-1986	7-Jan-1995	14-Jan-1995	6-Jul-2000	15-Jul-2000	10-Jun-2002	19-Jun-2002	3-Jun-2008	10-Jun-2008	13-Jan-2009	20-Jan-2009	17-Dec-2013	26-Dec-2013
Always Wet	0.703			0.051	0.478		0.041			0.036		0.140	0.082	
Always Wet	0.702			0.636	0.687		0.648			0.694		0.754	0.713	
Always Wet	0.834			0.822	0.812		0.733			0.822		0.850	0.824	
Always Wet	0.547			0.009	0.418		0.001			0.543		0.656	0.858	
Always Wet	0.236			0.072	0.116		0.011			0.330		0.233	0.698	
Always Wet	0.980	0.982	0.640	0.640	0.635	0.564	0.624	0.567	0.539	0.407	0.556	0.597	0.619	0.625
Always Wet	0.711	0.659	0.043	0.058	0.487	0.326	0.501	0.237	0.121	0.063	0.157	0.238	0.069	0.055
Always Wet	0.750	0.783	0.002	0.003	0.534	0.450	0.647	0.398	0.575	0.552	0.482	0.512	0.456	0.289
Always Wet	0.867	0.864	0.727	0.774	0.743	0.723	0.779	0.783	0.774	0.754	0.032	0.791	0.790	0.797
Always Wet		0.465	0.444			0.449		0.442	0.458		0.458			0.453
Always Wet		0.869	0.866			0.863		0.840	0.845		0.859			0.863
Always Wet		0.454	0.009			0.645		0.371	0.396		0.380			0.455
Always Wet		0.742	0.742			0.889		0.655	0.845		0.873			0.913
Always Wet		0.516	0.442			0.572		0.002	0.202		0.469			0.597
Always Wet		0.554	0.307			0.436		0.139	0.240		0.142			0.118
Always Wet		0.848	0.848			0.823		0.751	0.775		0.775			0.872
Always Wet		0.300	0.270			0.300		0.292	0.277		0.277			0.285
Always Wet		0.840	0.829			0.760		0.733	0.706		0.714			0.735
Always Wet		0.302	0.294			0.142		0.086	0.147		0.157			0.042
Always Wet		0.388	0.512			0.376		0.347	0.386		0.401			0.386
Always Wet		0.925	0.636			0.909		0.687	0.733		0.782			0.819
Always Wet		0.937	0.911			0.886		0.864	0.871		0.932			0.943
Always Wet		0.927	0.894			0.911		0.900	0.812		0.787			0.912
Always Wet		0.945	0.864			0.904		0.897	0.785		0.766			0.820
Never Wet	0.000			0.000	0.000		0.000			0.000		0.000	0.000	
Never Wet		0.000	0.000			0.000		0.000	0.000		0.000			0.000
Sometimes Wet	0.000			0.417	0.060		0.000			0.000		0.002	0.000	
Sometimes Wet	0.769			0.000	0.455		0.000			0.000		0.000	0.000	
Sometimes Wet	0.029			0.792	0.239		0.000			0.000		0.105	0.000	
Sometimes Wet	0.756			0.000	0.607		0.000			0.000		0.106	0.579	
Sometimes Wet	0.648			0.000	0.022		0.000			0.000		0.918	0.680	
Sometimes Wet		0.306	0.644			0.141		0.000	0.000		0.285			0.114
Sometimes Wet		0.269	0.060			0.019		0.000	0.028		0.016			0.011
Sometimes Wet		0.137	0.000			0.000		0.168	0.179		0.000			0.000
Sometimes Wet		0.078	0.005			0.014		0.000	0.052		0.026			0.000
Sometimes Wet		0.000	0.000			0.000		0.567	0.115		0.000			0.567
Sometimes Wet		0.166	0.090			0.031		0.004	0.025		0.034			0.000
Sometimes Wet		0.476	0.000			0.000		0.000	0.000		0.000			0.000
Sometimes Wet		0.435	0.099			0.098		0.000	0.000		0.000			0.205

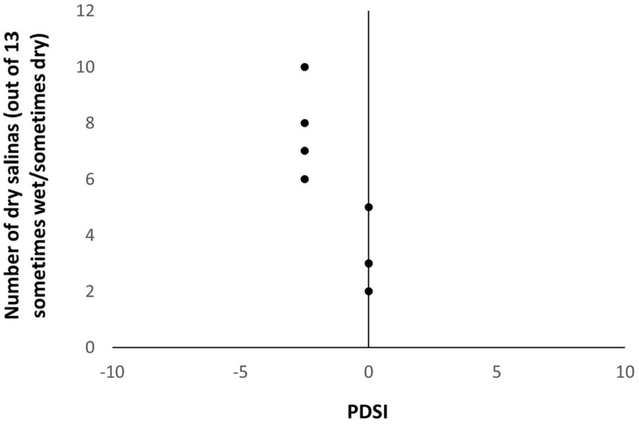


Fig. 6 Plot of the number of dry salinas out of 13 salinas that fluctuated in wet status for each of our seven focal dates against the midpoint value of the monthly Palmer Drought Severity Index (PDSI, which ranges from −10 to 10)

predicted. Those salinas that never contained water were nearly twice as far from the aquifer on average as those that always held water (ANOVA $F_{2,\ 933} = 25.35$, $p < 0.0001$; Table 4), but the overlap in the range of depths to the Ogallala Aquifer by wet status meant that there was no difference in distance to the water table between those salinas that held water on all dates and those that held water on only some dates (Tukey $p > 0.05$). The overlap in the range of these values indicates a disconnection with the groundwater supply. These non-significant relationships, combined with the presence of a significant relationship between water volume in salinas and the Palmer Drought Severity Index, indicate the importance of precipitation and surface runoff rather than groundwater for these ostensibly spring-fed wetlands. Some of the variation we observed in salinas in terms of seasonality of water held (summer and winter wet area), as well as differences in wet status with basin size, could also reflect distance to the nearest irrigation well, the amount of water being extracted from that well, and the seasonal nature of irrigation demands. There was an overall increase in the amounts of cropland and of irrigated cropland in our focal region from 1987 to 2012, although this area was already extensively cultivated well before 1987 (Table 5). Concomitantly, the Ogallala Aquifer experienced a drawdown between 0.2 and 14.7 m between 1990 and 2008 (Table 6): During this span for our study area, the saturated thickness of the underlying Ogallala Aquifer decreased by an average of 18.3%. The water table is not static throughout the course of a year nor is it homogeneously thick in space, which affects the dynamics of salinas.

There were a few instances of salinas that were relatively close together (<3000 m apart) but that differed in their wet status. Because of their proximity, these salinas had the same land use/land cover context as well as being served by the same portion of the Ogallala Aquifer, but they differed in inundation frequency. For the most part, the basins were similar in area, suggesting that factors other than the water table, basin size, and land use/land cover context were influencing hydroperiod. Closer examination of these salinas via inspection of satellite imagery revealed that in one case, seven salinas were in close proximity that could have possibly originally been part of the same spring-fed wetland complex but were now separated by roads, ditches, pits, and other anthropogenic constructions, and now differed in their inundation frequency. For one of these, a salina was bisected by a road ~20 m wide, which created two basins with relatively independent hydroperiods (i.e., differing in wet status), possibly due to different landowner activities on either side of the road. These patterns point to the importance of anthropogenic drivers other than land use/land cover on salina hydroperiod.

Discussion

A third of the 37 wet salina basins went dry at least once and then held water again. These dry periods were spread out in space and time. It should be noted that the 16-day minimum satellite interval (with typically longer spans between subsequent images that were cloud-free) meant that salinas could have gone wet or dry in between dates without detection. Moreover, wet areas smaller than 900 m^2 (30 m × 30 m) would not have been detected. However, these factors should have been equally likely across basins of our study region and so does not account for the inundation associations that we saw.

Table 3 Average across dates (range in parentheses) of basin area (in hectares, ha), depth (in meters), and wet surface area (in ha) of salinas by wet status (i.e., those that held water on every date examined, those that were dry on every date examined, and those that held water on some dates but not others) and season (summer = June/July, winter = December/January). Basin area and depth are static whereas wet area could and did change by season

Wet status	Basin area (ha)	Basin depth (m)	Summer wet area (ha)	Winter wet area (ha)
Always wet (*n* = 24)	296.3 (3.7–2255.0)	11.4 (0.4–29.8)	187.2 (0.1–2085.7)	165.2 (0.5–1845.7)
Always dry (*n* = 2)	40.2 (40.1–40.2)	4.6 (4.0–5.2)	Not applicable	Not applicable
Sometimes wet/sometimes dry (*n* = 13)	80.5 (13.56–327.9)	5.3 (1.0–9.1)	8.0 (0–88.1)	9.2 (0–67.6)

Table 4 Average (range in parentheses) of minimum depth in meters to top of the Ogallala Aquifer for salinas by wet status (i.e., those that held water on every date examined, those that were dry on every date examined, and those that held water on some dates but not others)

Wet status	Minimum depth (m) to top of aquifer
Always wet (*n* = 24)	11.7 (0.5–40.2)
Always dry (*n* = 2)	21.1 (8.6–35.2)
Sometimes wet/sometimes dry (*n* = 13)	14.2 (0.85–73.0)

Our results suggest that salinas are being impacted by landscape change. Human activities appear to be diminishing groundwater inputs to these wetlands, effectively breaking their connection to the water table. Irrigation in the SHP peaked in the 1970s and then declined for various reasons, many of them related to aquifer depletion (Musick et al. 1990). At its peak (1974), over 2.25 million hectares of the SHP were in irrigated cultivation, which then dropped to 1.62 million ha by 1989 (Musick et al. 1990). Since then, we documented some resurgence in cultivation and in irrigated cultivation, which should indicate renewed demands on the aquifer and, thus, effects on salinas.

Playa ecology is relatively well-documented in terms of birds (e.g. Davis and Smith 1998; Tsai et al. 2012), plants (e.g. Haukos and Smith 1997; Smith and Haukos 2002), invertebrates (e.g. Mericke and Wangberg 1981; Hall et al. 2004; Reece and McIntyre 2009a, b), amphibians (e.g. Anderson et al. 1999; Gray et al. 2004; Venne et al. 2012), and microbes (e.g. Gorden and Hill 1971; Daniel et al. 2015). Salinas, in contrast, are much less studied and, thus, much less well-understood. They are known to have a diverse and regionally unique flora more similar to the Gulf Coast and Intermountain West than the rest of the Great Plains (Rosen et al. 2013). Playas are characterized by wet-dry dynamics, being dry more often than wet (Starr et al. 2016). Salinas, however, are more consistently wet because of their springs. Mound, Rich, and Tahoka Lakes have been considered the best remaining salinas in the region (Saalfeld et al. 2011; Rosen et al. 2013) because they still have good spring flow, although both Mound and Rich Lakes contain oil-extraction infrastructure built within their basins, and Tahoka Lake is not considered a salina in the PWD (is a permanent lake with three springs with less steady flow than in the recent past; Saalfeld et al. 2011; Conway et al. 2005a, b). Thus, formerly, there were two types of depressional wetlands in the SHP: playas (precipitation-fed) and salinas (groundwater-fed). With groundwater depletion, however, there is now a third type of wetland that was formerly groundwater-fed and has salt deposits and associated halophytic biota (like a salina) but that is now fed primarily or even solely by precipitation (like a playa). Their salt deposits would require geologic rather than ecologic timescales to eliminate and make the wetlands into "true" playas. These novel wetlands no longer have the same hydrological or ecological dynamics as salinas and may exacerbate their vulnerability to projected climate change. As nearly all of the remaining salinas are on private property, conservation measures will be difficult to implement unless they are incentivized, but such measures are imperative given the regional uniqueness and importance of these vanishing wetlands.

Table 6 Change in saturated thickness of the Ogallala Aquifer between 1990 and 2008 for the eight counties in Texas that contain salinas (http://www.gis.ttu.edu/center/Ogallala/OgallalaData.html)

County	% change	Change in meters
Andrews	−1.5	−0.2
Bailey	−16.1	−3.6
Dallam	−29.6	−14.7
Gaines	−27.1	−8.7
Hockley	−17.7	−2.5
Lamb	−26.6	−7.1
Lynn	−4.8	−0.7
Terry	−22.7	−4.8

Table 5 Area (in hectares, ha) of total cropland and of irrigated cropland from the eight counties in Texas that contain salinas, from the 1987 and 2012 USDA Censuses of Agriculture. Trends indicate whether amounts increased (+) or decreased (−) over time (2012–1987)

County	1987		2012		Trend in total cropland	Trend in irrigated cropland
	Total cropland (ha)	Irrigated cropland (ha)	Total cropland (ha)	Irrigated cropland (ha)		
Andrews	31,693.0	2115.7	28,941.9	2020.2	−	−
Bailey	118,920.2	26,294.5	124,515.4	19,644.7	+	−
Dallam	155,360.2	54,511.2	157,160.2	71,081.1	+	+
Gaines	212,975.7	64,604.9	230,894.4	91,860.5	+	+
Hockley	154,889.9	30,357.9	161,923.0	43,267.0	+	+
Lamb	162,683.4	72,161.2	189,852.4	72,653.7	+	+
Lynn	157,330.6	12,462.7	164,567.6	28,975.1	+	+
Terry	156,360.6	32,932.9	152,554.5	39,760.0	−	+

Acknowledgements We are grateful for funding from the National Science Foundation's Macrosystems Biology grant 1340548 ("Collaborative Research: Climatic and Anthropogenic Forcing of Wetland Landscape Connectivity in the Great Plains"), the National Science Foundation's Proactive Recruitment in Introductory Science and Mathematics (NSF-PRISM) grant 1035096 ("RMR-TTU: Recruitment, Mentoring, and Research in Mathematics and Science at Texas Tech University"). LJH was funded in part by an Elo and Olga Urbanovsky Assistantship, and SMS was funded in part by a Water Conservation Research Fellowship, The CH Foundation, and a Texas Tech University Doctoral Dissertation Completion Fellowship. We thank Caroline Claassen (NSF-PRISM Scholar, Dept. Mathematics and Statistics, Texas Tech University) for assistance in image processing. Comments from two anonymous reviewers improved the manuscript.

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