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EVALUATION OF SURFACE FEATURES FOR DELINEATING THE ORDINARY HIGH WATER BOUNDARY ON PLAYAS IN THE ARID WESTERN UNITED STATES

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Abstract: Delineation of Ordinary High Water (OHW) under the Clean Water Act (CWA) is based on the use of physical features that represent "ordinary" levels of ponding or flowing waters. On arid western United States playas, where the climate is an unevenly distributed series of precipitation events that are spread over many years, the use of surface water monitoring can be limiting due to occasional years with almost no hydrological information. To substitute for a general lack of monitored surface water conditions, we used processed satellite images and precise topographic modeling to determine ponded water areas. To test the reliability of select field indicators for delineation purposes, we used a two-phase field test on a hard playa in the Mojave Desert, California. First, we verified that ponded water was associated with these playa surface features. Then, to test the statistical reliability of these surface features, we developed a decile ponding zone map by stacking processed satellite imagery, collected detailed laser altimetry (LiDAR) elevation data, sampled surface features occurring in the various decile zones, and developed reliability statements for these OHW delineation features. These field indicators represent surface features that have developed over a series of years representing the wetter portion of the El Niño climatic cycle.

Key Words: Delineation, LiDAR, remote sensing

INTRODUCTION

Playas are an important surface water resource in the arid deserts of the United States and globally (Shaw and Thomas 1997). They are located in the bottoms of basins with internal drainage (Stone 1956, Rosen 1994, Briere 2000). Even though they are not perennial surface water features, some playas have been reported to contain water for over two weeks in many years and upwards to 34 weeks in some years (Lichvar et al. 2004a). Seasonally, these landscape features are important in providing habitat for migratory birds and ephemeral aquatic species (Eriksen and Belk 1999, Miller and Payne 2000). Their importance to other wetland functions varies depending on their near-surface geology, soil texture, piping (surface-to-subsurface drainage feature), or soft-textured surfaces that allow infiltration of water for recharge of regional aquifers during climatically wet periods (Snyder 1962, Lines 1979, Rosen 1994, Shaw and Thomas 1997).

In the United States, playas may be regulated under Federal Regulations 33 CFR 328.3 [a] of the Clean Water Act (CWA), along with other "Waters of the United States" (WoUS) if there is a hydrologic or "significant nexus" to navigable waters (Downing et al. 2003). When WoUS are delineated, the outermost regulated extent is determined by observing either ponded water or physical features that remain after the water has receded, which represent the Ordinary High Water (OHW) mark. The final determination of whether a playa is considered jurisdictional requires a regulatory interpretation of site conditions to determine whether it represents "isolated waters" or has a "significant nexus" to navigable waters. This regulatory interpretation is a separate evaluation from delineating the extent of OHW on a playa surface (Downing et al. 2003). The definition of WoUS lacks any statement about the frequency or duration of ponded or flowing water, but it is widely accepted that frequency and duration are not intended to represent an extreme discharge event or flooding (Lichvar et al. 2004a). In comparison, the hydrology criterion for wetlands, one criterion in a three-factor approach to delineation, specifies that wetlands experience flooding during one out of two years, five out of 10 years, or a 50% probability of occurrence for more than 5% of the growing season (Environmental Laboratory 1987, Office of the Chief of Engineers 1992).

OHW delineation of playas can be problematic (Doub and Colberg 1996), depending on whether there is ground water near the surface or not (Lichvar et al. 2006a). The surface morphology of most playas is related to several factors, the most important being the ratio of surface-water flooding to capillary discharge from ground water (Motts 1970, Rosen 1994). Playas influenced by capillary discharge from ground water are classified as soft playas (Motts 1970, Neal 1975). A playa lacking capillary discharge is classified as a hard playa. A single playa can have spatially separate features of more than one type and can change between types over long periods of time (Neal 1975, Malek et al. 1990). In the case of soft playas, the soils are modified to have low bulk density and high porosity resulting from negative evapotransporation rates that wick ground water through the soil and causing a porous effect (Langer and Kerr 1966, Motts 1970, Malek et al. 1990). These porous soils allow for surface water infiltration and thus may preclude ponding due to high infiltration rates. When vegetation is present on soft playas, it tends to be dominated by Facultative Wetland (FACW) (Reed 1988) phreatophytic species that have the ability to go to great depths to obtain soil moisture (Stone 1956, Hunt 1975, Dahlgren et al. 1997). Thus, delineation determinations for vegetated soft playas are more appropriately handled by standard wetland delineation protocols. In contrast, hard playas have impermeable surfaces, are mostly devoid of vegetation except for the outermost margins, and frequently pond water on the flattened surfaces (Stone 1956, Rosen 1994, French et al. 2005). When making delineation determinations for hard playas, it is necessary to use the OHW mark indicators (Lichvar et al. 2004a, Lichvar et al. 2006a). Typically, the entire hard playa does not pond water during a particular inundation event (Dinehart and McPherson 1998, Lichvar et al. 2004a, French et al. 2005), so it is necessary to use OHW marks to determine the presence and extent of the OHW.

Because of the highly ephemeral nature of ponded water on playas, most playas lack surface water monitoring instruments for describing the presence, frequency, or duration of ponding. Recent efforts to construct statements about the surface hydrology of playas have relied on remote sensing and other extrapolated methods. Many of these efforts dealt with methods for modeling climate (Mishra et al. 1994) or flooding (Verdin 1996, Bryant 1999, Bryant and Rainey 2002, Castañeda et al. 2005, French et al. 2005, French et al. 2006), determining evaporation rates (Prata 1990) or surface water duration and frequency of ponding (Lichvar et al. 2004a, Castañeda et al. 2005), or defining sediment transfers on playa surfaces (Millington et al. 1987). Lichvar et al. (2004a) provided statistical statements pertaining to the frequency and duration of ponding on Buckhorn Playa, at Edwards Air Force Base, California, but did not discuss any correlations between ponded zones and playa surface features. Recently, in an effort to support field delineations to locate the outer extent of the OHW on playas, Lichvar et al. (2006a) reviewed all surface features of playas and rated them based on the literature and field experience for reliability for use in locating the WoUS boundary.

The efforts by Lichvar et al. (2006a) to identify physical features useful for delineation were based on repeated field observations without any numerical data to correlate playa surface features with frequency or duration of ponded water. Without a statistical correlation of surface features with playa surface hydrologic data, it is not possible to characterize "ordinary" ponding events. To overcome the lack of surface hydrology instrumentation, we used remote sensing to document ponded water. The distinct spectral signature of water makes remote sensing an ideal tool for determining water inundation in playas. Much of the small body of remote sensing research on playas has utilized National Oceanic and Atmospheric Administration (NOAA) advanced very high-resolution radiometer (AVHRR) data (Bryant 1999, Bryant and Rainey 2002) and Landsat 5 TM data (Castañeda et al. 2005). These data have the advantages of reasonable availability and continuous global coverage stretching from 1979 onwards. The relatively poor spatial and spectral resolution of these data has created difficulties for precise detection of the ponded water perimeter and subsequent mapping of the surface area of water bodies. However, remote sensed monitoring of playa hydrology is more successful when used as a cumulative time-series for large basins where the ponded area can vary in size from year to year (Bryant and Rainey 2002).

Other efforts to model flood events on playas have relied on the use of environmental parameters combined with climatic models to estimate discharge rates on playas to substitute for the lack of hydrologically monitored data (French et al. 2005, 2006). To support their flood modeling efforts, French et al. (2005, 2006) used a variety of landscape variables and climatic data to build a series of inferences associated with infiltration rates and overland flow discharges to estimate 100-year flood levels on Mojave Desert playas. The results of this flood modeling effort produced a 100-year flood estimate boundary. The published modeling results lacked subsequent frequency estimates for the 2-, 5-, 10-, and 25-year flood events, which would have been useful for comparing ponded water duration and physical features caused by "ordinary" ponding events on playas. In addition, these types of models are not intended to define "ordinary" events associated with physical features on the ground but are intended to estimate the spatial extent of the 100-year flood hazard. Defining "ordinary" for use in CWA delineation exercises is a complex and challenging undertaking in arid climatic regions.

Recent efforts to define "ordinary" and related OHW delineation field indicators by Lichvar et al. (2006b) for intermittent stream channels in the arid west used high-resolution, LiDAR-driven HEC-RAS models from a series of gauged channels with up to 60 years of record. Flood frequency analyses of events from these arid stream channels and their relationship to OHW mark indicators implied that the most consistent and repeating series of discharge events associated with an "ordinary" discharge was in the range of a 5- to 8-year event.

To support delineation of the OHW boundary using surface features on hard playas, we designed a study to test the responses of the field indicators to ponding and their relationships with various increments of ponded water duration on a playa. These ponding increments are labeled as deciles for the purposes of this paper and are intended to increase the reliability in delineating the limits of OHW. The study used both field and remote sensed data to show the distinct relationships of OHW field indicators along ponding and topographic gradients on playas.

METHODS

Study Area

Buckhorn Playa and a selection of the nearby small playas on Edwards Air Force Base (AFB), Kern County, California, were used as test examples of arid southwest playas. Edwards AFB is located in the western Mojave Desert, northeast of Los Angeles. These playas are positioned in low-lying areas of the Antelope Valley, which is a closed basin. Nearby mountain ranges on the northwest and southern borders of the Antelope Valley include the Tehachapi and the San Gabriel. The study area included all of Buckhorn (4.4 km^2 in area) and several unnamed small playas (5.8 km^2) adjacent to Buckhorn (Figure 1). The playas are contained within the boundary of the bed of Pleistocene Lake Thompson (Orme 2004). Following Holocene desiccation and widespread progradation of alluvial and aeolian deposits, Lake Thompson developed into two large playas—Rosamond (57 km^2) in the west and Rogers (130 km^2) in the east—separated by a suite of smaller playas, of which Buckhorn is the largest (Orme 2004, French et al. 2005) (Figure 1). These are hard playas, having impenetrable surfaces with a ground-water depth greater than 10 m (Stone 1956). Hardened surfaces play an important role in the ability of playas to retain water on the surface for extended periods of time, depending on climatic conditions (Rosen 1994, Shaw and Thomas 1997). The playa bed surfaces within the boundary of former Lake Thompson average 692 m in elevation (Orme 2004) and range from 696–698 m for Buckhorn and the small playas.

Most of the vegetation within Lake Thompson's bed is on the exposed lake plains and sand dunes that surround the unvegetated playas (Lichvar et al. 2004b). These lake plain and sand dune features are dominated by members of the chenopod family, with several phases of saltbush plant communities, including spinescale (*Atriplex spinifera* Macbr.), shadscale [*A. confertifolia* (Torrey & Fremont) S. Watson], and fourwing [*A. canescens* (Pursh) Nutt.] (Sawyer and Keeler-Wolf 1995).

Approach

This research focuses on developing an approach that uses playa surface features for delineating the boundary of the OHW on playas. The development of indicators was a two-step process. First, by setting up a field test we were able to establish that new surface features develop after a season of ponded water. Second, we tested the potential field indicators by combining high-resolution topographic data acquired from airborne laser altimetry [Light Detection and Ranging (LiDAR)] and field sampling of surface features from zones developed from processed satellite imagery for 10 ponding increments. This combined field and remote sensing approach provided support for the selection of reliable surface delineation features with specific relationships to duration of ponding and OHW.

In December 2000, to assess the association of ponding with the formation of new playa surface

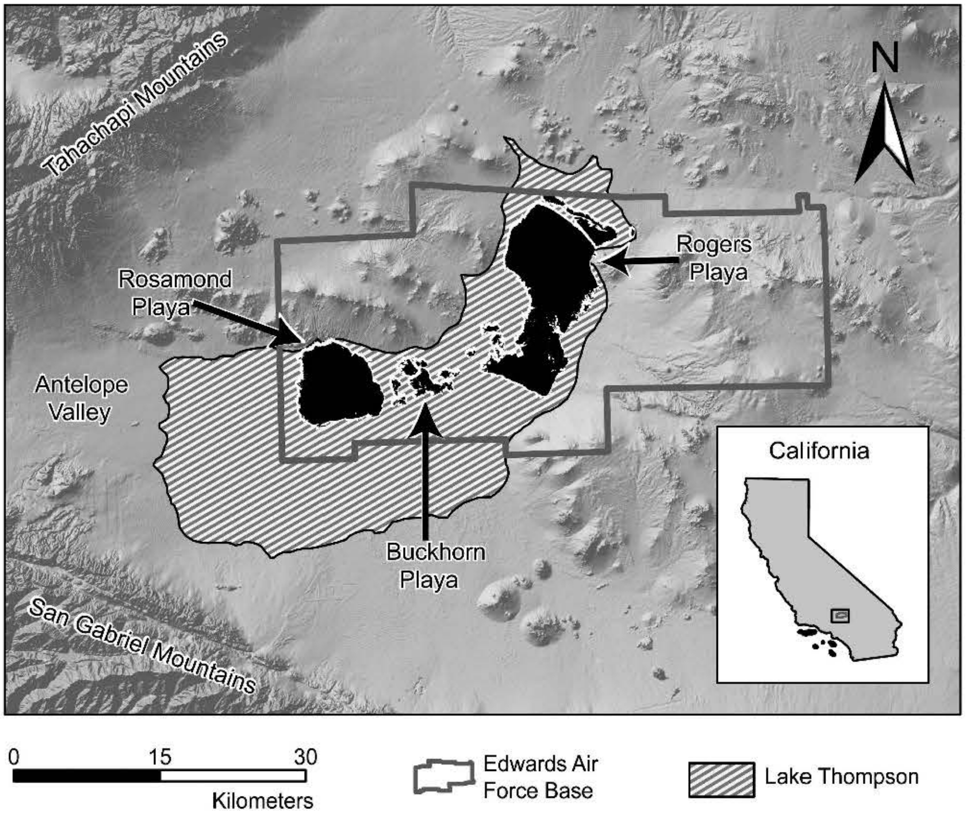

Figure 1. Pleistocene Lake Thompson with Buckhorn, Rosamond, and Rogers playas highlighted.

features, we placed 10 plots within Buckhorn and another small nearby playa. These plots extended to the outermost unvegetated edge of the current playa boundary. Five of these plots were placed in lower topographic locations with features associated with ponded water (Lichvar et al. 2006a), and the other five were positioned nearby in locations that lacked evidence of ponding. At each plot, we placed two 1-m sampling frames side by side. In one frame, we recorded the cover of all surface features present within the frame. In the other frame, we disturbed the surface by chipping to a depth of 5 cm and lightly smoothing the surface back flush to its original height. The playa surface features measured included closed flat mud crack polygons, closed domed mud crack polygons, and algal flakes (Table 1). After a winter of precipitation and ponding, the plots were revisited in June 2001, and we recorded the playa surface features again in the two adjacent marked locations for each plot.

A ponding map was constructed by stacking the available multi-temporal sequence of 30 satellite images in which flooding occurred. These images were previously obtained to detect and map ponded water on playa surfaces. Technical details pertaining to image availability, quality, and processing are discussed by Lichvar et al. (2004a). Thirty images were selected from eight years of Buckhorn satellite imagery collected between 1982 and 2001, resulting in the Landsat Thematic Mapper (TM) and Department of Energy (DOE) Multi-spectral Thermal Imager (MTI) imagery listed in Table 2. After processing the images, we created a series of ponding maps. Ponding occurrence was based on the detection of ponded water with the use of remote sensing algorithms (Lichvar et al. 2004a) in each processed image. The processed images were stacked and compared statistically for overlapping ponding zones and for ponding frequency. The maximum observed occurrence of ponding in the set of imagery was 30, and some areas of Buckhorn Playa were observed to pond water in all of the imagery listed in Table 2. This frequency distribution of ponding occurrences was divided into increments of three each to construct decile ponding zones. These were labeled starting at a value of 10; areas that were not observed to pond water in the available imagery were assigned a value of 0. Table 3 lists these ponding decile zones formed using the ponding occurrences from the 30 satellite images and also includes values for total and percent of area within Buckhorn Playa occupied by each decile ponding zone.

In May 2003, 50 plots were sampled in the field (Figure 2) within the decile increment zones devel-

Table 1. Description of playa surface features recorded on Buckhorn and the other nearby small playas.

Closed flat mud crack polygons	Closed, level mud crack polygons that generally form 4- to 6-sided mud crack feature (Neal 1975)
Closed domed mud crack polygons	Closed mud crack polygons that are highly raised or "mounded" in the center (Lichvar and Sprecher 1998)
Algal flakes	Features that form when algae and other phototrophic and heterotrophic microbes present in ponded water dry and form a flaky crust (Brostoff 2002)
Open mud cracks	Mud crack polygons that are open along one or more edges (Lichvar and Sprecher 1996)
Closed raised mud crack polygons	Closed mud crack polygons that are slightly raised in the center (unlike closed domed mud cracks, which are highly raised in the center)
Closed multiple mud crack polygons	One or more subsurface layers of closed mud crack polygons stacked on top of each other (Lichvar et al. 2006a)
Piping	Small drainage tubes that appear as drain holes on the playa surface (Lichvar et al. 2006a)
Soil hue	Soil color of the undisturbed soil horizontal surface measured using the Munsell Color system (Gretag-Macbeth 2000); soil character changes are listed as indicators of OHW by regulation 22 CFR 329.11[a][1]
Mud crack depth	Depth in millimeters of the observed mud crack along the edge of a mud crack polygon
Mud crack width	Width in millimeters of the observed mud crack along the edge of a mud crack polygon

oped from the ponding map. Playa surface features were recorded at each plot within a 1-m frame. These surface features are described in Table 1 and include open mud cracks, closed flat mud crack polygons, closed raised mud crack polygons, closed domed mud crack polygons, closed multiple mud crack polygons (polygons that have subsurface polygons beneath them), algal flakes, and piping; also noted were playa Munsell soil surface hue (Gretag-Macbeth 2000) and mud crack depth and width.

Through a collaborative effort with the National Aeronautics and Space Administration's (NASA) Airborne Topographic Mapper (ATM) Group, ATM-III LiDAR data were acquired over Buckhorn Playa in late September 2003. The ATM-III uses a blue-green laser to calculate a returned spatial vector from the platform to the point of reflection, providing extremely precise XYZ coordinates of the laser footprint on the ground. The ATM-III measures surface topography to a precision of approximately 8.5 cm vertically (Krabill et al. 2002). The survey was flown using a Twin Otter International twin-engine light aircraft flown at an altitude of approximately 1,500 m. Following airborne acquisition, the raw data were reduced to essential components, projected to a Universal Transverse Mercator (UTM) projection, filtered for atmospheric triggers and redundant data points, and binned into a final 1-m Digital Elevation Model using software developed with Research Systems Interactive Data Language (Research Systems Inc. 2005).

Statistical Analysis

The significance of playa surface feature occurrence in ponded areas and the significance of feature re-occurrence on chipped surfaces after ponding were determined using the Kruskal-Wallis analysis

Table 2. Satellite images used to estimate Buckhorn Playa ponding occurrence.

Landsat 4 TM	Winter 1982–83: 12/10/82, 12/26/82
Landsat 5 TM	Winter 1984–85: 01/08/85, 01/24/85, 02/25/85, 03/29/85
	Winter 1986–87: 01/14/87
	Winter 1990–91: 03/30/91, 04/15/91, 05/17/91
	Winter 1991–92: 01/12/92, 03/16/92
	Winter 1992–93: 11/27/92, 12/13/92, 01/14/93, 02/15/93, 03/03/93, 03/19/93, 04/04/93, 04/20/93, 05/22/93,
Landsat 7 TM	Winter 1999–2000: 3/14/00
	Winter 2000–01: 01/28/01
DOE MTI	Winter 2000–01: 02/04/01, 02/20/01, 03/08/01, 03/26/01 04/13/01, 05/03/01, 05/23/01

Table 3. Decile ratings for ponded water occurrence used in the overlaid satellite imagery.

Ponding decile value	Number of observations of inundation in the stacked multi-temporal satellite imagery	Area of Buckhorn Playa (decile km^2 and %)
0	0	0.80 (18%)
10	1,2,3	1.45 (33%)
20	4,5,6	0.52 (12%)
30	7,8,9	0.43 (10%)
40	10,11,12	0.36 (8%)
50	13,14,15	0.25 (6%)
60	16,17,18	0.18 (4%)
70	19,20,21	0.10 (2%)
80	22,23,24	0.13 (3%)
90	25,26,27	0.09 (2%)
100	28,29,30	0.10 (2%)

of variance (ANOVA) test. The Kruskal-Wallis ANOVA is a statistical method that evaluates the differences between sets of ranked measurements such as percentages (Sprent and Smeeton 2001). Significance levels were calculated for the total surface feature cover in ponded vs. unponded plots and control (unchipped) vs. chipped plots using SigmaStat software (SYSTAT 2004a). A bar graph of average surface feature cover for the control (unchipped) plots before ponding, the control plots after ponding, and the chipped plots after ponding was created using SigmaPlot (SYSTAT 2004b).

To determine the correlation between ponding and elevation, we spatially sampled from the LiDAR topographic data in each ponding decile zone on Buckhorn Playa to build five replicate sets of data. A stratified random selection method was used to choose 20 elevation values within each ponding zone. LiDAR elevation values were calculated from a 20 m × 20 m rectangular window

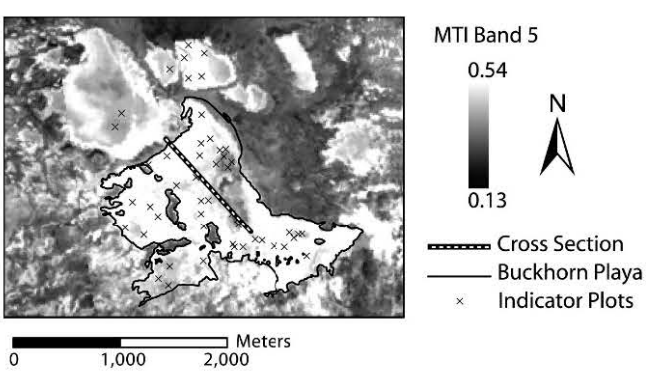

Figure 2. Custom MTI Image from July 3, 2001 with 50 indicator points individually plotted. The location of a representative cross section (for Figure 13) is shown as a dashed line.

average to match the spatial resolution of the ponding grid. The relationship between playa elevation and ponding decile values was computed using Kendall correlation. Kendall correlation is suitable for analyzing ordinal or ranked data (Kendall and Gibbons 1990). The computer software package "R" (R Development Core Team 2005) was used for correlation calculations, which also required the statistical library Kendall (McLeod 2005) for the analysis. The average elevation in each ponding zone was computed and plotted for each of the five sets of data. Five correlation values, one for each replicate set of LiDAR data, were used to list the range for the correlation between elevation and ponding on Buckhorn Playa.

The correlation between playa surface features and ponding decile values was determined using the data from the 50 plots collected in 2003, and response curves were constructed for the features. The GPS position for each plot was used to assign the ponding decile from the duration stacked map, and the elevation was determined from the LiDAR topography data. Then the decile ponding values were used to calculate the Kendall correlation between each surface feature and ponding duration. Graphs were plotted for each feature in SigmaPlot, and a three-parameter Gaussian curve was used to model indicator distributions along the ponding decile values. The 50 surface feature plots included eight that were located in two small playas adjacent to Buckhorn. Because these playas had slight differences in base elevation, we calculated the average elevation and standard error for each playa surface feature only for the 42 plots within Buckhorn Playa.

RESULTS

Ponded Water Association with Surface Features

New playa surface feature development within the formally chipped surfaces was found to be significantly associated with plots where ponding occurred ($p = 0.008$, Figure 3). Total feature cover in the ponded plots was 100% in 2000; in 2001 after ponding, it was 86.0 ± 14.0% (mean ± standard error) for the unchipped plots and 89.0 ± 11.0% for the chipped plots. The values did not differ significantly within the ponded plots ($p = 0.581$) for the two years. The total feature cover in the unponded plots was 0% in 2000; in 2001, it was 2.2 ± 1.6% for the unchipped plots and 7.1 ± 5.8% for the chipped plots. Surface feature cover also did not differ within the unponded plots ($p = 0.156$). The cumulative total of surface feature cover in each plot was used to calculate these values.

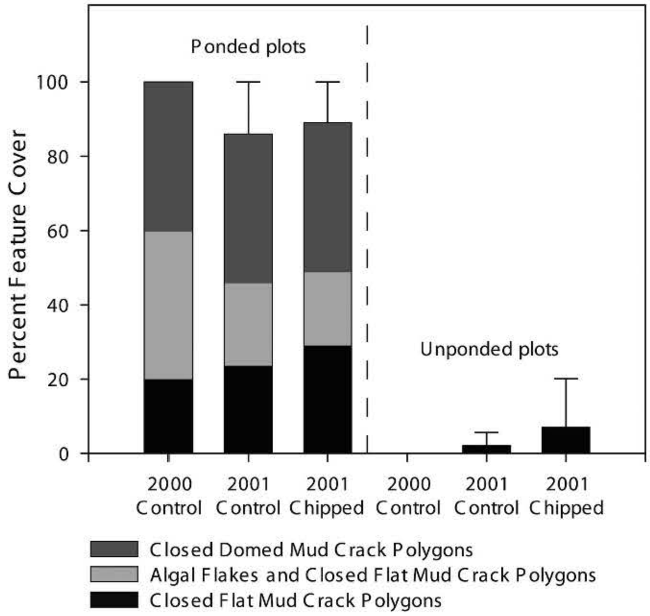

Figure 3. Percent cover of features in ponded and unponded plots.

LiDAR and Surface Feature Correlations with Ponding Deciles

The stacked multi-temporal satellite images were substituted for surface hydrologic instrumentation on the playa to produce a zoned decile rating map (Figure 4). Using the results of the 50 samples observed throughout the zones, we sorted the surface features into three groups: always within the ponded area, always outside the ponded area, and overlapping the ponded and unponded areas. The areas of longest ponding duration were located in the lowest elevation (Figure 5). The correlation

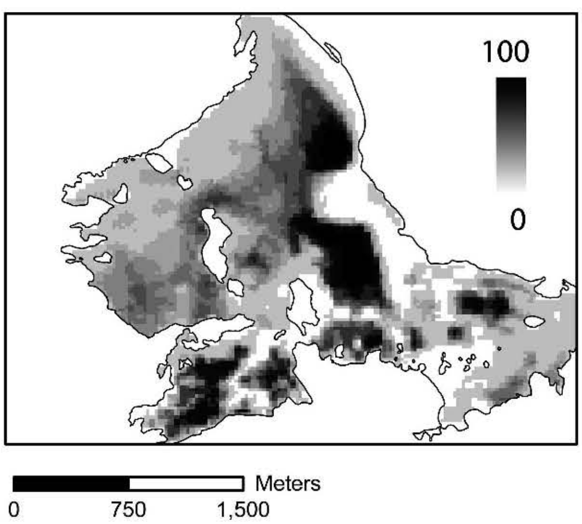

Figure 4. Inundation map, showing the greatest ponding duration as black (100 decile) and the lowest as pale gray (10 ponding decile) on Buckhorn Playa (outlined in black).

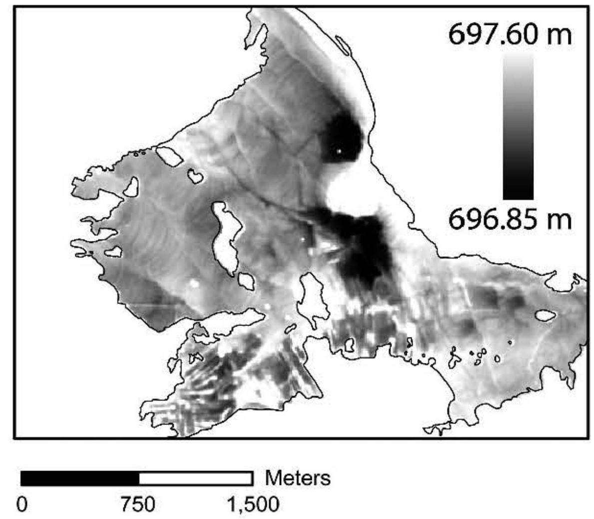

Figure 5. Selected Buckhorn Playa LIDAR elevations between 697.50 m and 696.75 m. White areas within the black boundary of Buckhorn are ≥ 697.50 m in elevation.

between the ponding and LiDAR topography is plotted in Figure 6, and the correlation between the ponding deciles and elevation ranges from −0.754 to −0.796. Each calculated correlation was found significant ($p < 0.0001$) and indicated that ponded water occurred more frequently at the lower elevations. By overlapping the ≥ 50 ponding decile areas (0.85 km^2) and the areas with elevations below 697.28 m (0.92 km^2), the lowest topographic areas with highest observed ponding on Buckhorn (Figure 7) also corresponded with the highest probability of ponding indicators and contained closed multiple mud cracks and algal flakes.

Distribution of Features across Various Decile Zones

Most of the playa surface features considered here had a strong association with a distinct flooding

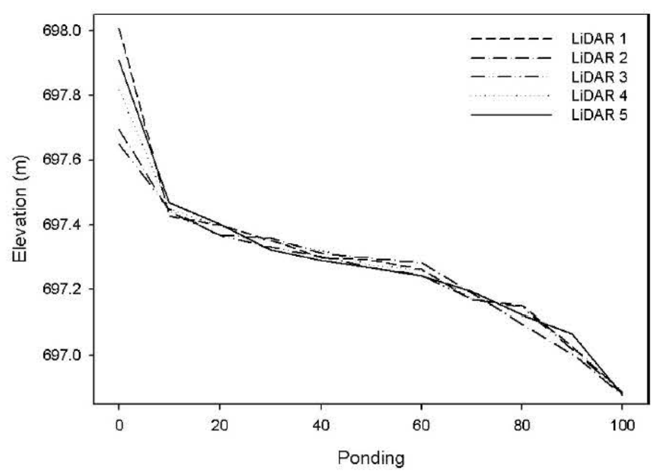

Figure 6. Average elevation for the ponding deciles sampled within Buckhorn Playa.

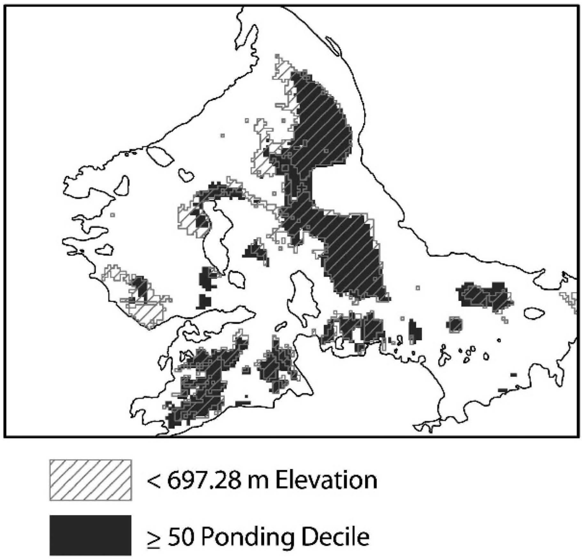

Figure 7. The ≥ 50 ponding decile is represented in dark gray and the corresponding elevation of ponding < 697.28 m is represented by gray slashes.

regime described by the ponding decile zones. The surface features most likely to occur in areas with decile zones less than 50 were piping, open mud cracks, and yellow, 5Y, hue playa surfaces (Figures 8 and 9). The surface features most likely to occur in the decile zones greater than 50 were algal flakes, closed multiple mud crack polygons, closed domed mud crack polygons, and greater mud crack depth and width (Figures 8, 10, and 11).

Two playa surface features were bimodal in their distribution patterns across the playa, occurring

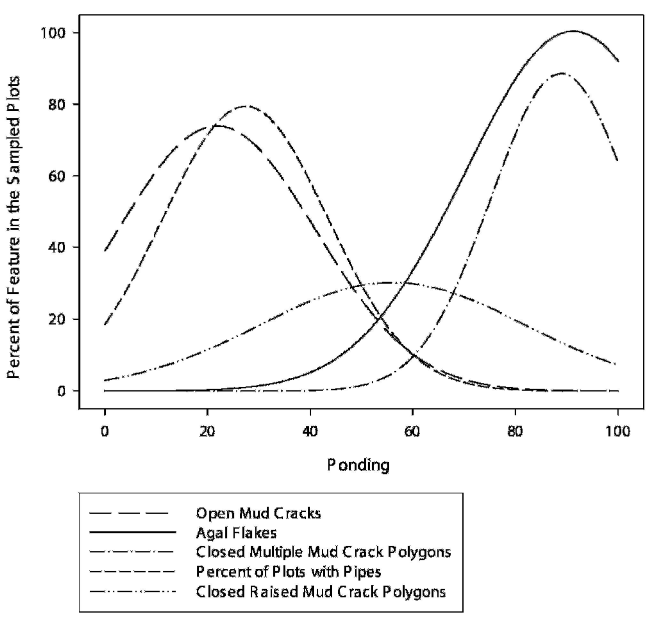

Figure 8. Occurrence of five features in the sampled plots associated with various ponding durations.

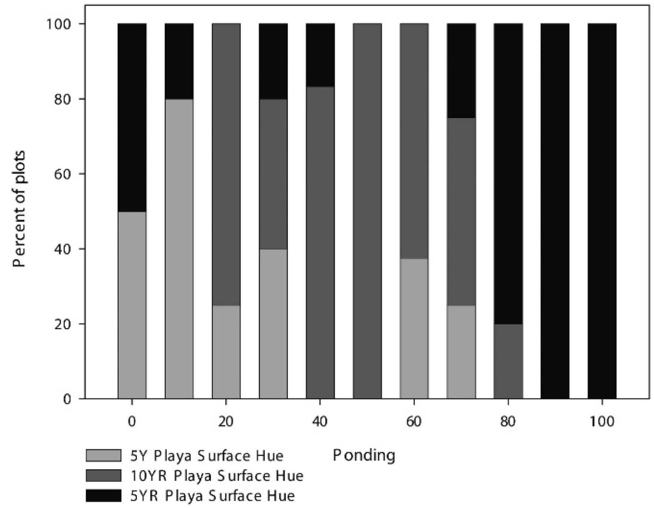

Figure 9. Relationship between playa surface color hue and ponding in the sample plots.

both in the strongly ponded and strongly unponded areas although not across the middle deciles: red, 5YR, hue playa surfaces (Figure 9) and closed flat mud crack polygons (Figure 12).

There were several areas that straddled the 50-decile ponding zone. Both intermediate, 10YR, and red (5YR) hue playa surfaces were scattered within the 10–90 decile zones. The flat, raised, closed polygons were located in the 20–80 decile zones. Closed flat mud crack polygons, closed raised mud crack polygons, and intermediate (10YR) hue playa surfaces were located between the 20th decile and the 100th decile.

Reliability of Features Associated with Ponding Duration Zones

The strength of playa surface feature correlation with unponded and ponded water deciles (for the 50

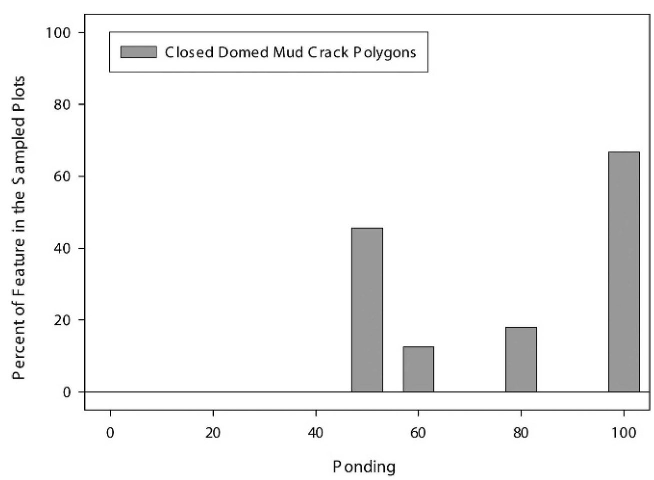

Figure 10. Relationship between closed domed mud crack polygons and ponding in the sample plots.

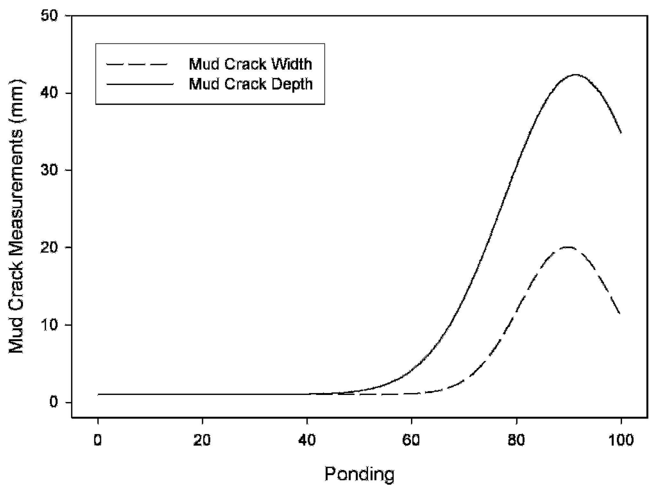

Figure 11. Relationship between mud crack dimensions and ponding.

plots) is shown in Table 4, along with the mean LiDAR elevation values for the 42 plots that were within Buckhorn Playa. The surface features significantly correlated with ponded water were closed domed mud crack polygons, red (5YR) hue playa surfaces, change of playa surface hue from yellow (5Y) to red (5YR), closed multiple mud crack polygons, algal flakes, and greater mud crack width and depth. These surface features were also at the lowest topographic positions within Buckhorn, ranging from 696.91 to 607.11 m average elevation. The surface features significantly correlated with unponded playa surfaces were open mud cracks, pipes, and yellow (5Y) hue playa surfaces. These surface features were found at the highest topographic positions, ranging from 697.38 to 697.43 m in average elevation. Closed flat and closed raised

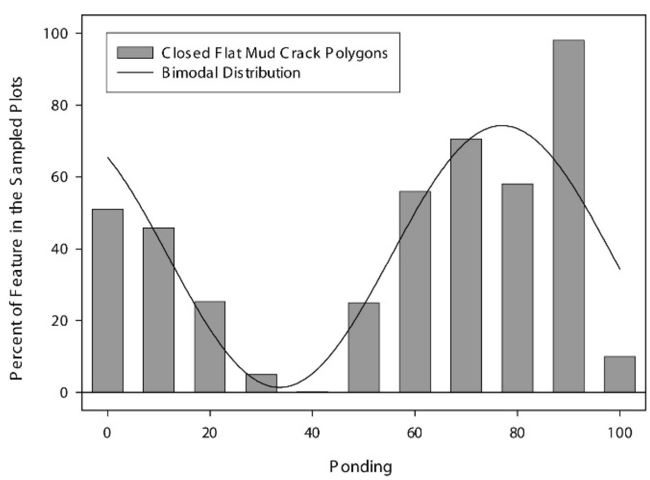

Figure 12. Bimodal distribution of closed flat mud cracks occurring both in less than and greater than 50 decile ponding zones.

mud crack polygons were not highly associated with the decile ponding zones because one had a bimodal distribution and the other had a very wide range of occurrence. Closed flat mud crack polygons had a bimodal distribution across the playa ponded zones (Figure 12), so they were not highly correlated with the ponding decile zones (although these mud cracks had another feature that is highly associated with ponded water, which will be discussed later). Closed raised mud crack polygons were distributed throughout Buckhorn Playa but were most abundant at the intermediate ponding deciles (Figures 8 and 13).

DISCUSSION

We recognize that the physical processes brought about by ponding, sediment transport, and wind along with their interaction with soil chemistry and texture are actually responsible for the formation of playa surface features (Neal 1968, 1972, Kubly 1982, Malek et al. 1990). Without the aid of hydrologic monitoring of surface water and laboratory testing of soil responses to ponding, we relied on our data to indicate that there are specific features associated with ponded water duration on playas. To interpret the OHW field indicators for delineating a playa using these features requires an interpretation of "ordinary" ponding events. To support the reliability of the indicators tested here, we defined "ordinary" as ponded water detected in 50% or more of the imagery for zones on the playa from the 20 years of record analyzed (Table 2). This definition parallels the hydrology criteria for wetlands (Environmental Laboratory 1987, Office of the Chief of Engineers 1992), which says that the hydrology must have a 50% probability of occurrence.

Five of the OHW delineation field indicators rated by Lichvar et al. (2006a) had significant correlations with ponding duration. The surface features sorted into three groups of useful field indicators for delineation of the OHW on playa surfaces. Those features associated with a $<$ 50 decile occurrence were open mud cracks ($p < 0.0001$) and piping ($p = 0.0005$) and are good upland indicators. The piping features indicate drainage on playas and are therefore associated with areas lacking ponded water (Lichvar et al. 2006a). Those features associated with $\geq$ 50 decile ponded water were algal flakes ($p < 0.0001$), closed domed mud crack polygons ($p = 0.0037$), and closed multiple mud crack polygons ($p < 0.0001$). These are reliable indicators of ponded water and OHW. All of the $\geq$ 50 decile surface features increased in

Table 4. Rating OHW indicators by their Kendall correlation with ponding and mean elevation.

Feature	Correlation with ponding (significance level)	Mean LiDAR elevation ± SE
Open mud cracks	−0.509 ($p < 0.0001$)	697.38 ± 0.03 (n = 14)
Presence of pipes	−0.428 ($p = 0.0005$)	697.40 ± 0.04 (n = 12)
Presence of yellow 5Y playa soil surface hue	−0.333 ($p = 0.0068$)	697.43 ± 0.10 (n = 8)
Presence of intermediate 10YR playa soil surface hue	−0.102 ($p = 0.4090$)	697.27 ± 0.04 (n = 18)
Closed flat mud crack polygons	−0.061 ($p = 0.5847$)	697.24 ± 0.06 (n = 18)
Closed raised mud crack polygons	0.067 ($p = 0.5516$)	697.15 ± 0.09 (n = 5)
Closed domed mud crack polygons	0.348 ($p = 0.0037$)	696.91 ± 0.03 (n = 5)
Presence of 5YR playa soil surface hue	0.414 ($p = 0.0008$)	697.11 ± 0.06 (n = 16)
Change in playa soil surface hue from 5Y to 5YR	0.451 ($p = 0.0001$)	N/A
Closed multiple mud crack polygons	0.564 ($p < 0.0001$)	697.05 ± 0.05 (n = 9)
Presence of algal flakes	0.732 ($p < 0.0001$)	697.09 ± 0.04 (n = 23)
Mud crack width	0.743 ($p < 0.0001$)	697.10 ± 0.04 (n = 25)
Mud crack depth	0.746 ($p < 0.0001$)	697.08 ± 0.04 (n = 22)

frequency with longer periods of ponding duration (Figures 8, 9, 10, 11, and 13). Additionally, the occurrence of multiple features in a zone provided a stronger indication of ponding duration. For instance, in the areas with the longest ponding, closed domed mud crack polygons were highly associated with algal flakes. Likewise, many of the domed mud crack polygon areas had a high frequency of multiple subsurface layers of mud crack polygons.

The closed raised mud crack polygons found both above and below the 50 decile zone may be useful as OHW delineation field indicators because of their significant abundance at the middle deciles (40–60) of ponding. Since there is a strong increase in mud crack depth and width associated with longer ponded zones, closed mud crack polygons with deep and wide cracks (> 1 mm) can be used to determine if these mud crack polygons are current or remnant features. The closed raised mud crack polygons found in the < 50 decile zones were observed with cracks filled with distinct and differentiable sediments along the margins of the mud crack. This type of mud crack may represent remnant features in areas where there had been extreme ponding events; after drying, subsequent rain events caused water to flow across the surface en route to lower points on the playa, filling these cracks with sediments. Dinehart and McPherson (1998) observed such water movement and ponded water on lower portions of Rogers Playa. They reported that slightly elevated areas of the playa typically had

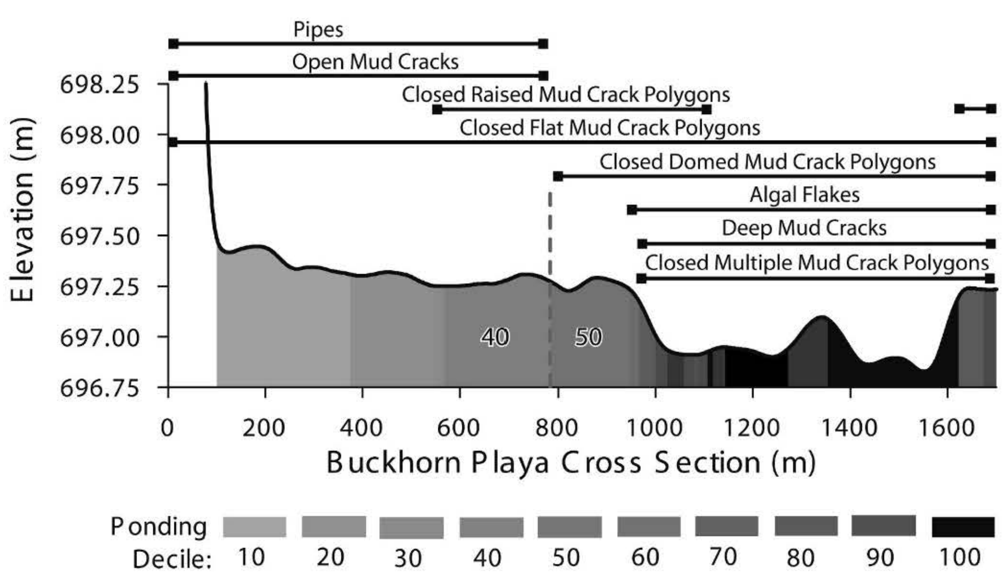

Figure 13. Representative cross section from Buckhorn Playa with the indicators placed in the locations along the ponding deciles where they were observed.

flowing waters and were mixed with a network of subtle depressions with a 0.002% slope that directed water to the lowest areas of Rogers Playa. They also reported that flowing water filled in desiccation cracks with sediment but that the cracks were not entirely erased by flowing water. Mud cracks may also fill or be erased over time from aeolian activity (Gutiérrez-Elorza et al. 2005, Reheis 2006). On the other hand, recently formed closed mud crack polygons useful for delineation have open cracks along the margins that are deeper and wider in areas with longer ponded water duration.

The reliability of field indicators we tested were against the boundary of ≥ 50 ponded water decile areas, but three factors can affect the reliability of the resultant OHW boundary. First, wind is constant in open desert basin locations. Wind can move ponded water during heavy and extended gusts and can distort the edge of the ponded zone (Lines 1979, Malek et al. 1990, Dinehart and McPherson 1998), so elevation alone can be misleading in determining the ponding extent. Second, the outer boundary of the ≥ 50 ponded water zone represents the cumulative climatic conditions that have occurred over a number of years. A series of dramatically different storm events causing various levels of ponding over a short period of time can create non-overlapping surface features at the OHW boundary. Third, the cyclic conditions of wet and dry periods over 10–20 years of El Niño-Southern Oscillation (ENSO) cycles are well documented in the literature for this general region (Cayan et al. 1998, 1999). Our field sampling and testing occurred during some of the wettest years on record during a recent wet cycle (Lichvar 2004a), so these indicators capture the ≥ 50 decile ponding boundary for the most recent wet period.

CONCLUSIONS

Correlating surface features with ponded water duration is useful for delineating the boundary of the OHW on unvegetated hard playas since standard wetland delineation methods (Environmental Laboratory 1987) require the presence of hydric soils and hydrophytic vegetation, which are problematic on hard playas (Lichvar and Sprecher 1996). Playa surface features can be used as field indicators for delineation since they have statistically significant relationships with ponding. Others have reported that surface features occur from ponded water based on field observations and that these and similar features have been used to establish OHW limits on playas throughout the arid west (Lines 1979, Lichvar and Sprecher 1996, 1998). Lichvar et al. (2006a) also reported these same features occurring on playas through the desert southwest. With the results of this study and an acknowledged occurrence of these features throughout the arid west on other playa surfaces, it is now possible to use the presence of one or more field indicators on a playa surface with confidence to delineate the OHW limits in the arid west, with a better understanding of their development, frequency, and duration of ponding to support their use. Even though there is a strong correlation of occurrence between OHW indicator presence and the lowest elevations on our test playa surface, using elevation alone on another playa surface would not provide a presence/absence statement that water has ponded within a low point and would not be useful for establishing the OHW outer limits because elevation alone is not an indicator of ponded water. Therefore, the OHW boundary is positioned at the outer extent of where one or more OHW mark indicators are present.

In defining Ordinary High Water on a desert playa, one needs to be aware of the past and present conditions. Playas are recognized as one of the most sensitive systems to changes in rainfall patterns (Cooke et al. 1993, Bryant and Rainey 2002), making them valuable indicators of climatic fluctuations (Endzel et al. 1992) but a challenge when establishing the limits of the "ordinary" ponded water for the purposes of delineation for the CWA. The outermost extent of current playas may well represent a post-Pleistocene pluvial lake developed during wetter past climatic periods (Endzel et al. 1992, Benson et al. 1996, Orme 2004) and its subsequent influences on salts, soil compaction, and other features that limit plant growth (Dahlgren et al. 1997, Lichvar et al. 2004b). The boundary that we tested and used to develop the OHW mark indicators represents parts of a wet cyclic period of the El Niño phase of the ENSO cycle within the outer limits of the playa boundary proper. At best, defining OHW on a playa is limited to the most recently developed OHW indicators from ponding at that particular locale within the recent wet period. In the absence of long-term precipitation and monitoring data, determining what represents the ponded water limits of "ordinary high water" on a playa has its limitations.

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