WETLANDS, Vol. 24, No. 2, June 2004, pp. 406–413

PONDING DURATION, PONDING FREQUENCY, AND FIELD INDICATORS: A CASE STUDY ON THREE CALIFORNIA, USA, PLAYAS

Robert Lichvar[1], Greg Gustina,[2] and Robert Bolus[1]
[1] *Engineering Research and Development Center*
Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire, USA 03755
E-mail: Robert.W.Lichvar@erdc.usace.army.mil

[2] *U.S. Department of Interior*
Bureau of Land Management
226 Cruz Alta
Taos, New Mexico, USA 87571

Abstract: Playas are temporarily ponded, shallow, intermittent lakes found in the arid southwest United States formed by rainfall and runoff in the wet season. Because playas are considered ''Waters of the United States'' (WoUS) under Federal Regulations 33 CFR 328.3 [a], their jurisdictional extent is delineated by either observation of ponded water or physical characteristics that represent *ordinary* high water marks that remain after the water has receded. To date, no surface hydrologic studies have described the frequency and duration of ponded water within desert playa systems to facilitate the understanding of ''ordinary'' for delineation purposes. To establish a baseline to support further the concept of ''ordinary,'' we used 20 years of historical satellite imagery of playas in the western Mojave Desert, California, in combination with 59 years of precipitation records, to provide a case study of frequency and duration of ponding in playas in the arid southwestern United States. Ponding was found to occur for at least 16 days, with a frequency of 51% or approximately every other year. We estimated the average antecedent precipitation needed to initiate ponding to be 8.29 cm. In years when rainfall exceeded 8.29 cm between October and March, the playas also ponded for 16 days into the growing season (March–November). The total length of the ponding period through the wet season ranged between 1 and 32 weeks, with a predictable relationship between length of inundation and total rainfall during the wet season. This range of occurrence of ponded water on these arid playas expresses the climatically unevenly distributed precipitation pattern, both spatial and temporally. Analysis of the ponding duration and frequency from this study site acts as a baseline for further refinement of the concept of *ordinary* high water and provides a basis for further development of field indicators for delineation purposes of arid southwestern playas.

Key Words: playa, ponding, duration, frequency, indicators, inundation, Mojave desert, satellite imagery, MTI, TM, delineation

INTRODUCTION

Playas, landforms in the arid southwest, are defined as the flat, lower portions of an arid basin with internal drainage that periodically flood and accumulate sediment (Neal 1975). They are covered with water less than 25% of the time, have evaporite accumulations or lacustrine activity (Neal 1975, Shaw and Thomas 1989), or both, and have a negative hydrologic balance 75% of the year (Briere 2000). Sparse vegetation of the Chenopod family and saltbush communities exists only on lake plains and sand dunes surrounding playa lakebeds. Two major information gaps make the delineation of playas in the arid southwestern United States problematic. First, there are no data on frequency and duration of ponding (inundation), and second, the surficial features remaining on the playa after ponding events that could provide data on the areal extent of water have not been investigated or correlated to ponding events. Under Federal Regulations 33 CFR 328.3 [a] of the *Clean Water Act* (CWA), playas and other ''Waters of the United States'' (WoUS) are delineated to their outermost extent either by observing ponded water or physical characteristics that remain after the water has receded that represent the Ordinary High Water (OHW) mark. For WoUS, ordinary means the presence of physical features representing the ordinary high water of ponded or flowing water. Temporal data pertaining to the surface hydrology of playas have only recently been described using remote sensing methods for climate modeling (Mishra et al. 1994), flood modeling (Verdin 1996, Bryant 1999, Bryant and Rainey 2002), determining evaporation rates (Prata 1990), and defining sediment transfers on playa surfaces (Millington et al. 1987). However, these data have not been analyzed to the extent necessary to allow us to determine duration and frequency in support of what ordinary high water events represent or to support the development of reliable use of physical features to determine OHW on playas. Precise information about the location, frequency, and duration of ponded water is essential to determine OHW (e.g., Doug and Colberg 1996, Lichvar and Sprecher 1996, Brostoff et al. 2001) and to assist us in selecting reliable surficial features that may be associated with it.

The surface waters on playas have not been fully described in either space or time, and the problem of measuring them is compounded by the ephemeral nature of the lakes, by evaporation, and by ground-water influences (Rosen 1994, Bryant 1999). Water accumulates on playas from runoff, precipitation, or ground-water discharge, but a particular playa may or may not pond at all during a particular year or it may remain ponded for up to 3 years (Cooke et al. 1993). The extent to which water remains on the surface is influenced by the current climate, playa surface conditions, evaporation rate, salinity, and infiltration or discharge of ground water. In addition, the extent of the water cover changes rapidly, in both the short and long terms (e.g., Kubly 1982) owing to, for example, changing wind direction that creates waves that push water to different parts of the playa (Saville et al. 1962, Weigel 1964). Bryant et al. (1994) and Bryant and Rainey (2002) identified four key stages of the ponding processes within playas that also create spatial shifts: 1) inundation, 2) evaporation of the water body, 3) relocation of shallow brine pools that can be moved easily by the surface action of winds, and 4) final desiccation of surface water. These spatial and temporal factors hinder our ability to estimate the duration and frequency of ponding that is required to model flood events accurately (Dinehart and McPherson 1998) or to determine whether certain Federal environmental regulations apply.

Some Federal, state, and private sector personnel are inclined to apply wetland delineation protocols to delineate playas. However, there are differences in both the rules and field characteristics for differentiating areas of wetlands and playas. For wetlands, there are formal definitions and guidelines. Wetlands are identified on the basis of three parameters: soils, vegetation, and hydrology, as specified in the Corps of Engineers *Wetlands Delineation Manual* (Environmental Laboratory 1987). By regulation, to be considered a wetland, specific hydrology must be met for 5% of the growing season or 1–2 weeks of the year, depending on latitude and altitude (''frequency and duration criteria,'' Office of the Chief of Engineers 1992). In contrast, frequency and duration criteria for playas are not defined under the CWA or guidance from the Corps to establish the extent of OHW. For background information about the physical characteristics of xeric fluvial systems, U.S. Army Corps of Engineers (COE) Districts in the southwestern United States have provided guidelines for making jurisdictional determinations for WoUS, including playas. However, without set criteria for frequency and duration of ponding, identifying and developing field indicators for both inundation areas and OHW boundaries that are useful in playa delineation remain problematic (Brostoff et al. 2001).

This paper describes a study of three playas in the western Mojave Desert, California. Our main objectives were to provide data on the occurrence of surface hydrology to support refinement of the concept of ordinary high water of playas and to establish a basis for further development of field indicators for playa delineation purposes by using the surface hydrology data and correlations of surface features remaining after water has receded. To establish frequency and duration of ponding without field gauging stations being available, we analyzed 59 years of precipitation data and 20 years of historical Landsat images that were custom-processed to identify surface water.

METHODS

Study Area

Three playas on Edwards Air Force Base (Edwards AFB), Kern County, California, were used as examples of arid southwest playas. Edwards AFB is in the western Mojave Desert northeast of Los Angeles. The study area included the eastern portions of Rosamond (total area 53 km^2), all of Buckhorn (5 km^2), and a small southwestern portion of Rogers Dry Lakes (total area 114 km^2) (Figure 1). Our thesis of frequency and duration as delineation indicators is based upon this population set. The playas are contained within the boundary of the bed of Pleistocene Lake Thompson (Orme 2001). Following Holocene desiccation and widespread progradation of alluvial and aeolian deposits, Lake Thompson developed into two significant playas, Rosamond in the west and Rogers in the east, separated by a suite of smaller playas, of which Buckhorn is the largest (Orme 2001). These three remnant playa bed surfaces within the boundary of former Lake Thompson are located at slightly different elevation levels: they range between 693 and 697 m. The ma-

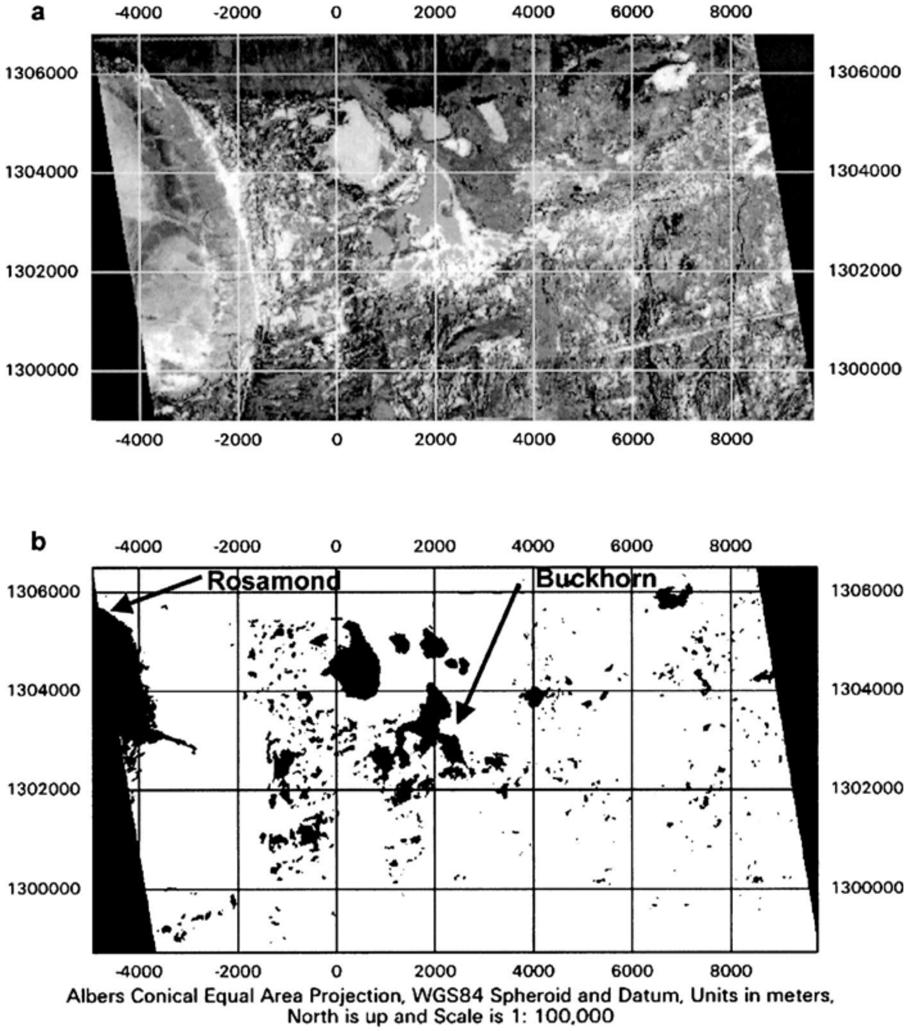

Figure 1. Example of visible band MTI satellite image. a. showing the study area with water ponded on Rosamond and Buckhorn; b. image processing result for the same area showing ponded surfaces in black.

jority of the vegetation located on Lake Thompson's bed surrounding the unvegetated playas is on exposed lake plains and sand dunes. These two landscape 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).

Under present climatic conditions, the surfaces of the playas remain dry for most of the year, sometimes for several consecutive years (Orme 2001). However, winter rainstorms caused by cyclonic systems from the Pacific Ocean, and summer thunderstorms caused by monsoons from the Gulf of California and tropical Pacific may sometimes inundate these playas, the duration of flooding depending on the magnitude and location of precipitation and ambient climate. Significant temporary flooding is also associated with El Niño events in the Pacific Ocean that lead to above-normal precipitation in the Mojave Desert (Redmond 2001).

Remote Sensing

Landsat 4, 5, and 7 Thematic Mapper (TM) and Multi-spectral Thermal Imager (MTI) satellite imagery was used to detect and map ponded water on playa surfaces. From these images, the following were verified: 1) that the ponding occurred for a minimum of two satellite passes (16 days) and 2) that the ponding happened during the growing season. The total length of time that water remained ponded in the study area, for the years analyzed, was extracted. A list of images acquired for analyses is shown in Table 1.

We verified the signature of ponded water on MTI and Landsat images by using a sequence of verification steps between the various types of images and actual ground positions. First, the standing water in the MTI

Table 1. List of satellite images obtained for analysis by platform and date.

Landsat 4 TM
Winter 1982–83: 12/10/82 12/26/82

Landsat 5 TM
Winter 1984–85: 1/8/85 1/24/85 2/25/85 3/29/85 4/14/85 5/16/85 6/1/85 6/17/85 7/3/85 8/20/85
Winter 1986–87: 1/14/87 1/30/87 3/3/87 3/19/87 4/4/87 4/20/90 5/6/87 5/22/87 6/7/87 6/23/87 7/1/87 7/9/87 7/25/87 8/10/87
Winter 1989–90: 5/14/90
Winter 1990–91: 3/30/91 4/15/91 5/17/91
Winter 1991–92; 1/12/92 2/13/92 2/29/92 3/16/92 4/17/92 5/3/92 5/19/92 6/4/92 6/20/92 7/6/92 7/22/92 8/7/92
Winter 1992–93: 11/27/92 12/13/92 1/14/93 2/15/93 3/3/93 3/19/93 4/4/93 4/20/93 5/22/93 6/23/93 7/9/93 7/25/93

Landsat 7 TM
Winter 1999–2000: 1/10/00 1/26/00 2/11/00 3/14/00 3/30/00 4/15/00 5/1/00 5/17/00 6/2/00 6/18/00 7/4/00 7/20/00
Winter 2000–01: 1/28/01

DOE MTI
Winter 2000–01: 2/3/01 2/4/01 2/20/01 2/21/01 3/8/01 3/9/01 3/25/01 3/26/01 4/12/01 4/13/01 5/2/01 5/3/01 5/23/01

image of 23 May 2001 was verified in the field by Global Positioning System (GPS) fixes taken on 7 June 2001 of the position of the ponded water boundary for two of the largest ponds. Second, these field positions of ponded water were compared to identified water signatures on the processed MTI image to verify coincidence between the field locations and the processed water signatures. Third, to verify the accuracy of ponded water signatures between the TM images and MTI images and field positions, we compared a processed TM image from 28 January 2001 to a processed MTI image from 3 February 2001 to field positions fixed by GPS on 11 January 2001. The processed TM image identified and matched the same boundaries of ponded water as did the processed MTI image, and both matched the GPS positions. By using this ground truth, we verified that the calibration settings used in the processing procedure identified only ponded water and did not include any moist or muddy surfaces.

Custom-flown MTI images over our study area were acquired from the Department of Energy. Two sequential daily MTI images were taken at intervals of approximately 16 days from February through May of 2001. By imaging on sequential days, the probability of blockage by a cloud cover was greatly lowered; a complete record of seven clear shots was acquired in the early part of 2001.

Two types of Landsat TM images were obtained from the USGS archive at the EROS Data Center in Sioux Falls, South Dakota: full resolution and reduced resolution browse imagery. The interval of the Landsat is every 16 days, with only one image per interval taken, regardless of cloud cover. We searched the TM archive, starting in 1982, up to and including January 2001 (Table 1). When available, images were obtained that represented dry periods prior to ponding, the ponding sequence, and dry periods following ponding. However, we were unable to obtain complete sets of images for many years because of a lack of consecutive archived records, clouds, and poor image quality.

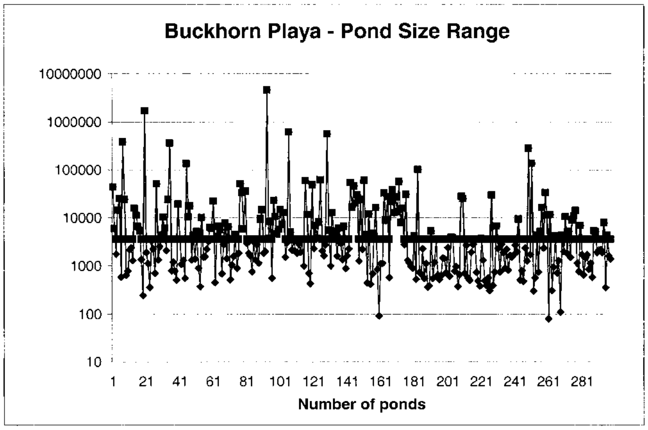

Figure 2. Pond size range showing that enough ponds were above Landsat TM resolution for proof that frequency and duration can be delineation indicators (USGS Earthexplorer, Victorville, CA vector hydrology coverage, 1982).

The pixel size and radiometric accuracies of the TM and MTI sensors are suitable for detection of ponds of average size and above on Buckhorn playa. Landsat 4 and 5 TM have a 30-m Ground Sample Distance (GSD) in their reflective bands, and Landsat 7 is similar to its predecessors but has an extra 15-m pan band. Their radiometric accuracy is specified as being between 3 and 5%. Because the detection algorithm takes the ratio of two bands, the accuracy of the result may vary from 0 to 10%, depending on whether individual band accuracies track each other or diverge. The use of the mid-range IR band of 30 m for the resampled MTI images and 30 m for the TM images in the detection algorithm identified ponded water areas within a minimum size of 60 m on edge. The general size range of the ponded water on Buckhorn Playa is shown on Figure 2. Out of a total of 298 ponds, there are 129 that are above the resolution of the Landsat TM pixel size. This size is determined from the potential of having ponded and non-ponded mixed pixels at the edge. The minimum size equates to 0.36 ha in comparison with the size range of the playa ponds on Buckhorn that are from .008 up to 460 ha. Statistics from the USGS hydrology vector coverage of 1982 show that the average size of ponds on Buckhorn playa is 3.6 ha (Figure 2). In certain years, the acquisition of complete sequences of full resolution TM images was not justified or available, so the winter sequence of images was supplemented with reduced resolution TM browse images from the Landsat 5 and 7 archives. The reduced resolution TM browse images with a 480-m GSD were found to be useful for establishing duration on the large playas once ponding had begun.

A spectral separation scheme was used to create the algorithm that detected water versus the rest of the imagery. Water is separated out based on it having a high reflectance relative to its surroundings in the visible green band (Landsat band 2) and a low reflectance relative to its surroundings in the short-wave reflective infrared band (Landsat band 5). When the ratio of band 5 to band 2 is taken, high values indicate reflectances other than water and low values indicate water. Each full resolution TM and MTI image scene was classified by the ratio of equivalent Landsat band 5 to band 2. This produced a gray level image made up of floating point numbers ranging from 0 to 4 or 5. A ratio threshold, determined using the pooled areas from ground truth determined for the MTI scene of 23 May 2001, was set halfway between two normal histogram distributions at a level of 1 that accurately separated pooled water from everything else in the imagery (Rees 2001). Every value above 1 was driven into saturation, or to display as white, and every value below 1 was driven to zero, or to display as black, indicating water (Figure 1). Co-registered pooled water maps were developed using the same technique with the same projection as the imagery maps. Even though the transmissions through the atmospheric and water media are not quite the same at band 2 as at band 5, they are close enough to consider this ratio as an invariant indicator over time. Reduced resolution TM previews were analyzed for water qualitatively by using standard aerial photography interpretation techniques of observing the presence of color, texture, size, location, and other physical attributes that indicate water.

Precipitation Data

We developed an average antecedent precipitation level necessary for ponding by using precipitation data from years that had Landsat imagery that showed ponding. The average antecedent precipitation level was calculated by summing recorded precipitation events from 1 October to the date at which ponding was first visible (and this ponding had to last for at least two consecutive satellite images). Archived weather data, containing daily total precipitation at the main base area from January 1942 to the present, were obtained from the 412th Operations Support Squadron, Weather Flight office (OSS/OSW), Edwards Air Force Base. Making sure that the ponding was seen in two consecutive images ensured a duration greater than 16 days, as Landsat images are taken every 16 days. This is a conservative approach because ponding visible for only one image could correspond to duration of up to 31 days: 15 days before, 15 days after, and the day the image was captured.

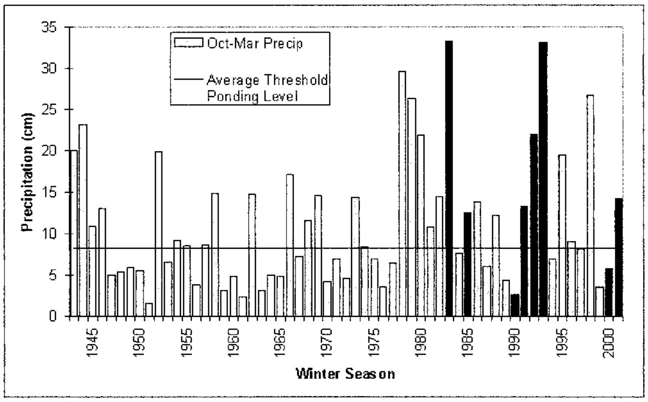

Figure 3. Winter precipitation since 1942 by year in chronological order where, for example, the 1945 bar means 1 Oct 1944 to 31 March 1945; highlighted bars show years analyzed for frequency and duration from the imagery.

Using the average antecedent precipitation level for ponding, we analyzed the frequency of occurrence for the 59 years of precipitation record. We determined the frequency of ponding by reviewing the historical climate record from 1942 to 2001 to find the number of years that equaled or exceeded the average antecedent precipitation between 1 October and 31 March. This time represents a period of maximum precipitation level and minimal evapotranspiration (Figure 3). Frequency of inundation was calculated as the number of years equaling or exceeding the average antecedent level, divided by the 59 years of historical record analyzed.

We analyzed the duration of ponding on playa surfaces in three ways. First, we verified that all available Landsat, reduced resolution TM, and MTI images had two consecutive images showing ponding. Thus, for all years analyzed, the study area had at least some ponding for a minimum of 16 days. Second, once we verified the minimum ponding duration, we analyzed all available images for the period after 3 March to determine if ponding was present for at least 14 consecutive days or 5% of the growing season, following guidance set by the COE for wetland hydrology criteria (Office of the Chief of Engineers 1992). The start date for the growing season was obtained from the table of probabilities of growing season dates in the local USDA Soil Survey (1997) for the −2.2°C date, which was 3 March (Office of the Chief of Engineers 1992). Third, to analyze duration, we determined the

Table 2. Antecendent precipitation level data and bracketing dates.

Precipitation Level (cm)	Dates
6.07	10/01/82–12/10/82
12.17	10/01/84–01/08/85
13.34	10/01/90–03/30/91
5.77	10/01/91–01/12/92
9.53	10/01/92–12/13/92
5.74	10/01/99–03/14/00
5.44	10/01/00–01/11/01
8.29	Average
3.37	Standard Deviation

total length of time in weeks that at least some water remained on the playa surface by looking at consecutive dates of imagery for each year analyzed. Because the archival record of full resolution imagery was incomplete, we increased the sample size by using reduced resolution TM browse images to track playa ponding and drying. These were visually compared to the processed images using aerial photo interpretation techniques to determine water signatures and to delineate pond boundaries. When these images were used, only conservative estimates of duration were made.

Verification of ponding via satellite imagery was limited to seven years (′82, ′84, ′90, ′91,′92, ′99, and ′00) for frequency and six (′85, ′90, ′92, ′93, ′00, ′01) for duration, owing to an incomplete image archival record and cloudy conditions. To verify a lack of ponded water in years that fell below the average antecedent precipitation level with no winter or spring precipitation, a series of images was obtained and processed to confirm the lack of ponding. To verify lack of spring ponding, March through April, an image from 14 May 1990 was obtained and used as a baseline to establish dry spring conditions. To establish a baseline for non-ponded surfaces for an entire winter, a series of reduced resolution TM browse images from 1989 to 1990 were used for verification.

RESULTS

Using precipitation data from 1942 to 2001, including drought years, we estimate that playas in our study area ponded with a frequency of 0.51 (Figure 3), or every other year, based on an average antecedent precipitation level of 8.29 cm (Table 2). Our antecedent precipitation level method, which used ponded water signatures on satellite images in combination with precipitation records, produced a range from 5.44 to 13.34 cm, with a standard deviation of 3.37, until ponding occurred (Table 2). The range would likely have been much smaller if more images in shorter time increments had been available. Winter precipitation totals by year (weeks of inundation) are shown in Table 3.

Table 3. Winter precipitation by years and weeks of inundation.

Precipitation (cm) Oct–Mar	Years	Weeks Inundated
2.64	1989–90*	0
5.74	1999–00	6
12.55	1984–85*	14
14.22	2000–01	16
22.00	1991–92*	25
33.15	1992–93	32

* Used USGS Earthexplorer browse image to verify inundation.

Analysis of images starting on 3 March verified that for the six years analyzed for duration, some part of the playa surface was inundated for at least 5% or more of the growing season. Analysis of the precipitation records for the six years of image records used to establish the duration (Table 3) best fit a second order polynomial (Figure 4). This curve allows for prediction of potential duration of ponding during future events.

DISCUSSION

The portions of the playa surface that were inundated and subsequently dried during the study period showed distinct signatures of wet soils and mud as the standing water and soil moisture receded; non-ponded areas lacked such a signature. The smaller pixel size of MTI and TM (5 to 30 m), compared with that of Advanced Very High Resolution Radiometer (AVHRR) [1.1-km pixel size], as used in other remote sensing efforts on playa surface hydrology (Drake and Bryant 1994, Bryant and Rainey 2002), was an im-

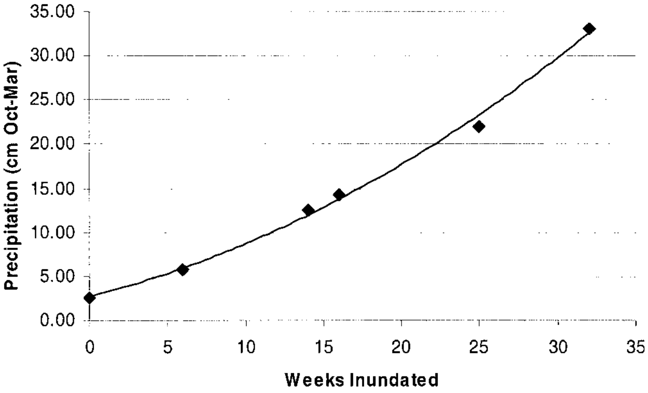

Figure 4. Plot of data shown in Table 3 with second-order polynomial trend line ($y = b + c_1x + c_2x^2$ where $b = 2.74$cm, $c_1 = 0.4448$cm/week and $c_2 = 0.0152$ cm/week squared with an RMS fit error of 0.977648).

portant step in establishing frequency and duration of ponded water. The smaller pixel size of MTI and TM images provided the capability of distinguishing the areal extent and gradation between ponded water from wet soil and mud, which is critical for delineation purposes.

While fluctuations in the temporal and spatial patterns of ponded water were apparent in the images, we did not analyze them in detail here. However, the spatiotemporal pattern of ponded water is fundamental to understanding the concept and manifestation of ''ordinary'' on playas. Unfortunately, we were limited in our ability to interpret in detail the temporal and spatial patterns of surface hydrology during several El Niño years. Images were lacking or degraded by cloud cover during 3 of the 20 years we analyzed. However, future efforts to analyze and understand the influences from temporal or spatial responses of surface fluctuations and ponding, including the wettest periods of El Niño years, would further the refinement of the concept of ''ordinary'' on playas.

The data we collected from these playas at Edwards AFB meet the hydrology criteria for a wetland (Environmental Laboratory 1987, Office of Chief Engineers 1992). The hydrology criteria used for wetland delineation best fit the eastern humid regions in the U.S., where the inter- and intra-annual patterns of rainfall have a more statistically normal distribution than the apparently chaotic patterns of the arid southwest (Graf 1988). However, even with extremes in climatic conditions of three El Niño and seven drought years occurring during our study period, ponding still occurred at least every other year on our study playas. Even with an every-other-year probability of occurrence, this study shows that occurrences need to be determined over longer time periods versus shorter or annual time frames. Therefore, to refine future regional hydrology criteria for playas, baseline surface-hydrology data need to be developed for other playas systems in the arid southwest to fully capture the degree of inter-annual precipitation associated with ponded water on playas typical of this region.

The algorithm we determined relating rainfall to areal extent of inundation could be useful for predicting seasonal ponding duration and future development of field indicators across the arid southwest. The relationship between the amount of rain and total weeks the playa remains ponded that fits a second-order polynomial may be helpful in supporting decisions regarding the presence of hydrology at a site and determining if it meets hydrology criteria for delineation purposes. Also, this relationship may be useful in supporting the development of field indicators and their reliability if precipitation for the winter is known.

By developing a quantitative method for documenting the frequency and duration of ponded water, this study provides a basis for future development of field indicators useful for delineation throughout the region. In their report, Brostoff et al. (2001) discussed differences in indicators for inundation and ordinary high water marks in the field. Using the methodology we present here, it may be possible to develop field indicators for delineation by establishing the time each spot on a playa is inundated and then correlating the boundaries of those ponded zones to surface features on the playas.

ACKNOWLEDGMENTS

Opinions expressed in this manuscript are those of the authors and do not necessarily reflect policy of the U.S. Army Corps of Engineers. Funding was provided in part by the Corps of Engineers, Wetland Regulatory Assistance Program. We gratefully acknowledge the Department of Energy MTI mission, at Los Alamos and Sandia National Laboratories, for providing the authors with custom-flown and timed MTI satellite images from over our study area. Edwards Air Force Base generously provided logistical support and allowed satellite overflights. We further appreciate critical comments provided by James Wakeley and Steven Sprecher, two anonymous reviewers, and Randy Hunt, assistant editor. Finally, special thanks are accorded William Brostoff for encouraging us to articulate the critical points of this study to add to the scientific aspects of playas and delineation of WoUS.

LITERATURE CITED

Brierre, P. R. 2000. Playa, playa lake, sabkha: Proposed definitions for old terms. Journal of Arid Environments 45:1–7.

Brostoff, W., R. Lichvar, and S. Sprecher. 2001. Delineating playas in the arid southwest: A literature review. U.S. Army Corps of Engineers, Hanover, NH, USA. ERDC Technical Report ERDC TR-01-4.

Bryant, R. G. 1999. Application of AVHRR to monitoring a climatically sensitive playa. case study: Chott El Djerid, Southern Tunisia. Earth Surface Process and Landforms 24:283–302.

Bryant, R. G. and M. P. Rainey. 2002. Investigation of flood inundation on playas within Zone of Chotts, using a time-series of AVHRR. Remote Sensing of Environment 82:360–375.

Cooke, R., A. Warren, and A. Goudie. 1993. Desert Geomorphology. UCL Press, London, UK.

Dinehart, R. L. and K. R. McPherson. 1998. Topography, surface features, and flooding of Rogers Dry Lake, California. U.S. Geological Survey, Water Resources Investigations Report 98–4093.

Doug, P. J. and J. Colberg. 1996. Delineation of playa features in the western Great Basin. Wetland Journal 8:6–13.

Drake, N. A. and R. G. Bryant. 1994. Monitoring the flooding ratios of Tunisian Playas using AVHRR data. p. 87–96. *In* A. Millington and K. Pye (eds.) Climate Change in Drylands. John Wiley and Sons, London, UK.

Environmental Laboratory 1987. Wetlands delineation manual. U.S. Army Waterways Experiment Station, Vicksburg, MS, USA, Wetlands Research Program Technical Report Y87-1.

Graf, W. L. 1988. Fluvial Processes in Dryland Rivers. Springer-Verlag, New York, NY, USA.

Kubly, D. M. 1982. Physical and chemical features of playa lakes in southeastern California, U.S.A. Archives of Hydrobiology Supplement 62:491–525.

Lichvar, R. and S. Sprecher. 1996. Delineation and characterization of ''Waters of the United States'' at Edwards Air Force Base, California, USA. Waterways Experiment Station, Vicksburg, MS, USA.

Millington, A. C., A. R. Jones, N. A. Quarmby, and R. J. Townsend. 1987. Remote sensing of sediment processes in playa basins. p. 369–381. *In* L. Frostick and I. Reid (eds.) Desert Sediments, Ancient and Modern. Geological Society, London, UK. Special Publication 35.

Mishra, J. K., M. D. Joshi, and R. Devi. 1994. Study of desertification processes in Aravalli environment using remote-sensing techniques. International Journal of Remote Sensing 15:87–94.

Neal, J. T. 1975. Playas and Dried Lakes. Dowden, Hutchinson & Ross, Inc., Stroudsberg, PA, USA.

Office of the Chief of Engineers. 1992. ''Clarification and interpretation of the 1987 Manual.'' Memorandum for SEE Distribution, 6 March 1992, Washington, DC, USA.

Orme, A. 2001. Geomorphic classification report. Appendix B. *In* R Lichvar, S. Sprecher, A. Orme, G. Gustina, D. MacDonald, M. Ericsson, C. Racine, J. Campbell, and A. Kane (eds.) Ecological land classification and floodplain assessment for Pleistocene Lake Thompson bed: a comprehensive report including Phase I: Rosamond Dry Lake and Phase II: Buckhorn and Rogers Dry lakes. Cold Region Research and Engineering Laboratory, Hanover, NH, USA.

Prata, A. J. 1990. Satellite-derived evaporation from Lake Eyre, South Australia. International Journal of Remote Sensing 11: 2051–2068.

Redmond, K. 2001. Northern Hemisphere Oct–Mar El Niño vs. La Niña. 700 Mb Height Anomalies. Western Regional Climate Center. http://www.wrcc.dri.edu/enso/700enln.html

Rees, W. G. 2001. Physical Principles of Remote Sensing, Second Edition. Cambridge University Press, Cambridge, UK.

Rosen, M. R. 1994. The importance of groundwater in playas: a review of playa classifications and the sedimentology and hydrology of playas. Geological Society of America Special Paper 289. *In* M. R. Rosen (ed.) Paleoclimate and Basin Evolution of Playa Systems, Boulder, CO., USA.

Saville, T. E., W. McClendon, and A. L. Cochran. 1962. Freeboard allowances for waves in inland reservoirs. Journal of the Waterways and Harbors Division, American Society of Civil Engineers 88:93–124.

Sawyer, J. O. and T. Keeler-Wolf. 1995. A Manual of California Vegetation. California Native Plant Society, Sacramento, CA, USA.

Shaw, P. A. and D. S. G. Thomas. 1989. Playas, pans, and salt lakes. p. 184–208. *In* D. S. G. Thomas (ed.) Arid Zone Geomorphology.Belhaven Press, London, UK.

U.S. Army Corps of Engineers, South Pacific District. 2001. Final Summary Report: guidelines for jurisdictional determinations for ''Waters of the United States'' in the arid southwest. http://www.spl.usace.army.mil/co/co5.html#reg.

U.S. Department of Agriculture. 1997. Climatic analysis for wetlands by county. http://www.wcc.nrcs.usda.gov/water/wetlands.html. Accessed September 2001.

Verdin, J. P. 1996. Remote sensing of ephemeral water bodies in western Niger. International Journal of Remote Sensing 17:733–748.

Weigel, R. L. 1964. Oceanographical Engineering. Prentice Hall, Inc. Englewood Cliffs, NJ, USA.

Manuscript received 14 January 2002; revisions received 24 February 2003 and 20 January 2004; accepted 3 March 2004.