Journal of Hydrology 510 (2014) 92–102

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Surface water hydrology and geomorphic characterization of a playa lake system: Implications for monitoring the effects of climate change

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ARTICLE INFO

Article history:
Received 1 October 2013
Received in revised form 5 December 2013
Accepted 7 December 2013
Available online 16 December 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ellen Wohl, Associate Editor

Keywords:
Black Rock Playa
Landsat
Hydrology
Geomorphology
Climate change

SUMMARY

Playa lakes are sensitive recorders of subtle climatic perturbations because these ephemeral water bodies respond to the flux of diffuse and channelized flow from their watersheds as well as from direct precipitation. The Black Rock Playa in northwestern Nevada is one of the largest playas in North America and is noted for its extreme flatness, varying less than one meter across a surface area of 310 km^2. Geo-referenced Landsat imagery was used to map surface-area fluctuations of ephemeral lakes on the playa from 1972 to 2013 to provide baseline data on surface water hydrology of this system to compare to future hydrologic conditions caused by climate change. The area measurements were transformed into depth and volumetric estimates using results of detailed topographic global positioning system (GPS) surveys and correlated with available surface hydrological and meteorological monitoring data. Playa lakes reach their maximum size (<350 km^2) in spring, fed by melting snows from high mountains on the periphery of the drainage basin, and usually desiccate by early- to mid-summer. The combination of a shallow groundwater table, sediment deposition, and hydro-aeolian planation probably are largely responsible for the flatness of the playa. When lakes do not form for a period of several years, the clay- and silt-rich playa surface transforms from one that is hard and durable into one that is soft and puffy, probably from upward capillary movement of water and resultant evaporation. Subsequent flooding restores the hard and durable surface. The near-global availability of Landsat imagery for the last 41 years should allow the documentation of baseline surface hydrologic characteristics for a large number of widely-distributed playa lake systems that can be used to assess the hydrologic effects of future climate changes.

1. Introduction

The Great Basin of the western United States is characterized by more than 80 closed basins, most of which contained large lakes in the late Pleistocene with levels fluctuating according to prevailing climate conditions (Benson and Thompson, 1987; Morrison, 1991). Today, only a few extant lakes are found in the basin bottoms, which are fed by perennial streams that have their headwaters in high mountains on the periphery of the Great Basin. More typically, the floors of most of the pluvial lake basins are currently occupied by playas that are occasionally flooded by precipitation events and associated runoff (Scuderi et al., 2010).

In general, playas in the Great Basin can be grouped as 'wet' or 'dry' playas based on the depth to groundwater (Rosen, 1994; Reynolds et al., 2007). In wet playas, groundwater is shallow (<5 m depth) and capillary action allows for evaporation of the shallow groundwater, producing soft surfaces of loose sediment along with the formation of evaporate minerals (Reynolds et al., 2007). In contrast, the depth to groundwater is typically greater than 5 m in dry playas, precluding evaporation from the capillary fringe, and the surfaces are composed of dense, compact silt and clays. Both types of playas, however, are subject to inundation from surface water (Rosen, 1994; Reynolds et al., 2007; Scuderi et al., 2010).

Even though the magnitudes of surface-water fluctuations in playa lakes are not as large as those associated with perennial lakes, playa lakes are still sensitive recorders of the hydrologic balance of closed basins over annual-to-decadal timescales (e.g., Harris, 1994; Bryant and Rainey, 2002; Castaneda et al., 2005). The seasonal timing of playa inundation also can help determine sources of precipitation responsible for the inundation, which may provide insight into past moisture sources during the Holocene (Scuderi et al., 2010).

The Black Rock Playa (BRP) is one of the largest playas in the Great Basin and is known for its flatness, which is why the world's land speed record is currently held there. Despite the relative lack of surface water in the BRP drainage basin, large, shallow lakes periodically appear on the playa in the winter and spring of some years. The appearance of these lakes represents accumulated surface-water discharge integrated over a large but relatively undeveloped watershed in the northern Great Basin. Thus, documenting the

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0022-1694/$ - see front matter
http://dx.doi.org/10.1016/j.jhydrol.2013.12.018

surface area, depth, and volumetric fluctuations of BRP lakes provides a measure of the absolute flux of water moving across the landscape in this semiarid region, thereby providing baseline data for quantifying the effects of future climate change on the hydrologic cycle.

When present at the right time of year, these lakes are also ecologically important because they support an ecosystem of producers (phytoplankton, bacteria, and other microbes) and consumers (branchiopods) that are a rich source of food for migrating birds (Plissner et al., 2000; Sada et al., 2013). At the end of each of these lake phases, usually lasting just a few months, the BRP desiccates, potentially becoming a large dust-emitting source.

The purpose of this paper is to document the surface water hydrology and geomorphology of the BRP to establish baseline conditions on how this system has operated during the recent past and how it may respond to future climate changes. This study uses a time series of Landsat imagery from 1972 to 2013 to reconstruct surface-area fluctuations of the playa lake and combines these measurements with the results of a detailed topographic survey of the BRP to develop relationships between surface area, depth, and volume to document the absolute flux of surface water through this system. An analysis of the timing and size of these lake-level fluctuations is also combined with field observations and hydrologic monitoring data to establish correlations between the connectivity of the fluvial and lacustrine hydrologic system. These correlations could then be applied to assess and monitor potential changes in the hydrologic cycle under future climatic scenarios. The data and analysis performed herein also could be applied to other semiarid to arid regions that are characterized by playa systems to determine regional, hemispheric, and global hydrologic responses to future climate change.

2. Geologic and geomorphic setting

The BRP in northwestern Nevada represents the lakebed of ancient Lake Lahontan and was submerged beneath as much as 145 m of water as recently as 15,500 years ago (Adams et al., 1999). At that time, Lake Lahontan was integrated across multiple subbasins and was fed by five major streams and numerous smaller ones (Fig. 1). Fluctuations in lake-surface elevation and area were a direct reflection of changing climatic conditions in this region during the late Pleistocene (Benson and Thompson, 1987). Upon desiccation of Lake Lahontan, the BRP drainage basin became isolated from the rest of the Lahontan system by the early Holocene (Adams et al., 2008) and was left without a major, inflowing river.

Evidence for significant lake-level fluctuations on the BRP in the Holocene is more equivocal. Davis and Elston (1972) inferred at least two late Holocene lake stands in the BRP basin at some time between 3300 and 1400 years ago and again after 1400 years ago based on the ages of clay deposits on the south side of the playa, but the exact timing and magnitude of these fluctuations are unclear. In the same general area, Davis (1987) described a section where the Mazama and Tsoyawata tephras were contained in clay deposits at an elevation of about 1196 m, which are either lacustrine or represent a clay dune. These tephras are about 7700–7800 cal - year B.P. in age and are found in lake deposits at relatively high levels in the other subbasins of Lahontan indicating wetter conditions than modern at that time (Davis, 1982; Adams et al., 2008). The Holocene record of lakes on the BRP requires additional work.

The BRP is located within the larger, but ill-defined Black Rock Desert (BRD), and both of these features are included in the Black Rock Desert-High Rock Canyon National Conservation Area in northwestern Nevada (Fig. 1). The BRP is in the middle of a system of three integrated basins that extend for about 180 km from the south end of the Smoke Creek Desert to the north end of the east arm of the BRD (Fig. 1). All three of these basins represent the lake bed of ancient Lake Lahontan, but only the BRP possesses the extreme flatness for which it is famous.

The very flat part of the BRP extends about 50 km in a northeast-southwest direction and ranges from 4 to 12 km wide. According to USGS topographic maps, approximately 280 km^2 of the playa is below an elevation of about 1190 m, the lowest measured point being about 0.5 m lower at 1189.5 m. Surrounding the very flat part of the playa on its northwest and southeast sides are range front piedmonts inscribed by Pleistocene shorelines and variously covered by young alluvial fans, some of which have prograded onto the playa. In places, scattered gravel extends onto the playa several hundred meters beyond the toes of the fans. Many of these fans obliterate the shorelines, which also points to their young age. Adjacent to the playa, small transverse dunes commonly cover the distal parts of fans. Their axes are generally oriented NW-SE with the slip faces on their northeast sides indicating a transport direction to the northeast, consistent with prevailing winds.

The active, down-to-the-west Black Rock fault zone (Dodge, 1982; Sawyer and Adams, 1998) bounds the western side of the Black Rock Range and extends to the south-southwest forming the eastern margin of the BRP (Fig. 2). This approximately 60 km long fault zone is represented by a series of en-echelon, discontinuous scarps that record two Holocene surface ruptures, the older of which is less than 7000–5000 years old and the most recent rupture is less than 1100 years old (Dodge, 1982). Maximum surface offsets for the scarps traversing the playa range from 1.4 to 2.2 m, and these features separate the very flat BRP to the west from the uplifted and dissected east arm of the BRD to the east (Figs. 1 and 2).

The drainage basin for the BRP encompasses about 17,630 km^2 and consists of a series of large mountain blocks separated by intervening basins (Fig. 1). Most of the runoff likely is generated in the mountains where precipitation is much higher than in the basins (Fig. 1). The two principal streams that flow onto the BRP, the Quinn River (QR) and Mud Meadows Creek (MMC), both terminate in the eastern part of the playa in what is known as the Quinn River Sink (QRS) (Fig. 1). Although both of the streams are primarily sourced from melting winter snows and other precipitation in the high mountains on the periphery of the basin, MMC also may derive a significant part of its flow from springs from the Soldier Meadows area and along the west side of the Black Rock Range (Figs. 1 and 2). During most summers, however, the channels of both of these streams are dry.

The climate of the BRP (as measured at the Gerlach, NV coop station) is semiarid with mean annual precipitation of about 19 cm/year. Summers are warm with maximum July daily temperature of 33.6 °C and winters cool with December daily minimum temperatures of about −6 °C (www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv3090; data accessed November, 2011). The most common winds at the Bluewing Mountain RAWS Station, located about 25 km south and 200 m higher than the playa (Fig. 1), are from the NW; but the strongest mean wind speeds come from the west-southwest (www.raws.dri.edu/cgi-bin/rawMAIN.pl?nvNBLU; data accessed November, 2011). The average shallow lake evaporation rate for the BRP was estimated to be about 127 cm/year by Houghton et al. (1975) and about 137 cm/year by Huntington and Allen (2010). Regardless of the slight differences in these estimates, both are larger than the depth of the typical lake that forms on the playa.

3. Previous work

Russell (1885) described the playas and playa lakes of the Lahontan basin in general and made specific reference to the playa lake that formed on the BRP. He surmised that the lakes of the BRP were more a product of snowmelt from distant mountains coursing