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Estimating playa lake flooding: Edwards Air Force Base, California, USA

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Abstract

Playa, or terminal lakes are essentially flat surfaces with minimal topographic relief, and they are common in most semi and arid-environments. Both ground and surface waters can accumulate within a terminal basin and result in flooding of the playa. Within the boundaries of Edwards Air Force Base, located in Southern California, there are four playas: Rosamond, Buckhorn, Rogers, and Rich Dry Lakes. The Rosamond and Rogers playas are currently and have historically been used as runways, taxiways, and industrial areas by the US Air Force and National Aeronautics and Space Administration. A flood assessment of Rogers Dry Lake was mandated due to Air Force regulations concerning delineation of 100-year flood hazard zones, and US Federal regulations, which specify that playas are 100-year special flood hazard zones. From an environmental viewpoint, when water is present, playa lakes can also provide habitat for migratory birds.

There is neither guidance nor a generally accepted approach for identifying flood hazards on playas. Therefore, an approach was developed to determine the 100-year regulatory floodplain associated with a dry lakebed, and this approach was used to define tile regulatory floodplain on Rogers and Rich Dry Lakes. This paper describes the application of the method developed to estimate the regulatory 100-year depth of water on Roger and Rich Dry Lakes.

Keywords: Playa; Rainfall–runoff; Flooding; Hydrophobic soils

1. Introduction

Playas, or terminal lakes, are essentially flat surfaces with minimal topographic relief; and they are common in most semi and arid-environments (see for example, Goudie, 1991). Both ground and surface waters can accumulate within a terminal basin and result in flooding of the playa. The terms ‘playa’ or ‘playa lake’ are often confused or inappropriately used, or have been replaced by a somewhat synonymous term at a specific locale, such as ‘dry lake’ that is used in California (Briere, 2000; Rosen, 1994). Within the boundaries of Edwards Air Force Base (EAFB), located in Southern California, there are four playas:

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Notation

C_I	climatic index
CLRF	channel loss reduction factor
CN	SCS curve number
$\mathrm{CN_u}$	SCS curve number for unburned soil conditions
$\mathrm{CN_b}$	SCS curve number for burned soil conditions
$\mathrm{C\bar{N}_b}$	time average curve number for burned conditions
f_b	burned soil infiltration rate
f_u	unburned soil infiltration rate
I	rainfall intensity
K	empirical factor to account for burned soil conditions
P_A	average annual depth of precipitation
P_C	causative event depth of precipitation
P_T	threshold precipitation
S	a parameter including both potential maximum retention and initial abstraction
S_b	a parameter including both potential maximum retention and initial abstraction for burned soil conditions
S_u	a parameter including both potential maximum retention and initial abstraction for unburned soil conditions
T_A	average annual temperature
T_D	precipitation event duration
Δt	time increment

Rosamond, Buckhorn, Rogers, and Rich Dry Lakes (Fig. 1). The Rosamond and Rogers playas are currently and have historically (since approximately 1942) been used as runways, taxiways, and industrial areas by the US Air Force and National Aeronautics and Space Administration (NASA); and EAFB is an emergency diversion airport for Los Angeles International Airport.

A flood assessment of Rogers Dry Lake (Rogers Lake) was mandated due to US Air Force regulations requiring the delineation of 100-year flood hazard zones, and Federal regulations, which specify that playas are 100-year special flood hazard zones. Therefore, all applicable criteria for federal facilities located within 100-year flood hazard zones must be addressed. Flooding of the playas on EAFB can also impact flightline operations. Runways, taxiways, apron areas, and buildings are either on or only slightly elevated above Rogers Dry Lakebed; and if the depth of inundation exceeds the elevation of these facilities, then operations must cease and infrastructure damage may be incurred. EAFB is also a diversionary landing location for NASA's space shuttle; and therefore, it is important that these facilities be available throughout the year. In addition, ponded water also attracts migratory birds that are a danger to aircraft operations and vice versa. Anecdotal information suggest flooding has in the past interrupted flightline operations at EAFB; and, if history is a guide, flooding will interrupt operations in the future. Thus, there are a variety of reasons to estimate the depth of water associated with the 100-year flood event. Fig. 2 shows water in Rich Dry Lake (Rich Lake) on 13 February 2003 that resulted from 62.7 mm of precipitation at EAFB on 11–13 February 2003. It is pertinent to observe that while this was an impressive precipitation event, it was not a 100-year *regulatory* precipitation event nor had there been significant precipitation in either December or January.

The study described here focused on the identification of the regulatory 100-year flood hazard on Rogers Lake; and therefore, also of Rich Lake, located just north of Rogers Lake, which under certain depth conditions, contributes water to Rogers Lake (Fig. 1). These two lakes are separated by a sand dune that forms a low topographic divide. Rogers Lake has a surface area of 114 km^2 and a tributary watershed of 1836 km^2, excluding the watershed tributary to Rich Lake. Rich Lake has a surface area of 7.8 km^2 and a tributary watershed of 976 km^2. This paper focuses on the application of the method to estimate the 100-year depth of water on Rogers and Rich Lakes.

2. Overview of approach

Although playas are defined by US Federal Regulations as a special flood hazard zone, there is

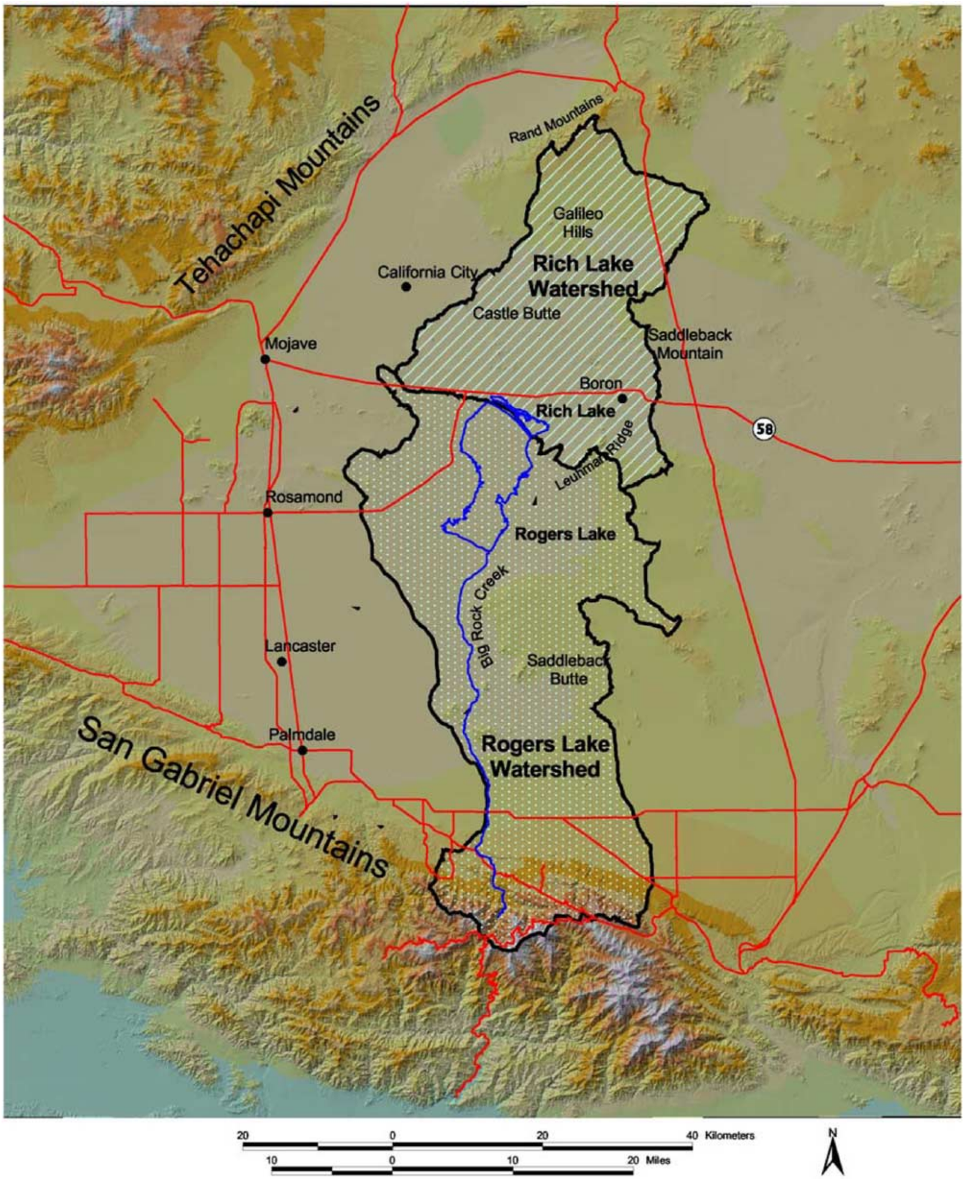

Fig. 1. Rogers and Rich Lakes and their tributary watersheds (French et al., 2003).

neither guidance nor a generally accepted approach to quantifying flood hazard on these features. Miller (1998, 2002) developed an approach to the problem of establishing the 100-year regulatory floodplain associated with a dry lakebed. The steps in the approach are briefly described below and the results of each step for EAFB are summarized in the sections that follow.

1. Typical of semi and arid-environments, the 100-year flood regulatory event is estimated using the precipitation event with a 100-year return period, which involves the tacit assumption that there is a direct correspondence between the return periods of rainfall and runoff events. At EAFB, the 100-year precipitation event has a duration of 24 h and a depth of 90.2 mm (Miller

Fig. 2. Photograph of Rich Lake taken on 13 February 2003. Note historic railroad alignment to the left.

and French, 2002). The hyetograph used was that adapted by Los Angeles County Department of Public Works (LACDPW, 1991).

2. The tributary watersheds must be delineated, often not an easy task in large basins, particularly in areas where the topographic relief is slight and the contour interval of the available maps is large.
3. In the mountainous western United States, precipitation varies with elevation (French, 1983; Osborn, 1984), with the depth of precipitation increasing with elevation. Therefore, a location specific functional relationship between the depth of precipitation and elevation for the causative precipitation event must be developed. A similar functional relationship between the annual average temperature and elevation is also needed.
4. As elevation increases, the relationship between rainfall and runoff changes because of changes in the soil types and thicknesses, land use, and vegetative types and density. The Natural Resources Conservation Service, formerly the Soil Conservation Service (SCS), curve number (CN) approach to estimating the initial abstraction of precipitation, infiltration, and runoff was used (USDA, 1984, 1986). The watersheds tributary to Rogers and Rich Lakes were divided into elevation intervals on the basis of vegetative type and cover. For each interval, the threshold precipitation was estimated based on the causative event depth of precipitation and the CN.
5. The goal of the playa lake flood hazard analysis model is to estimate the total volume of water delivered to the lakebed by the design precipitation event; and if the lakebed area and topography are known, then the water depth can be estimated. Conceptually, if the elevation intervals (Step 4) are viewed as a series of leaky buckets, one above another, which tip once the threshold precipitation is exceeded, the water cascades from the top of the watershed to the lakebed (Fig. 3). The buckets leak because of the initial abstraction and infiltration, accounted for with the CN, and channel transmission losses, taken into account using the SCS climate index approach (Mockus, 1972).

Additional information must be considered in estimating the regulatory 100-year depth of water on the playa. Although playas are essentially flat surfaces with little topographic relief, there are always undulations and depressions present (Dinehart and McPherson, 1998). Therefore, the accuracy of the estimated 100-year flood depth depends on the resolution of the topographic data available both on

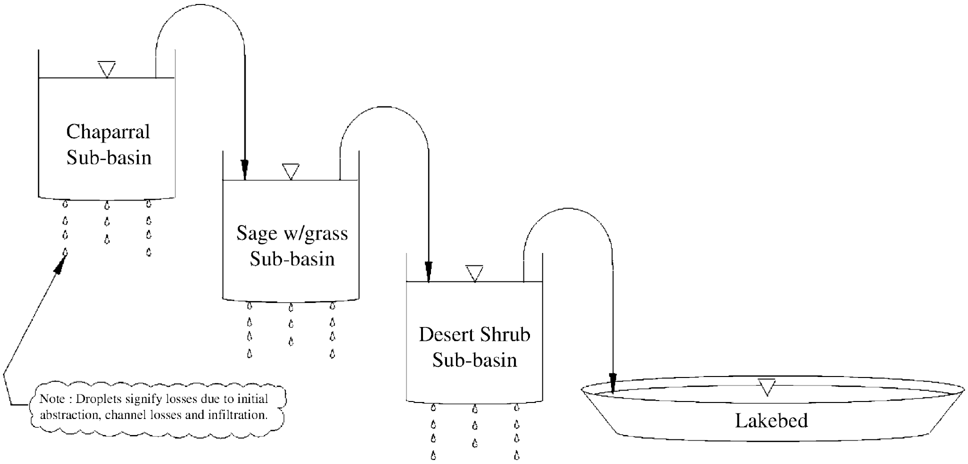

Fig. 3. Schematic overview of modeling flood hazard on a playa lake (French et al., 2003).

the lakebed and in the immediate surrounding area. Playas are typically found in areas subject to relatively high and sustained winds that can move all of the water from one end of the playa to the other. Therefore, there are two flood depth estimates: a flat pool elevation and a location specific estimate that includes the wind set up. Although wind set up is a recognized problem in inland reservoirs (Bretschneider, 1966; Linsley and Franzini, 1979; Saville et al., 1962), there have been no *quantitative* studies on playa lakes. Although this effect was considered in delineating the regulatory floodplain (French et al., 2003), it is not discussed in this paper because the effects on the regulatory depth of water were not significant. In the San Gabriel Mountains, soil transformation, as a result of intense wildfires, is also an issue; and this issue is addressed in this paper.

3. Watershed delineation

The Rogers and Rich Lakes watersheds were delineated using Arcview 3.2 with the ESRI extension ‘Watershed Delineator.’ The Watershed Delineator uses the digital elevation map (DEM) of the area of interest to define the watershed once the user has specified the terminus, or ‘pour point,’ of the watershed. There were a number of limitations using this method to define a watershed, including the vertical resolution of the DEM. On several edges of the watershed, the computer-delineated watershed was manually truncated along divides that were not digitally recognized. These divides were found and confirmed during field investigations (French et al., 2003) or in previous studies (Miller and French, 2002).

The watershed directly tributary to Rogers Lake (the South Watershed) has an area of approximately 1836 km^2 and extends from the top of the San Gabriel Mountains to Rogers Lake (Fig. 1). The highest point in the watershed is approximately 2560 m and the lowest point at Rogers Lake is at approximately 701 m above mean sea level.

The watershed directly tributary to Rich Lake (the North Watershed) has an area of approximately 976 km^2, with the highest point in the watershed at approximately 1402 m of elevation in the Rand Mountains to the north (Fig. 1). The southern boundary, which is the terminus of the North Watershed, is a sand dune separating Rogers and Rich Lakes. When the depth of water in Rich Lake exceeds 1.1 m, the terminus of the North Watershed is Rogers Lake (French et al., 2003).

4. Division of the watersheds into elevation-bounded sub-basins and curve number assignment

The South and North Watersheds were partitioned into elevation-bounded sub-basins, based on the type and density of vegetation and soil types found within elevation intervals. These intervals closely follow

Table 1

Summary of vegetation, areas, and curve number values for each watershed by elevation interval assuming both unburned and burned watershed conditions

Elevation interval (m)	610–914	914–1280	1280–1524	1524–2134	2134–2560
South Watershed					
Vegetation class	Sparse desert scrub brush with Joshua trees and agricultural land	Sage with a grass understory	Chaparral, mountain brush, herbaceous plants, and heavy grass understory	Ponderosa pines, black oak, and aspens	Ponderosa pine and Juniper
Hydrologic condition	Weighted average	Fair (n/a, %)	Good (80%)	Good (80%)	Good (70%)
Soil group	B	B	D	D	D
Sub-basin area (km^2)	1132	383	88	111	10
Curve number					
Unburned	76	51	82	71	71
Avg. burned			86	77	77
Max. burned			90	83	83
P_T (mm)					
Unburned	16.0	48.8	11.2	20.8	20.8
Avg. burned			8.4	15.2	15.2
Max. burned			5.6	10.4	10.4
North Watershed					
Vegetation class	Desert shrub	Sage with grass	Chaparral	–	–
Hydrologic condition	Poor (n/a, %)	Fair (n/a, %)	Fair (50%)	–	–
Soil group	B	B	D	–	–
Sub-basin area (km^2)	842	124	2.1	–	–
Curve number				–	–
Unburned	77	51	88		
Avg. burned			90		
Max. burned			93		
P_T (mm)				–	–
Unburned	15.2	48.8	6.9		
Avg. burned			5.6		
Max. burned			3.8		

the vegetation zones defined by the US Forest Service (Table 1).

Curve numbers for these elevation intervals were estimated from the Clark County Regional Flood Control District (CCRFCD, 1999) guidance using Antecedent Moisture Condition (AMC) II. The exception to this was the elevation interval 1280–1524 m where the predominant vegetative type is chaparral. In this interval, CNs were estimated using information from Mockus (1969) for forest range complexes in the Western United States.

The relationship between the threshold precipitation; that is, the depth of precipitation that must occur before there is runoff, is

$$P_T = 25.4(0.2)\left(\frac{1000}{\mathrm{CN}} - 10\right) = 5.08\left(\frac{1000}{\mathrm{CN}} - 10\right) \tag{1}$$

where P_T is the threshold depth of precipitation in millimeters. Values of P_T for each elevation interval are summarized in Table 1.

5. Precipitation and temperature

The method used to estimate the 100-year depth of water on Rogers and Rich Lakes requires that the annual average depth of precipitation and temperature and the precipitation depths of the causative precipitation event all be estimated throughout the watershed. Each of these variables is a strong function of elevation.

There are six precipitation gages in each the South and North Watersheds (Table 2) that can be used to estimate the annual average depth of precipitation and annual average temperature as a function of elevation (French et al., 2003). Review of these data shows that precipitation generally increases with elevation; however, the increase is not consistent. Also, the distribution of the gages, as a function of elevation is poor, particularly in the South Watershed at the higher elevations. It is pertinent to observe that this distribution of gaging stations is typical of the arid and mountainous west (French, 1983; Osborn, 1984). Further, as evidenced by the precipitation maps in LACDPW (1991) and the data in Table 2, there is a strong precipitation gradient across the valley.

Following the approaches of French (1983) and Osborn (1984), linear least-squares regression was used to derive equations for the functional relationships between elevation and both annual average depth of precipitation and annual average temperature were developed (Table 3). In the case of annual temperature, there is an independent check of the gaging station temperature data. As part of its mission, EAFB performs atmospheric soundings, and sounding data for the period 1989–2001 were recovered and a linear regression performed on these data with the results summarized in Table 3. There is a close match between the station data and the sounding data. In all subsequent calculations, the equations based on station temperatures are used.

The equations shown in Table 3 were used to estimate the annual average depth of precipitation and annual average temperature at the mid-point of each elevation interval (Table 4).

6. Causative event depths of precipitation

The regulatory precipitation event (causative event) for EAFB is a 24-h winter storm (Miller and French, 2002), which is typically a frontal storm originating from the Pacific Ocean. Therefore, it is assumed that the storm occurs over both the South and North Watersheds, and that the depths of precipitation vary with elevation. However, a conservative

Table 2
South Watershed meteorologic gage locations for annual average depth of precipitation and annual average temperature calculations (source: www.wrcc.dri.edu and http:cdec.water.ca.gov)

Location (gage name)	Longitude (degrees)	Latitude (degrees)	Elevation (m)	Annual average depth of precipitation (mm)	Annual average temperature (°F)
South Watershed					
EAFB	−117.83	34.9	701.6[a]	148	17.2
Lancaster	−118.22	34.73	713.2	199	16.1
Palmdale	−118.12	34.58	810.8	199	16.6
El Mirage field	−117.60	34.60	871.7	150	15.6
Fairmont	−118.43	34.70	932.7	396	15.6
Sandberg	−118.73	34.75	1377.7	301	13.2
North Watershed					
Cantil	−117.97	35.30	612.6	105	17.9
EAFB	−117.83	34.90	713.2[a]	148	17.2
Barstow FS	−117.00	34.90	707.1	124	18.4
Mojave	−118.17	35.05	835.1	148	16.9
Randsburg	−117.65	35.37	1088.1	155	17.1
Tehachapi	−118.45	35.13	1225.3	279	12.4

[a] This is the official elevation of the precipitation gage. The available topographic data suggest that this elevation may be in error or that it is based on a different topographic datum.

Table 3
Equations representing the functional relationship between elevation, annual average depth of precipitation (P_A), annual average temperature (T_A), and causative event depth of precipitation (P_C) for both the South and North Watersheds

Equation	North Watershed	South Watershed
Annual depth of precipitation (mm)	$P_A=-25.3+0.215E$ $R^2=73.1\%$	$P_A=40.0+0.213E$ $R^2=29.7\%$
Annual temperature (°C) gage data	$T_A=22.5-0.00695E$ $R^2=61.7\%$	$T_A=20.5-0.00535E$ $R^2=91.7\%$
Annual temperature (°C) sounding data	$T_A=20.0+0.00465E$ $R^2=88.7\%$	
Causative event depth of precipitation (mm)	$P_C=90.2+0.0328(E-701.6)$ $R^2=70.4\%$	$P_C=90.2+0.257(E-701.6)$ $R^2=96.9\%$

assumption was made that no depth-area reduction factor was applied to reduce the precipitation depth as a function of watershed area.

The method used in this analysis is based upon the NOAA Atlas (Miller et al., 1973); however, the original paper data source has been replaced with an electronic source (www.nws.noaa.gov). Using the electronic source, the longitude and latitude of the precipitation gage locations in the South and North Watersheds were entered and precipitation depth for the 100-year, 24-h event was returned (French et al., 2003).

Linear least-squares regression was used to develop a functional relationship between the 100-year, 24-h depth of precipitation and elevation. Transformed variables were used in developing these relationships. Miller and French (2002) established the depth of the 100-year, 24-h design precipitation event at the EAFB gage (elevation 702 m) as 90.2 mm; therefore, 90.2 mm was subtracted from the precipitation depths at each gage and 702 m was subtracted from the gage elevations. The least-squares regression line through the origin of the transformed variables was computed (Table 3); and these equations were used to estimate the causative event depth of precipitation at the mid-point of each elevation interval (Table 4).

7. Flow transmission losses

The initial abstraction and infiltration of precipitation in a sub-basin does not include channel transmission losses. There are a number of approaches to estimating channel transmission losses; however, most of these approaches require more detailed data than are available for the South and North Watersheds. For example, the method described by Lane (1983) requires definition of all channels and a characterization of the infiltration capacity of each channel bottom. The channel transmission loss approach chosen for this study is that developed by the SCS using a climatic index (C_I) (Mockus, 1972). This approach has been previously used in large watersheds to estimate water yield (Miller, 1998, 2002; Buchanan, 1997) and is based upon a climatic

Table 4
Annual depth of precipitation, annual temperature, and causative event depth of precipitation at the mid-point of each elevation intervals in the South and North Watersheds

Elevation interval (m)	Mid-point elevation (m)	Annual depth of precipitation at mid-points (mm)		Annual temperature at mid-points (°C)		Causative event depth of precipitation at mid-points (mm)	
		South	North	South	North	South	North
610–914	762	205.5	139.7	16.5	17.3	105.7	92.2
914–1280	1097	278.1	212.3	14.7	14.9	192.3	103.4
1280–1524	1402	344.2	278.4	13.1	12.8	271.0	113.5
1524–2134	1829	436.6	–	10.8	–	381.3	–
2134–2560	2347	548.9	–	8.1	–	515.1	–

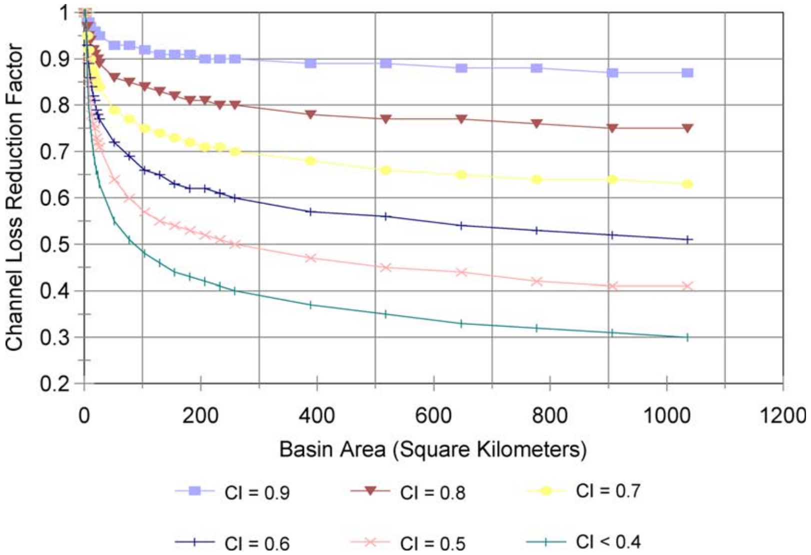

Fig. 4. Channel loss reduction factor (CLRF) as a function of the climatic index and the basin area based on Mockus (1972).

index. By definition (Mockus, 1972), the C_I is given by

$$C_I = \frac{3.937P_A}{(1.8T_A + 32)^2} \quad (2)$$

where T_A, average annual temperature (°C) and P_A, average annual depth of precipitation (mm).

With the C_I determined and the area associated with each elevation interval defined, Fig. 4 or the table in Mockus (1972) can be used to estimate the channel loss reduction factors (CLRFs). The resulting CLRF values are summarized in Table 5.

8. Estimated 100-year depths on Rogers and Rich Lakes

With reference to Table 5, the procedure to estimate the 100-year depths of water on Rogers and Rich Lakes was as follows:

1. For each elevation interval, the net excess precipitation (Column 5) is calculated by subtracting the threshold precipitation depth (Column 3) from the 100-year, 24-h precipitation depth (Column 4).
2. For each elevation interval, the net runoff (Column 6) is calculated by multiplying the area in the interval (Column 2) by the net excess precipitation (Column 5).
3. The cumulative runoff (Column 8) is calculated by summing the cumulative runoff from the previous higher elevation interval with the net runoff (Column 6) from the current elevation interval and multiplying by the CLRF (Column 7).
4. The 100-year depths of water on the lakebeds are calculated by dividing the total cumulative volume (bottom figure in Column 8 for each South and North Watersheds) by the lakebed area (bottom figure in Column 2 for both the South and North Watersheds).

Following the steps outlined above and with reference to Table 5, it is concluded that the 100-year depth of water in Rich Lake is 2.9 m [(22.5 m km^2)/(7.8 km^2)]; and therefore, the sand dune barrier between Rich and Rogers Lake is overtopped and the total volume of water in Rich Lake (22.5 m km^2) flows to Rogers Lake. Therefore, the 100-year estimated depth of water in Rogers Lake is 0.65 m [(22.5 + 51.4 m km^2)/(114 km^2)].

9. Hydrophobic soil conditions

One of the special considerations in identifying and mitigating flood hazard in Southern California,

Table 5
Summary of calculations to estimate the 100-year depths of water in Rogers and Rich Lakes assuming both unburned and burned watershed condition

Elevation interval (m) (1)	Area (km^2) (2)	Thresh. depth of precip. (mm) (3)	100-Year depth of precip. (mm) (4)	Net excess precip. (m) (5)	Net runoff (m km^2) (6)	CLRF (7)	Cumm. runoff (m km^2) (8)
South Watershed							
2134–2560	10		515.1			1.00	
Unburned		20.8		0.494	4.94		4.94
Burned		15.2		0.500	5.00		5.00
1524–2134	111		381.3			0.74	
Unburned		20.8		0.360	40.0		33.3
Burned		15.2		0.366	40.6		33.7
1280–1524	88		271.0			0.57	
Unburned		11.2		0.260	22.9		32.0
Burned		8.4		0.263	23.1		32.4
914–1280	383		192.3			0.40	
Unburned		48.8		0.144	55.2		34.9
Burned		48.8		0.144	55.2		35.0
610–914	1132		105.7			0.30	
Unburned		16.0		0.090	102		41.1
Burned		16.0		0.090	102		41.1
Lakebed	114		90.2			1.00	
Unburned		0		0.090	10.3		51.4
Burned		0		0.090	10.3		51.4
North Watershed							
1280–1524	2.1		113.5			1.00	
Unburned		6.9		0.107	0.224		0.224
Burned		5.6		0.108	0.227		0.227
914–1280	124		103.4			0.46	
Unburned		48.4		0.055	6.82		3.24
Burned		48.4		0.055	6.82		3.24
610–914	842		92.2			0.32	
Unburned		15.2		0.077	64.8		21.8
Burned		15.2		0.077	64.8		21.8
Lakebed	7.8		90.2			1.00	
Unburned		0		0.090	0.702		22.5
Burned		0		0.090	0.702		22.5

particularly in the San Gabriel Mountains, is the potential for the watershed to burn previous to the winter precipitation period. During a wildfire, temperatures at ground level may reach 600–700 °C. At these temperatures, the oils, resins, and waxy fats stored in plants and associated litter vaporize and collect slightly below the surface creating a hydrophobic layer. This layer is relatively impermeable; and therefore, can dramatically reduce infiltration.

Given the potentially significant role hydrophobic layers can play in the rainfall–runoff process, the LACDPW (1991) developed an empirical relationship between infiltration in burned areas and infiltration in unburned areas by running infiltrometer tests in adjacent areas. The relationship derived is

$$K = \frac{0.677}{\left(\frac{I}{25.4}\right)^{0.102}} \tag{3}$$

where K, burn factor $= (f_b/f_u)$; I, rainfall intensity (mm/h); f_b, burned area infiltration rate; and f_u, unburned area infiltration rate.

The empirical burn factor (K) can be used to estimate a SCS CN for burned areas. By definition, the CN is

$$\mathrm{CN} = \frac{1000}{S + 10} \tag{4}$$

where S is a parameter that includes both the potential maximum retention and the initial abstraction, which includes interception, infiltration, and surface storage. Given the empirical origins of both CN and K, it is asserted

$$S_\mathrm{b} = KS_\mathrm{u} \tag{5}$$

where the subscripts b and u indicated burned and unburned, respectively. Rearrangement of Eq. (4) yields

$$S_\mathrm{u} = \frac{1000}{\mathrm{CN}_\mathrm{u}} - 10 \tag{6}$$

and substituting Eq. (5) and rearranging yields

$$S_\mathrm{b} = KS_\mathrm{u} = \frac{1000}{\mathrm{CN}_\mathrm{b}} - 10$$

or

$$\mathrm{CN}_\mathrm{b} = \frac{1000}{KS_\mathrm{u} + 10} \tag{7}$$

With regard to Eq. (7), the following observations are pertinent. First, the relationship between the parameter S and the initial abstraction is poorly understood, particularly in semi and arid-environments (Hjelmfelt, 1991). Therefore, it is assumed that the effects of burning are expressed adequately by Eq. (5). Second, given the functional relationship expressed in Eq. (3), CN_b is a function of the temporal distribution of precipitation. In Fig. 5, the design event hyetograph for EAFB (Miller and French, 2002) is plotted as a function of time along with CN_b, assuming that $\mathrm{CN}_\mathrm{u}=70$. As would be expected given the functional form of the value of CN for a burned area, CN_b has a maximum value at the point where the precipitation intensity is a maximum. Further, the CN for a burned area is increased even when the intensity of precipitation is slight. In Table 1, values of the CNs and threshold precipitation for unburned and burned conditions are summarized.

Given the foregoing development and observations, and the approach used to estimate the 100-year depth of water on playa lakes, a CN must be estimated that is reasonable for the duration of the event. In this situation, it was decided to use a time-weighted approach. The time weighted curve number is then estimated by

$$\bar{\mathrm{CN}}_\mathrm{b} = \frac{\sum \Delta t(\mathrm{CN}_\mathrm{b})}{T_\mathrm{D}} \tag{8}$$

where $\bar{\mathrm{CN}}_\mathrm{b}$, time weighted, burned area curve number; Δt, time increment; CN_b, instantaneous burned area curve number; and T_D, precipitation event duration. The results are summarized in Table 1.

In Table 1, the unburned, time-averaged burned, and maximum burned CNs are summarized with the corresponding threshold precipitation (P_T) depths. Review of Table 1 shows that the vegetation in the 610–914 and 914–1280 m elevation intervals is sparse; and therefore, it is assumed that a fire in these intervals would not burn at sufficient temperatures to result in a hydrophobic layer. Also, during the 100-year precipitation event, it is likely that the hydrophobic layer will be eroded and the CN returned to its unburned value; however, the point in time during an event when the layer would be removed is not known. Therefore, in subsequent calculations, it is conservatively assumed that the hydrophobic layer is not removed. There are no elevation intervals above 1524 m in the North Watershed.

With reference to Table 5, it is concluded that the 100-year depth of water, under burned conditions, in Rich Lake is 2.9 m [(22.5 m km^2)/(7.8 km^2)]; and therefore, the sand dune barrier between Rich and Rogers Lake is overtopped and the total volume of water in Rich Lake (22.5 m km^2) flows to Rogers Lake. Therefore, the 100-year estimated depth of water in Rogers Lake is 0.65 m [(22.5 + 51.4 m km^2)]/(114 km^2)]. That is, from the viewpoint of the 100-year depth of water in either Rich or Rogers Lakes, there is no difference between burned and unburned conditions.

10. Water source

In Table 6, the source of water to Rogers and Rich Lake is estimated. With regard to the data in this table, the following observations are pertinent. First, very little water from the high and distant portions of the watersheds reaches either lake. For example, for the South Watershed only 0.34% of the water generated

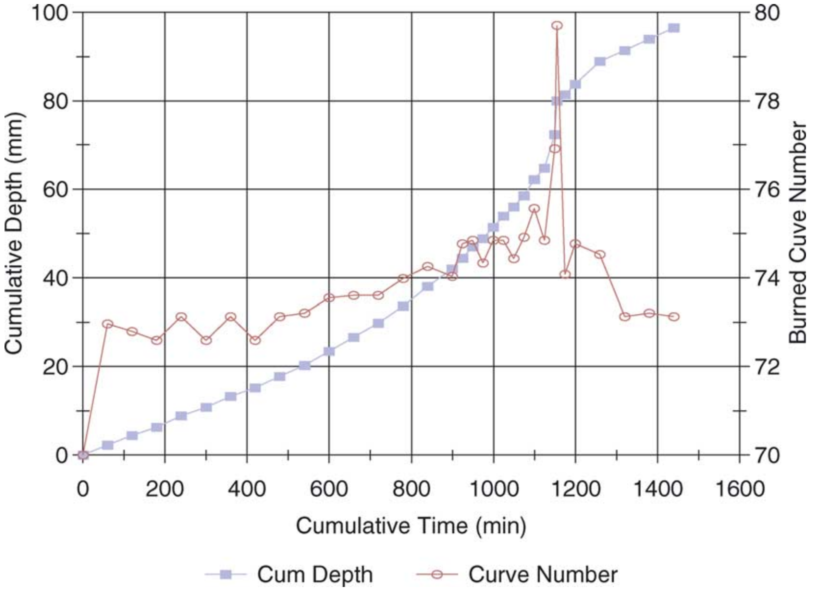

Fig. 5. Curve number as a function of time and precipitation intensity for burned areas (French et al., 2003). Also shown is the design hyetograph for the study area (LACDPW, 1991).

in the 2134–2560 m elevation interval reaches Rogers Lake. Although this is not a surprising result, it does demonstrate that the methodology produces results that fit with intuitive expectations. Second, approximately 15% of the 100-year depth of water on Rogers Lake derives from precipitation that falls directly on the lakebed. Third, approximately 70% of the 100-year volume of water on Rogers Lake derives from the lowest and closest elevation interval; that is, the 610–914 m interval (this does not include the volume resulting from direct precipitation on the lakebed). This observation demonstrates that land use in this interval has a significant effect on the 100-year depth of water on Rogers Lake. For example, without proper planning and engineering, the conversion of the land in this interval from primarily agricultural or undisturbed desert to suburban or industrial uses could dramatically increase the 100-year depth of water on the lakebed. Fourth, 10% of the 100-year depth of water derives from elevation interval 914–1280 m. Again, changes in land use in this area could have a significant effect on the 100-year depth of water on Rogers Lake. Fifth, almost 95% of the 100-year depth of water results from areas in close proximity to the lakebed or on the lakebed itself. Although this is not a surprising result and again fits the intuitive

Table 6
Volume of water generated in each South and North Watershed elevation interval delivered to Rogers Lake

Elevation interval (m)	Net volumetric run-off South Watershed (m km^2)	Volume transferred to Rogers from the South Watershed (m km^2)	Net volumetric run-off North Watershed (m km^2)	Volume transferred to Rogers from the North Watershed (m km^2)	Percent of total 100-year Rogers Lake volume (%)
2134–2560	4.94	0.250	0	0	0.338
1524–2134	40.0	2.02	0	0	2.74
1280–1524	22.9	1.57	0.224	0.033	2.16
914–1280	55.2	6.62	6.82	1.00	10.3
610–914	102	30.6	64.8	20.7	69.5
Lakebed	10.3	10.3	0.702	0.702	14.9

expectation, it does clearly identify the concern EAFB must have with land use in the surrounding area. Fifth, as noted in the previous section, unburned versus burned watersheds have no effect on the 100-year depth of water, and the results in Table 6 demonstrate this is due to the fact that very little water from the elevation intervals susceptible to burning reaches Rogers Lake.

11. Additional studies

Additional studies are being undertaken to use remote sensing analysis techniques to verify and calibrate the model by analyzing Landsat multispectral images in the Infrared (IR) bands to determine the area change of inundation on Rosamond Lake over a defined temporal resolution (Dettling et al., 2004). Although Advanced Very High Resolution Radiometer (AVHRR) images have a much higher temporal resolution than Landsat, the spatial resolution of the Landsat pixels of approximately 900 m^2 is much higher resolution than that of AVHRR; therefore, Landsat images are being used. In previous studies to determine area changes in inundation of very large playas, AVHRR images have been used (Bryant and Rainey, 2002); however, given the relatively much smaller size of the playas studied at EAFB, the spatial resolution of AVHRR creates problems. AVHRR has a pixel size of $<$ 1 km^2; however, Rogers Playa is only approximately 114 km^2 and Rich Playa only 7.8 km^2. Thus, if AVHRR was used, a significant number of AVHRR pixels would be along the lakebed edge. As pointed out in Bryant and Rainey (2002), using AVHRR for determining areas of inundation on small lakes resulted in relatively large errors of accuracy, and that the difficulty in handling the lakebed edge pixels was a large part of this error.

12. Conclusions

The analysis of the runoff from the Rogers and Rich Lake watersheds as a result of the 100-year, 24-h precipitation event leads to the following conclusions:

1. The runoff from the Rogers Lake (South) watershed results in a level pool depth on lakebed of 0.46 m. If the upper portions of the South Watershed are burned, the resulting depth on the lakebed remains the same. Note, this should not be taken to imply that burning the upper portion of the watershed has no effect on flooding; rather, it is a statement that Rogers Lake is sufficiently removed from the sub-basins susceptible to burning that there is no quantifiable effect.
2. The runoff from the Rich Lake (North) watershed results in a level pool depth on lakebed of 2.9 m. This depth of water in Rich Lake will result in the topographic divide between Rich and Rogers Lakes being breached; and the result will be all of the water from Rich Lake will flow into Rogers Lake. As is the case with the South Watershed, the effect of burning the upper portions of the North watershed has no effect on the 100-year depth of water in Rich Lake.
3. Given the first and second conclusions, the 100-year level pool depth of water in Rogers Lake is approximately 0.65 m. It is pertinent to note that this estimated depth is in good agreement with the historical data summarized in GRW (1994).
4. The analysis of runoff from both the South and North Watersheds demonstrates that changes in land use in the vicinity of EAFB could have a significant effect on the 100-year depth of water on the Rogers Lake lakebed. For example, the conversion of mainly agricultural or undisturbed desert to suburban or industrial uses could increase the volume of runoff to Rogers and Rich Lakes.

It is pertinent to note that the analysis incorporates a number of assumptions that are conservative; that is, these assumptions likely result in an over-estimation of the 100-year depth of water on Rogers Lake. Among the conservative assumptions made are the following:

1. The 100-year, 24-h precipitation event covers the entire watershed tributary to Rogers and Rich Lakes; that is, the precipitation event covers an area of 2930 km^2. While the design precipitation event is a winter period frontal system (Miller and French, 2002), it is unlikely that the total watershed would be affected by this event.
2. The analysis did not use precipitation depth-area reduction factors; rather, the analysis used point

precipitation depths. Point precipitation depths are always greater than the average depth of precipitation over an area, particularly when the area is very large.

3. The analysis did not take into account the storage of runoff either behind transportation alignments or in micro-playas such as those found in the Buckhorn region of the South Watershed or those upstream of Rich Lake (North Watershed). The effect of storage would be to reduce the estimated 100-year depth of water on Rogers Lake. In addition, storage would also reduce the travel time of the water allowing for increased infiltration.

This analysis has an additional limitation that also yields a conservative estimate. Cross-sections of Rogers Lake (Dinehart and McPherson, 1998) demonstrate that the lakebed is not flat. Therefore, the assumption of a level pool depth is incorrect; that is, an unknown portion of the 100-year volume of water will be stored in depressions on the lakebed. There is no sufficient topographic detail to accurately or reliably estimate the volume stored in lakebed depressions.

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