GIS-BASED ANALYSIS OF MOUNTAIN BLOCK RECHARGE FOR OWENS LAKE PLAYA, CALIFORNIA

Anna Draa[1] and Richard L. Orndorff[2]

Beginning in the mid 1800s, Owens Valley (Figure 1) served as an agricultural and ranching community utilizing abundant surface runoff from the eastern slopes of the Sierra Nevada; Owens Lake, at the terminus of Owens River, covered 270 sq km. In the early 1900s the city of Los Angeles acquired land and water rights in Owens Valley and constructed a 375 km (233 mile) long aqueduct. Diversion began in 1913 and led to the complete desiccation of Owens Lake by 1924. Initially the focus of the water project was to supply Los Angeles with the water needed to sustain its existing population; ultimately, a much greater quantity of water was allotted to secure the city's future growth and prosperity (Hundley 1992). As southern California's population increased, the demand for more water prompted exploitation of additional sources including diversion from Mono Basin to the northwest and the pumping of groundwater from Owens Valley in the 1970s, precluding down-valley flow (southward) in the subsurface. Since initial diversion, the Los Angeles Department of Water and Power has apparently based water management decisions in Owens Valley on the assumption of hydrologic equilibrium with modern climate. This study tests the assumption of steady state by comparing measured playa discharge with estimated modern mountain block recharge (MBR).

Although the U.S. Geological Survey (USGS) and the Los Angeles Department of Water and Power (LADWP) continue to develop water budgets for Owens Valley, they have not published independent MBR estimates. Previous hydrologic studies disagree on the annual volume of MBR in the southern Owens Valley. Lopes (1988) developed a conceptual model to quantify the components of such a water budget, and Wirganowicz (1997) and Schumer (1997) developed numerical models based on Lopes's (1988) water budget values. Lopes (1988) stated that an MBR volume of approximately $2.5*10^6$ m^3/yr [2000 acre-feet/year (afy)] recharges playa aquifers. Wirganowicz (1997) used MODFLOW (McDonald and Harbaugh 1988) to simulate the groundwater system, and concluded that an MBR volume of $2.5*10^7$ m^3/yr (20,000 afy) was needed to sustain observed playa discharge (water below the playa moves upward through a series of confined aquifers before evaporating at the surface). Schumer (1997) produced a conceptual model for the groundwater system around Lone Pine, California, which extended the model domain of Wirganowicz (1997). Wirganowicz (1997) attributed differences in the calculated MBR and observed discharge to (1) a groundwater system in Owens Valley that may not be in equilibrium with modern climate, (2) the existence of additional recharge sources that have not been accounted for, and/or (3) methods of calculating MBR that result in underestimation of actual volumes. The focus of this research is to better understand the hydrologic system through the application of a spatially distributed, high-resolution approach to calculating MBR.

GEOGRAPHY AND CLIMATE

The study area lies east of the Sierra Nevada, west of the White and Inyo Mountains, and northwest of the Coso Mountains. North-south striking normal faults separate down-dropped valley fill from towering ranges to the east and west. This valley is both the westernmost valley of the Basin and Range physiographic province and the westernmost valley of the Great Basin hydrologic province. Typical of Basin and Range structure, the valley is oriented north-south and is 208 km long and 50 km wide. The southern region that directly recharges the playa aquifers under modern conditions is approximately 45 km long and 42 km wide. Owens Valley is currently a hydrologically closed drainage basin (Figure 1); water last flowed south

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[1] Department of Geoscience, University of Nevada, Las Vegas

[2] Department of Geology, Eastern Washington University, Cheney

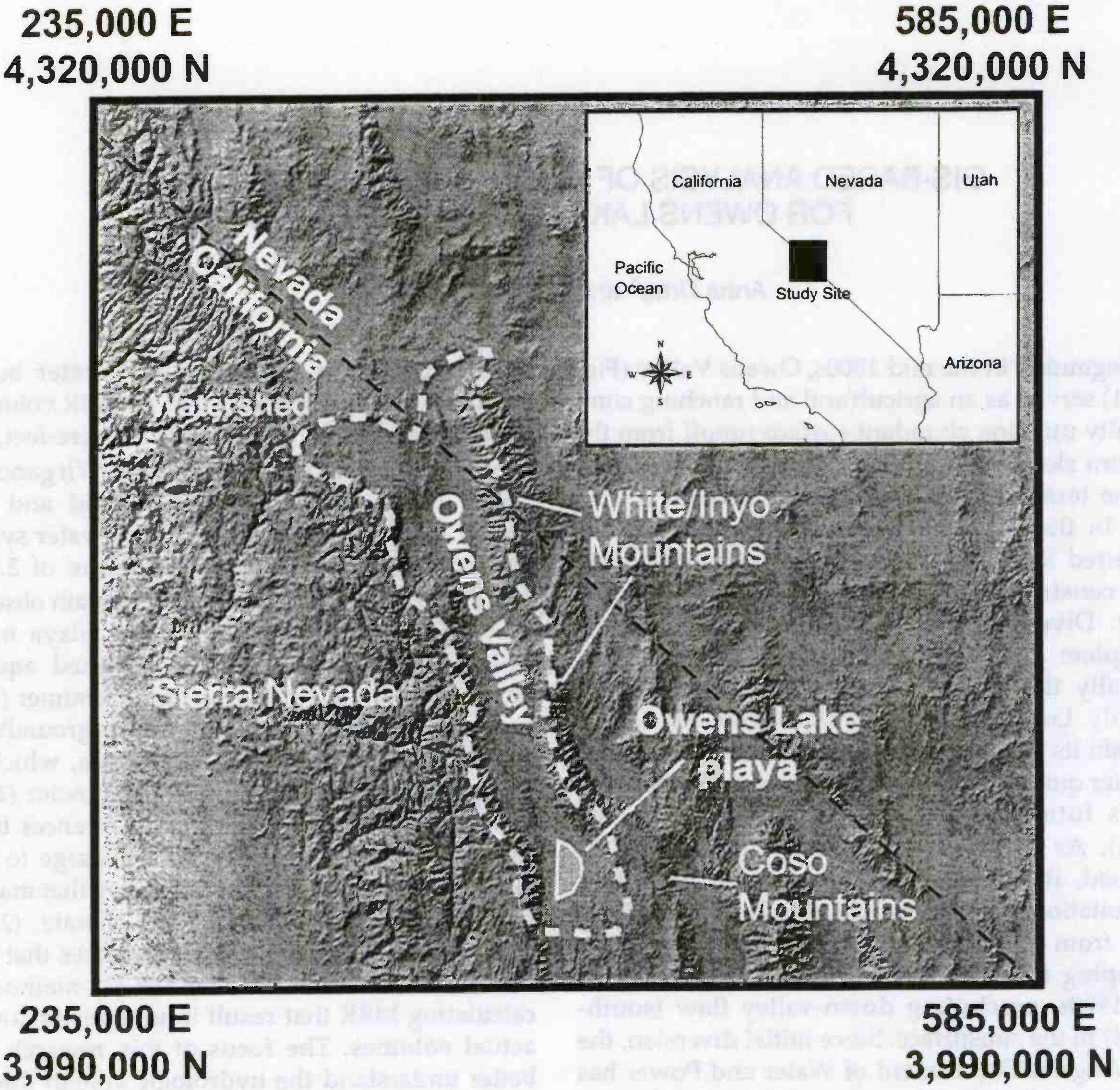

Figure 1. Owens Valley is a hydrologically closed basin located east of the Sierra Nevada near the California-Nevada border. The DEM shows the watershed and modern playa. Prior to diversion of Owens River water, Owens Lake covered 270 sq km of the lower valley.

from Owens Valley into China Basin about 14,000 years ago.

The Sierra Nevada range is a calc-alkaline batholith that formed during the Cretaceous, consisting mostly of granodiorite, granite, and quartz monzonite (duBray and Dellinger 1981). The batholith intruded Paleozoic and Mesozoic metasedimentary and metavolcanic rocks, which now dominate the valley fill in the form of eroded sediments (Lopes 1988). The Sierra Nevada range is home to Mount Whitney, which is the highest peak in the contiguous United States at an elevation of 4418 m (14,495 ft) above sea level. The eastern face of the range forms one of the steepest escarpments in North America; it is presently rising at a rate of 58 cm (23 in) per century (Smith 1979). The White and Inyo Mountains are composed of the same granitic batholith with Late Tertiary olivine basalts in the north and Paleozoic to Tertiary metavolcanics and sediments in the south. The Coso Mountains form the southernmost boundary of the basin. The Coso Mountains have a granitic core that is covered by volcanics and lakebed deposits of the Coso Formation (Duffield and Bacon 1981).

The climate in Owens Valley is dominated by the presence of the subtropical high, cold offshore ocean currents, and landform barriers, all of which create an arid to semi-arid climate. Owens Valley is characterized by low precipitation, warm temperatures, low humidity, frequent winds, and high rates of evapotranspiration (Kohen et al. 1994). The valley floor receives less than 15 cm (6 in) of precipitation per year. Underlying aquifers and surface streams, however, receive much higher quantities of water due to runoff and recharge from winter storms that originate in the Pacific Ocean and sweep over the Sierra Nevada (Figure 2; Houghton 1969). On the eastern flank of the Sierra Nevada precipitation increases at a rate of 28 cm/1000 m (11 inches/3281 ft) whereas on the drier western flank this rate is halved due to the rainshadow effect (Smith and Bischoff 1997). Smith and Bischoff (1997) estimated that 80 percent of precipitation arrives in the form of snow and ice in the winter months, dominating surface runoff from the Sierra Nevada. Convective storms originating in the Gulf of Mexico along with local recycling of snowmelt during the rest of the year provide the remaining 20 percent of precipitation. Average annual precipitation for the Sierra Nevada ranges from 100 to 200 cm/yr (40–80 in/yr), whereas the White and Inyo Mountains receive only 18–36 cm/yr (7–14 in/yr). The central Owens Valley receives just 13–15 cm/yr (5–6 in/yr) of direct precipitation (Figure 2; Kohen et al. 1994).

GIS METHODOLOGY

The first step in estimating the spatial distribution of playa MBR involved building a GIS database for the lower Owens Valley. We downloaded and tiled four 1:250,000 USGS digital elevation models (DEM), using neighborhood statistics to correct any null values along seams. We then reprojected this grid into a universal transverse mercator (UTM) coordinate system to ensure that all grid cells had a uniform metric spacing of 90 m. The DEM was clipped to isolate Owens Valley (see Figure 1).

We wrote a short algorithm to delineate the watershed boundary for the southern region surrounding the playa. We computed flow direction and flow accumulation for each grid cell, and then created a polygon by delineating the playa boundary. We converted the polygon to a raster grid

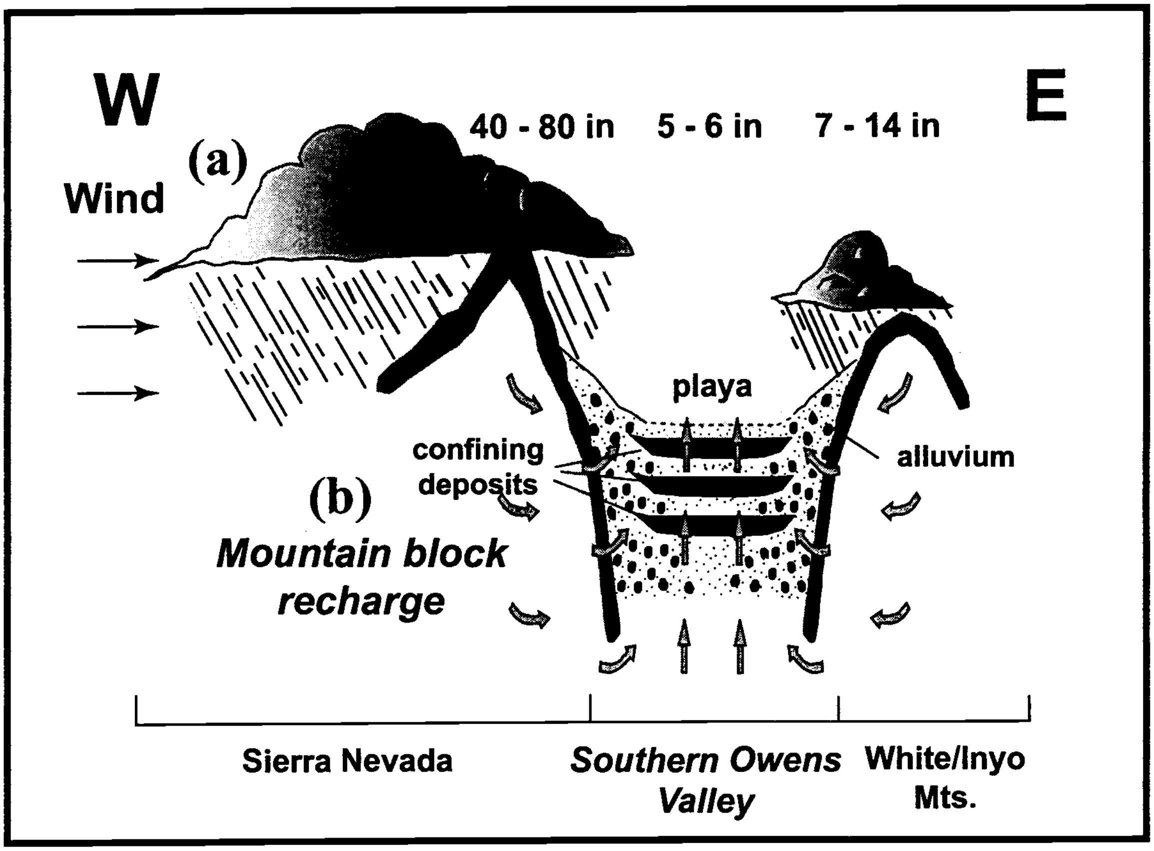

Figure 2. Cross section of Owens Valley depicting (a) the rainshadow effect on annual precipitation and (b) hypothesized pathways of mountain block recharge and playa discharge.

and used it as the source (the area into which flow accumulates) for watershed delineation. The playa watershed has an area of 1400 sq km. We delineated the upper limit of the contributing MBR zone based on the assumption that the water table mimics surface topography and that the MBR recharge boundary mirrors the surface watershed boundary. Due to high evapotranspiration rates on the valley floor and the vertical hydraulic gradient of the underlying groundwater, the valley portion of the watershed is omitted from the MBR zone. We derived a slope map (Figure 3a) from the DEM to determine the location of the contact between bedrock and valley fill. A sharp slope break was identified at the 1200 m contour line, and this break was hypothesized to represent the bedrock/fill transition. GPS field measurements verified the presence of the transition at an elevation of 1200 m in the lower valley. The area between the upper playa watershed boundary and the lower bedrock/fill boundary makes up the MBR zone, with an area of 938 sq km (Figure 3b).

We obtained annual precipitation data (Table 1) for 23 climate stations in Owens Valley from Wirganowicz (1997) and Lopes (1988). We plotted average annual precipitation against elevation for each station. A linear regression of precipitation on elevation resulted in an R^2 value of 0.87 (overall regression), which demonstrates a strong correlation (Figure 4). We know, however, that the west side of the valley receives higher precipitation than the east side due to the rainshadow effect; hence this regression under-predicts Sierra Nevada precipitation while over-predicting White and Inyo Mountain precipitation. To correct for these errors we divided the stations into geographic zones and conducted two additional regression analyses, one for the southeastern valley and another for the southwestern valley. The Sierra Nevada regression resulted in an R^2 of 0.94 and the White/Inyo regression resulted in an R^2 of 0.96, a significant improvement over the initial correlation (see Figure 4).

Table 1. Average annual precipitation for 23 climate stations in Owens Valley, California.

Station Name	Precipitation (cm)
B. P. Power House 3	22.4
B. P. Creek	40.7
B. P. Yard	16.2
Bishop Airport	13.7
Bishop Yard	15.7
Cottonwood Gates	16.1
Cottonwood Powerhouse	14.2
Golden Trout Camp	43.5
N. Haiwee Powerhouse	14.5
S. Haiwee Powerhouse	14.2
S. Haiwee Reservoir	16.7
Independence Yard	12.7
LAA at Alabama Hills	9.7
LAA Intake	14.1
Little Lake	17.8
L. Pine Yard	10.6
Onion Valley	50.9
Rock Creek Store	42.9
Sabrina Lake	42.4
South Lake	45.6
Tinemaha Reservoir	16.2
White Mountain 1	34.1
White Mountain 2	42.2

We then divided the playa MBR zone into two areas: the Sierra Nevada mountain block with an area of 374 sq km and the White/Inyo and Coso mountain block with an area of 640 sq km. We applied the Sierra Nevada precipitation equation to the western area and the White/Inyo Mountain equation to the eastern area to produce precipitation estimates for each grid cell within the MBR zone. The linear regression for the west side produced a maximum annual precipitation estimate of 60.5 cm, whereas the regression for the east side produced a maximum annual precipitation estimate of only 32.8 cm. Average annual precipitation per grid cell is 33 cm/yr in the west and 20 cm/yr in the east. The Sierra Nevada, with a smaller surface area but larger average precipitation per grid cell, has an estimated annual precipitation volume of $1.23*10^7$ m^3/yr (103,000 afy). The White/Inyo Mountains, with a larger surface area but a smaller average precipitation per grid cell, has an estimated annual precipitation volume (Table 2) of $1.28*10^7$ m^3/yr (104,000 afy). The southeastern side of the valley has nearly twice the area of the west, but lies at lower elevations with higher evapotranspiration rates, which reduces grid cell recharge. Figure 5 shows the modeled spatial distribution of annual precipitation.

ESTIMATING MOUNTAIN BLOCK RECHARGE

Maxey and Eakin (1949) developed a method of estimating MBR for southwestern valleys based on annual precipitation zones. Working in Nevada, they used precipitation/elevation maps produced by Hardman (1936). Maxey and Eakin (1949) assumed a direct relationship between precipitation and recharge, with areas experiencing the greatest

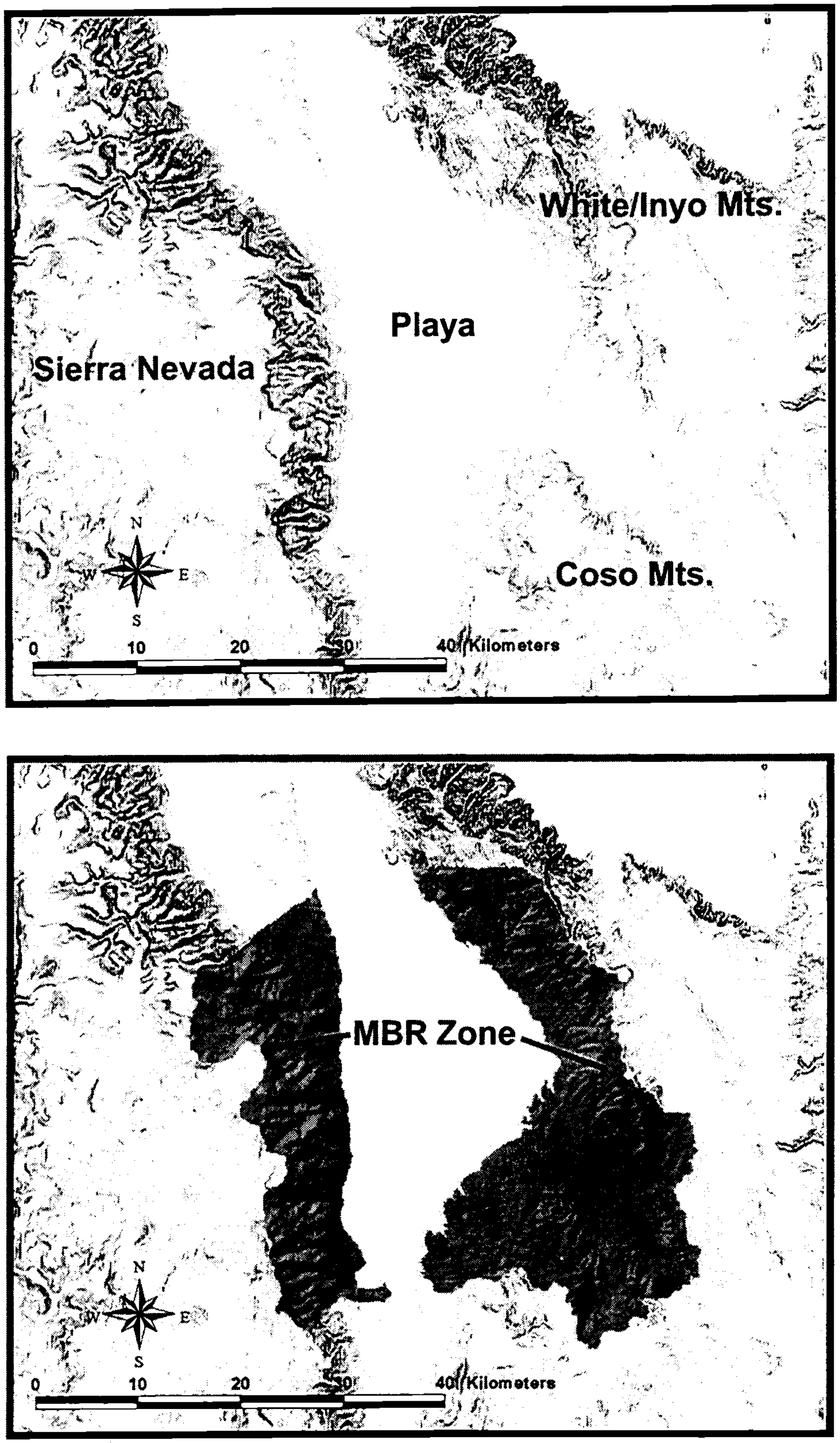

Figure 3. Slope map derived from (top) the DEM and (bottom) the playa MBR zone delineated from the playa watershed and slope map. Slopes vary from 0 degrees (white) to 67 degrees (black). The bedrock/fill boundary lies at an elevation of about 1200 m.

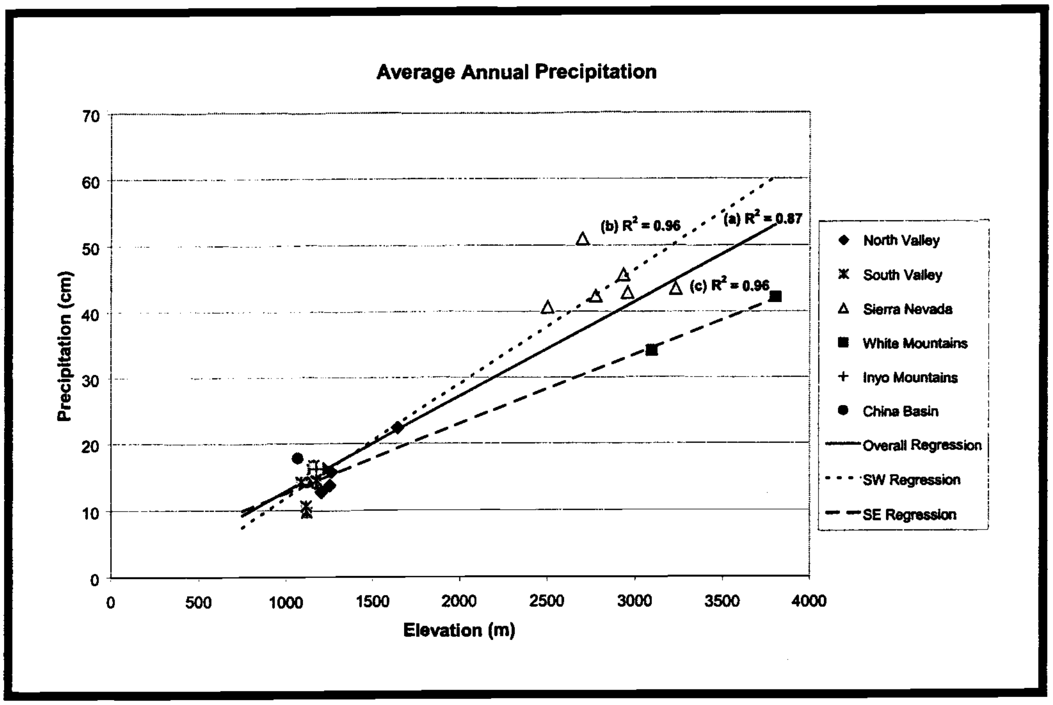

Figure 4. Linear regression of (a) average annual precipitation on elevation for the entire valley [R^2 = 0.87], (b) average annual precipitation on elevation for the west side of Owens Valley [R^2 = 0.94], and (c) average annual precipitation on elevation for the east side of Owens Valley [R^2 = 0.96].

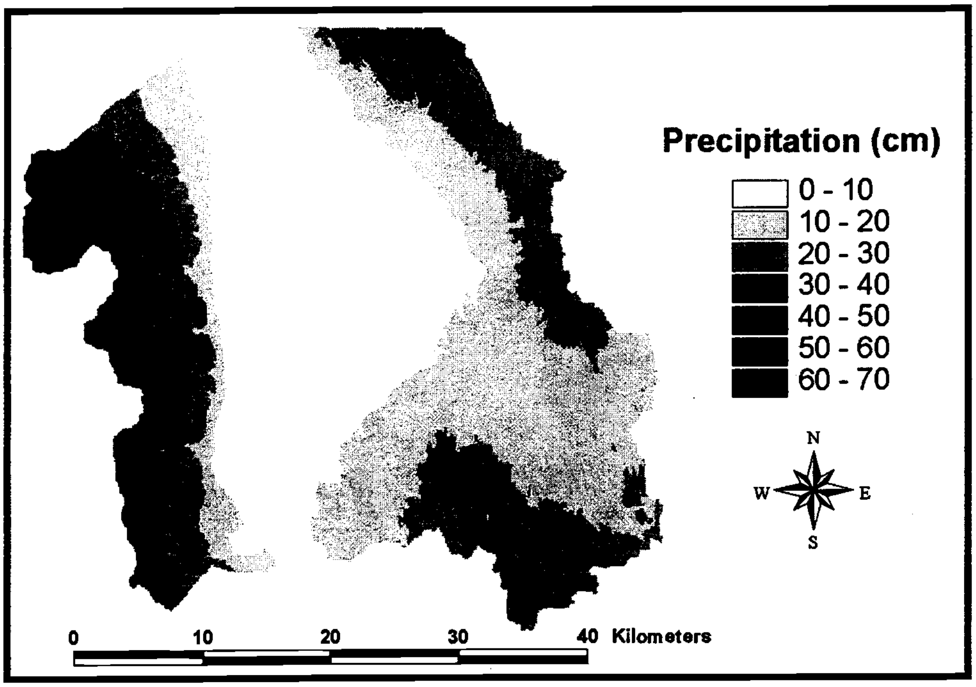

Figure 5. Average annual precipitation surface for the playa MBR zone based on east and west Owens Valley regression relationships.

amounts of precipitation yielding the greatest recharge. Based on fieldwork throughout the Great Basin, Maxey and Eakin (1949) denoted specific precipitation zones that contribute defined percentages of annual precipitation as recharge. If precipitation is greater than 50.8 cm (the uppermost precipitation zone), 25 percent contributes to recharge. Precipitation between 38.1 and 50.8 cm contributes 15 percent to recharge, precipitation between 30.48 and 38.1 cm contributes 7 percent to recharge, precipitation between 20.32 and 30.48 cm contributes 3 percent to recharge, and precipitation less than 20.32 cm contributes nothing to recharge. We used these coefficients in conjunction with our previously discussed annual precipitation surface to compute annual recharge to the Owens Lake playa (Figure 6a). We estimated an MBR volume of $1.28*10^7$ m^3/yr (10,400 afy) for the Sierra Nevada and a volume of $1.87*10^6$ m^3/yr (1500 afy) for the White, Inyo, and Coso Mountains, producing a total annual MBR volume of $1.47*10^7$ m^3/yr (11,900 afy). We define MBR efficiency as the total volume of MBR divided by the total volume of precipitation for a geographic zone. Although the Sierra Nevada side of the valley receives a lower annual precipitation volume than the White/Inyo side, it is more efficient at producing recharge due to high elevations and low evapotranspiration rates (Table 3). Sierra Nevada MBR efficiency is 10 percent, whereas White/Inyo MBR efficiency is only 1 percent.

Donovan and Katzer (2000) developed a modification of the Maxey and Eakin (1949) method for estimating recharge in the Las Vegas Basin in Nevada. Their method was developed under the same assumption—that recharge increases with increasing precipitation. Donovan and Katzer (2000) applied Maxey and Eakin's (1949) upper boundary condition but developed an exponential correlation for recharge percentages and annual precipitation values below 50.8 cm/yr (with no lower cutoff value):

$$r_e = 0.05(P)^{2.75} \tag{1}$$

where r_e is recharge efficiency (%) and P is annual precipitation in feet per year. This method produced MBR values that agreed closely with other studies in the Las Vegas basin. We applied this approach to the lower Owens Valley, which experiences a climate similar to that of the Las Vegas Basin. Table 3 summarizes the results of the application of the Donovan and Katzer (2000) method, and Figure 6b shows the spatial distribution of playa MBR. Annual MBR volume is $1.54*10^7 m^3/yr$ (12,500 afy), which is about 5 percent higher than our previous estimate. This may be due to the extended coefficient domain, as well as increased precision in estimating grid cell coefficients. Table 4 compares MBR efficiencies for both methods.

Table 2. Annual precipitation volumes for west and east sides of the playa MBR zone.

Area	Avg Precip Grid Cell (m)	Total Area (m^2)	Total Precip (m^3)
Sierra (west)	0.33	$3.70*10^8$	$1.23*10^8$
White/Inyo (east)	0.20	$6.40*10^8$	$1.28*10^8$

Table 3. MBR volumes for west and east sides of Owens Valley along with MBR efficiencies based on the Maxey and Eakin (1949) method and the Donovan and Katzer (2000) method.

Method	Avg MBR/ Grid Cell (m)	Total MBR (m^3)	MBR Efficiency
Maxey & Eakin			
Sierra (west)	0.034	$1.28*10^7$	0.104
White/Inyo (east)	0.0029	$1.87*10^6$	0.013
Donovan & Katzer			
Sierra (west)	0.035	$1.30*10^7$	0.106
White/Inyo (east)	0.0037	$2.35*10^6$	0.018

Table 4. A comparison of total MBR efficiencies for the Sierra Nevada and for the White and Inyo Mountains based on the Maxey and Eakin (1949) and Donovan and Katzer (2000) methods.

Method	Total Avg/ Grid Cell MBR (m)	Total MBR (m^3)	MBR Efficiency
Maxey & Eakin	0.018	$1.47*10^7$	0.058
Donovan & Katzer	0.019	$1.54*10^7$	0.061

CONCLUSIONS

Previous studies in the southern Owens Valley concluded that an MBR volume of $2.5*10^7$ m^3/yr (20,000 afy) is needed to sustain hydrologic equilibrium with the modern climate; this value is based on measured playa discharge (Wirganowicz 1997). We constructed a high-resolution GIS data

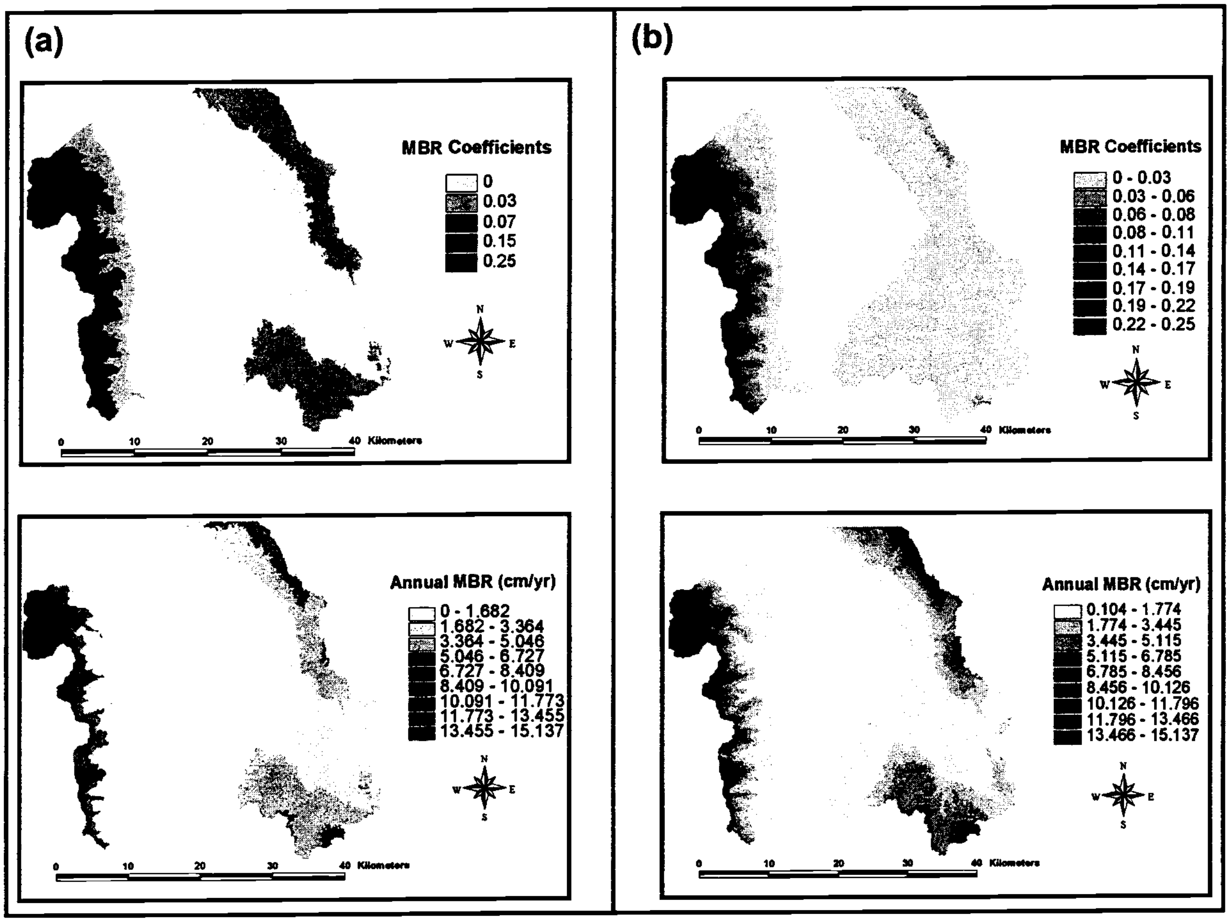

Figure 6. MBR coefficients and annual MBR for Owens Lake playa based on (a) the Maxey and Eakin (1949) method and (b) the Donovan and Katzer (2000) method.

base for the playa recharge zone and estimated average annual MBR based on the methods of Maxey and Eakin (1949) and Donovan and Katzer (2000). Both methods assume that recharge is directly correlated to precipitation. We assumed that the water table mirrored surface topography and that the groundwater system was hydrologically closed like the surface basin. GIS-based application of the Maxey and Eakin (1949) method produced $1.47*10^7$ m^3/yr (11,900 afy) in annual MBR volume, whereas the application of the Donovan and Katzer (2000) method produced $1.54*10^7$ m^3/yr (12,500 afy) in annual MBR volume. Based on this analysis, discharge at Owens Lake playa is not in hydrologic equilibrium with modern mountain block recharge. It should be noted that this study was conducted using an underlying assumption of restricted groundwater flow. Another possibility is that interbasin movement of groundwater may make up the difference between our estimated MBR volume and that required to sustain the discharge measured by Wirganowicz (1997).

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