Identifying sources of groundwater in the lower Colorado River valley, USA, with δ^{18}O, δD, and ^{3}H: implications for river water accounting

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Abstract Isotope measurements (δ^{18}O, δD, ^{3}H) indicate groundwater origin in the Lower Colorado River Valley (LCRV) and provide an alternative, or supplement, to the US Bureau of Reclamation's proposed "accounting surface" method. The accounting surface method uses a hydraulic criterion to identify certain wells away from the flood plain that will eventually yield mainstream Colorado River water. New isotope data for 5 surface-water and 18 groundwater sites around Topock Marsh, Arizona, are compared with river-water data (1974–2002) from 11 sites between Utah and Mexico and with groundwater data from previous LCRV studies. Three groundwater sources are repeatedly identified in the LCRV: (1) local recharge derived from precipitation, usually winter rain, plots slightly below the global meteoric water line (GMWL) and has δD values that are 20‰ greater than those of recent river water; (2) "older" (pre-1950) upper basin river-water plots on or near the GMWL, distinct from local rainfall and recent river water; and (3) recent (post-1950) Colorado River water, including Topock Marsh samples, plots below the GMWL along an evaporation trend. Large floods, as in 1983, complicate interpretation by routing less evaporated upper basin water into the LCRV; however, tritium content can indicate the age of a water. River-water tritium has declined steadily from its peak of 716 TU in 1967 to about 11 TU in 2002. Mixtures of all three groundwater sources are common.

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Résumé Les mesures isotopiques (d18O, dD, 3H) indiquent les origine de l'eaux souterraines dans la Vallée de la Rivière du Bas Colorado (LCRV) et sont une alternative, ou un supplément, à la méthode des bilans hydrologiques proposée par du «US Bureau of Reclamation». Cette méthode de bilan hydrologique utilise un critère hydraulique permettant d'identifier certains puits hors de la plaine d'inondation qui pomperaient une part non négligeable de leur eau dans la rivière Colorado. De nouvelles données isotopiques provenant de 5 sites d'eau de surface et 18 d'eaux souterraines autour de Topock Marsh en Arizona, sont comparées avec les données (1974–2000) de 11 sites localisés entre Utah et Mexico, ainsi que des données d'autres études sur la LCRV. Ces sources d'eaux souterraines sont identifiées à plusieurs reprises dans la LCRV: (1) la recharge locale dérivant des précipitations, généralement les pluies hivernales, se retrouvent légèrement sous la ligne d'eau météoritique globale (GMWL) et possède des valeurs de dD 20% supérieures aux valeurs des eaux récentes de la rivière; (2) les eaux vieilles (pre-1950) du bassin supérieur de la rivière possèdent une valeurs très proches de la GMWL, distinctes des valeurs de la pluie locale et des eaux récentes de la rivière; et (3) les eaux récentes (post-1950) de la Rivière Colorado, incluant les échantillons de Topock Marsh, se positionnent à côté de la GMWL sur une droite d'évaporation. Les grandes inondations, par exemple celle de 1983, compliquent l'interprétation en reprenant dans la LCRV moins d'eaux marquées comme évaporées et provenant du bassin supérieur; par ailleurs le pic de tritium est descendu de 716 TU en 1967 à 11 TU en 2002. Les mélanges de ces trois sources sont assez fréquentes.

Resumen Mediciones isotópicas (δ^{18}O, δD, ^{3}H) indican cual es el origen del agua subterránea en el Valle Bajo del Río Colorado (LCRV) y aportan una alternativa, o complemento, para el método "superficie de conteo" propuesto por el Buró de Reclamación de Estados Unidos. El método superficie de conteo utiliza un criterio hidráulico para identificar ciertos pozos alejados de la planicie de inundación que eventualmente producirán agua a partir de

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la corriente principal del Río Colorado. Los nuevos datos isotópicos para 18 sitios de agua subterránea y 5 sitios de agua superficial cerca de los Pantanos Topock, Arizona, se comparan con datos de agua de río (1974–2002) provenientes de 11 sitios localizados entre Utah y México, y con datos de aguas subterráneas de estudios previos realizados en el LCRV. Se identifican reiteradamente tres fuentes de aguas subterráneas en el LCRV: (1) recarga local derivada de precipitación, generalmente lluvia de invierno, cuya composición cae ligeramente por debajo de la línea de agua meteórica global (GMWL) y tiene valores δD que son 20‰ mayores que los reportados para agua de río reciente; (2) el agua de río “más vieja” (pre-1950) de la cuenca alta cuya composición cae sobre o cerca de la GMWL, diferente de la lluvia local y del agua de río reciente; (3) agua reciente (post-1950) del Río Colorado, incluyendo muestras de los Pantanos Topock, con composición por debajo de la GMWL a lo largo de una tendencia a la evaporación. Inundaciones grandes, como en 1983, complican la interpretación al transmitir menos agua evaporada de la cuenca alta hacia el LCRV; sin embargo, el contenido de tritio puede indicar la edad del agua. El contenido de tritio en agua de río ha disminuido constantemente desde la concentración pico de 716 TU en 1967 a cerca de 11 TU en 2002. Es común que exista mezclas de las tres fuentes de agua subterránea.

Keywords δ^{18}O, δD, ^{3}H · Groundwater · Lower Colorado River · Stable isotopes · Water accounting

Introduction

Stable hydrogen and oxygen isotopes and tritium are useful for establishing the origin of groundwater in areas where waters of different origin, age, and evolution are present. This is the setting in the Lower Colorado River Basin (LCRB) of the United States, where snow-melt from regions of higher altitude and latitude produce river water that eventually mixes with tributary water, or groundwater derived from local rainfall (Fig. 1). Distinguishing water origin is increasingly important for managing this over-allocated river system, and the application of environmental isotopes is recognized as a promising tool for dealing with legal and water accounting disputes.

One such dispute involves the accounting of Colorado River water in the LCRB, as required by court decree (*Arizona vs. California*; US Supreme Court 1964). The Secretary of the Interior (Secretary) and its agency, the US Bureau of Reclamation (Reclamation), must determine and report the diversions, return flows, and consumptive use of water from the mainstream. Consumptive use is calculated as the difference of water diversion and return flow. Article I of the decree also defines consumptive use to include, “water drawn from the mainstream by underground pumping.” Reclamation has presumed that wells located on the flood plain and certain other wells on the surrounding alluvial terraces yield river water (Wilson and Owen-Joyce 1994). The authors stated “no method was available for identifying wells [outside the flood plain] that yield water that will be replaced by water from the river and wells that yield water that will be replaced by water from precipitation or inflow from adjacent tributary valleys.” There are several thousand of these wells in Arizona and California, yet their withdrawal is expected to be a small portion of overall consumptive use (Jeff Addiego, USBR, Water Accounting Team, personal communication 2003).

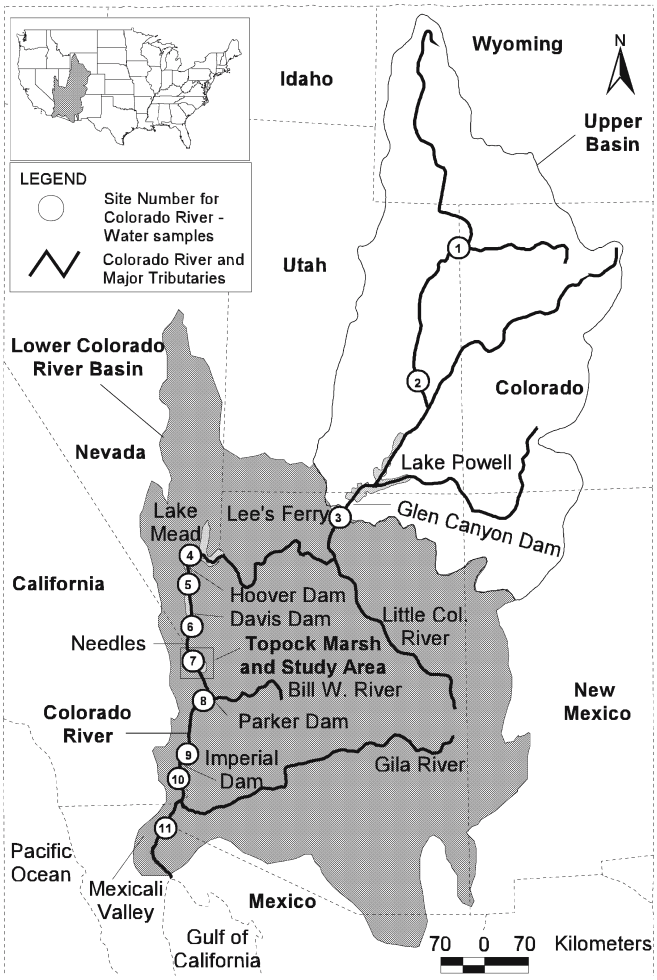

Fig. 1 Map of Colorado River watershed showing the Lower Colorado River Basin (*shaded*) and study area, Topock Marsh, Arizona. *Circled numbers* are approximate sampling sites for river water (Table 1)

In 1994, and with technical assistance from the US Geological Survey (USGS), Reclamation proposed an “accounting surface” method to address the wells outside the flood plain. The method relies on a hydraulic criterion that required the delineation of the river aquifer (the subsurface strata presumed hydraulically connected to the mainstream) and the accounting surface (the unconfined static water table within the river aquifer). Wells that have a static water-level elevation equal to or below the accounting surface are presumed to yield water that will be replaced by water from the river (Wilson and Owen-Joyce 1994). The river aquifer boundary and accounting surface

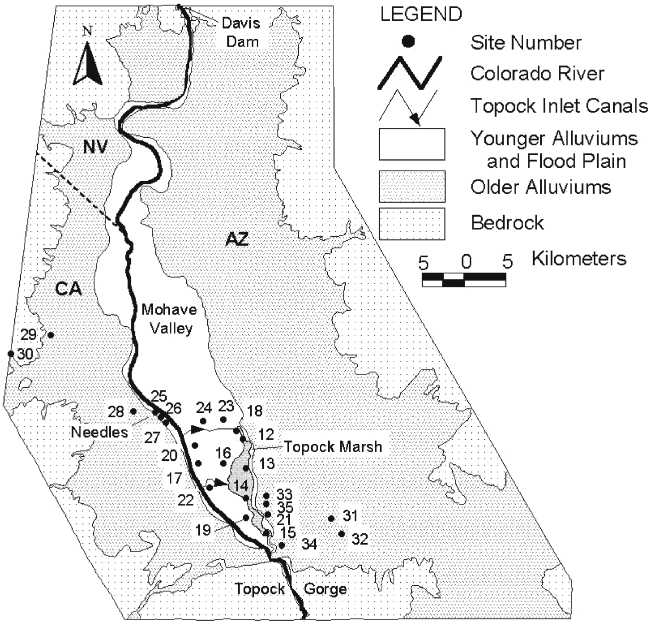

Fig. 2 Map of Mohave Valley and Topock Marsh sampling sites (Tables 2 and 3). The river is the border between states. Geohydrologic units are summarized from Metzger and Loeltz (1973): Younger Alluvium (includes flood plain), Older Alluviums (terraces), and bedrock. Two inlet canals gravity feed Colorado River water into the marsh. The marsh is impounded but flow is southerly. Topock Marsh (SN 12–15) sites are surface-water, all other sites are groundwater

elevation is depicted in a series of 19 plates that cover nearly 500 km from Utah to Mexico. Because no one is entitled to use Colorado River water without a contract with the Secretary (US Congress 1948), many well owners will, for the first time, need to purchase a contract while they are still available.

While the proposed changes to river-water accounting have several operational advantages for Reclamation, one foreseeable criticism is that the method does not provide direct evidence that a well yields mainstream water. Many well owners are concerned by the approach, and welcome an alternative method that directly confirms the withdrawal of mainstream water or better yet, quantifies the percentage of mainstream water in a mixed-source well.

In a recent hydrologic investigation of Topock Marsh, Arizona, Guay (2001) applied environmental isotopes (^{18}O, ^{2}H or deuterium or D, and ^{3}H or tritium) to investigate the sources of groundwater surrounding an impounded wetland located on the flood plain of the Lower Colorado River (Figs. 1 and 2). Not surprisingly, recent river water was the primary source to wells on the flood plain, but wells outside the flood plain showed different isotopic compositions. A review of previous isotope studies along the Lower Colorado River showed a recurring data pattern that suggested their use as a primary indication of water source.

In this paper, new environmental isotope data (δ^{18}O, δD, and ^{3}H) for waters in the southern Mohave Valley and the Colorado River are compared with earlier findings. It is shown that δ^{18}O–δD data, in some cases supported by tritium and geohydrologic data, provide a direct indication of a water's source. Groundwater is identified as originating from local precipitation, "older" (pre-1950, probably pre-dam) river water, and recent (post-1950) river water, with the latter approximately the legal equivalent of mainstream water. The objective of this paper is to interpret the recurring pattern of environmental isotope data and establish their use for identifying groundwater sources in the LCRV. If supported, the approach provides an alternative, or supplement, to the accounting surface method now being considered for river-water accounting.

Site Description

The Colorado River falls some 3,700 m from the Rocky Mountains of Wyoming and Colorado to the deserts of California and Arizona, flowing nearly 2,400 km through parts of seven US states (Fig. 1), before emptying into the Gulf of California in Mexico (Nathanson 1978). A canyon section near Lee's Ferry, Arizona, has provided a convenient division between the Upper and Lower Colorado River Basins. Below Hoover Dam, the river passes through a series of constricted bedrock canyons and wide alluvial flood plains. This paper concerns the Lower Colorado River Valley (LCRV), which refers to the river-corridor area between Hoover and the Mexico border.

The climate is arid along the LCRV; for instance, the cities of Needles, California and Yuma, Arizona receive about 119 mm (4.7") and 74 mm (2.9") rainfall per year, respectively (WRCC 1997). The precipitation occurs as rainfall in nearly equal amounts during the summer (convective) and winter (cyclonic) seasons (Hely and Peck 1964; Pyke 1972). Snowfall is rare within the LCRV, but it occurs at upper elevations north of Davis Dam.

Historically, the natural flows in the Colorado River varied tremendously, with peak flows occurring in April to June (USBR 1996). This late-spring snowmelt from Upper Basin tributaries is the primary source (~70%) of river water entering the LCRV (Bruce Williams, USBR engineer, personal communication 1999). Hoover Dam and several subsequent river engineering projects since 1935 have regulated river flow. Hydropower operations generally store spring runoff and increase outflows during the summer season. During some anomalous weather events, such as the strong El Niño-Southern Oscillation event in 1993 and hurricane Nora in the fall of 1997, heavy precipitation in the LCRB can influence river flows for days or even weeks. In 1993, for example, the Bill Williams River discharge into the Colorado River increased from <0.3 to 184 m^{3}/s in only a few days (USGS 2000). Overall, river flows decrease southward from Hoover Dam to Mexico because of consumptive uses of river water (Owen-Joyce and Raymond 1996).

Mohave Valley extends 64 km between Davis Dam and Topock Gorge (Fig. 2). Before dams, the river meandered and annually flooded backwaters areas, such as the former oxbow of Topock Marsh (Guay 2001). The pre-dam range in river stage at Needles, California was nearly 5 m, although in a few years it was about 8 m (Metzger and Loeltz 1973). The decline in river flows caused by dams eventually required the river be channelized and diked in the 1950s, with most of the modern flood plain on the Arizona side of the River (Fig. 2). Today, nearly one-quarter of the entire flood plain, mostly north of Topock Marsh, is agricultural land irrigated with Colorado River water.

The US Fish and Wildlife Service (USFWS) have managed Topock Marsh since 1941 as a refuge and breeding ground for migratory birds and other wildlife (USFWS 1994). The former riverine backwater was converted into a 13-km-long impounded wetland in the mid-1960s with the construction of an inlet canal and south dike (Guay 2001). Today there are two unlined inlet canals that feed Colorado River water directly into the northern half of the marsh. Water not lost to evaporation or seepage from the marsh reenters the river through an outlet structure on the south dike. Figure 2 shows the majority of sampling sites are on the flood plain, with a few sites located on the higher elevation older alluvial deposits.

The hydrology of the LCRV is dominated by the Colorado River; in fact, it provides 96% of the annual water supply and virtually all the recharge to the river aquifer (Wilson and Owen-Joyce 1994). Water budget estimates (Owen-Joyce and Raymond 1996; Metzger and Loeltz 1973; USDOI 2000; Guay 2001) and groundwater contour data (Metzger and Loeltz 1973) in Mohave Valley suggest the river loses water to the groundwater reservoir. For example, during a modulated river flow period (1950–1966), the river annually lost about 2% of its flow in the valley (Metzger and Loeltz 1973). Quantification of tributary inflow is recognized to be a difficult problem (Owen-Joyce and Raymond 1996), however, the average combined surface-water and groundwater inflow to the river from Mohave Valley tributaries and adjacent basins is estimated to be 3.4×10^7 m^3 (Owen-Joyce 1987), or about 0.3% of the typical river flow entering the valley (Metzger and Loeltz 1973). Together, these data suggest the discharge from the flood plain reservoir is almost 2.3% (river loss plus tributary inflows) of the mainstream flow, which is caused mainly by natural phreatophyte and crop evapotranspiration (ET), and open-water evaporation (Owen-Joyce and Raymond 1996; USDOI 2000). Most flood plain vegetation can easily reach the water table, which is generally less than 3 m below the ground surface (Metzger and Loeltz 1973; Guay 2001). Flood plain sediments are very permeable, commonly with high transmissivity values (e.g., 10,788 m^2/day; Metzger and Loeltz 1973). River stage varies several feet during daily and seasonal cycles and has been shown to have a direct effect on the water-table elevation (Guay 2001). In summary, Mohave Valley is a losing river reach where Colorado River water is later lost to ET and open water evaporation.

Previous Work

Owen-Joyce and Raymond (1996) and Wilson and Owen-Joyce (1994) have reviewed published reports and papers describing the geology, groundwater resources, water quality, and water-accounting methods along the lower Colorado River. Metzger and Loeltz (1973) performed a detailed geohydrology study of the Needles area. They used a comparison of chemical constituents in river and well water to support their conclusion that the Colorado River was the dominant source of groundwater recharge in the basin. Several wells, however, appeared to yield mixtures of river water and “local recharge.” The authors acknowledged the limitations of major-ion chemistry for identifying water source and provided two examples where unrelated waters (river and non-river) had nearly identical solute concentrations. The primary approach that establishes Colorado River water as the dominant source of recharge in the LCRV is a water balance (Metzger and Loeltz 1973; Owen-Joyce and Raymond 1996; US Department of the Interior 2000). These results and related studies (Owen-Joyce 1987; Wilson and Owen-Joyce 1994) suggest that the sum of hydrologic components argues against significant groundwater discharge to the river, inferring that recharge to the alluvium by local precipitation must be negligible in the LCRV.

Isotope data ($\delta^{18}O$, δD, and in some cases ^3H) were used to identify water sources and soil water processes in the LCRV (Robertson 1991), in Mexicali Valley (Payne et al. 1979), and in upper Mohave Valley (Wyman 1997). Collectively, these studies identified groundwater that originated from local precipitation, from recent (i.e., post-dam) Colorado River water, and from older (pre-dam) Colorado River water. In contrast, Payne et al. (1979) identified local groundwater whose source was the Gila River. Payne and Robertson relied on hydrologic and geochemical data to support their findings. The benefits of environmental tracers (e.g., ^3H) over Darcy’s Law and water balance approaches for determining water movement in desert soils of the American Southwest have been discussed by Phillips (1994).

Isotope data for precipitation in the LCRV were presented by Friedman et al. (1992). They found that the average δD values for summer and winter rainfall between 1982 and 1989 in Needles were –47 and –71‰, respectively, and the difference decreases southward along the river, where in Yuma the summer and winter rain are equivalent (–55‰). Smith et al. (1992) and Gleason et al. (1994) found that the majority of deeper wells and perennial springs in southeastern California had waters that were more depleted in deuterium (lower δD) than the lightest winter precipitation reported by Friedman et al. (1992). They postulated that the isotopically light water dated from an earlier period, possibly the late Pleistocene, with a different climatic regime and lower δD in precipitation. However, Davisson et al. (1999) disagreed, and using δD, $\delta^{18}O$ and ^{14}C data, they suggested that isotopically light water from higher latitudes is flowing as groundwater into southeastern Nevada along elongate north–south grabens.

Data and Analytical Methods

Table 1 provides sampling and isotope data for Colorado River water only (1974–2002), listed geographically from north to south. Tables 2 and 3 provide similar data for Topock Marsh and other southern Mohave Valley sites (1996–1998). The site number (SN) identifies sample locations on Figs. 1 and 2.

All stable isotope data are reported in notation, where $\delta = \left[\frac{R}{R_{std}} - 1\right] \times 1000‰$, and R represents either $^{18}O/^{16}O$ or D/H ratio of the sample. R_{std} is the isotope ratio of VSMOW (Vienna standard mean ocean water) or SMOW in the case of older measurements. The data are from several laboratories and were measured using different techniques, but are comparable. For this study $\delta^{18}O$, δD, and tritium values were measured at the University of Arizona's Geoscience Laboratory of Isotope Geochemistry. $\delta^{18}O$ and δD were determined on a Finnigan Delta-S mass spectrometer with automated CO_2 equilibration and Cr reduction attachments. Analytical precisions (1σ) for these techniques are 0.08‰ and 0.8‰ for $\delta^{18}O$ and δD, respectively. Some early δD values were measured using the Zn reduction technique with an analytical precision (1σ) of 1.8‰. Data from other laboratories, where reported, have analytical precisions (1σ) of 0.05 to 0.1‰ for $\delta^{18}O$ and 0.4 to 0.5‰ for δD (Payne et al. 1979; Friedman et al. 1992; Smith et al. 1992; Gleason et al. 1994). For this study, tritium values were measured by liquid scintillation counting on electrolytically enriched water in a Quantulus 1220 Spectrophotometer, with a detection limit of 0.7 TU for 8-fold enrichment and 1,500 min of counting. Available precisions for other tritium data ranged from ±5 to ±0.6 TU, or typically ±4% of the reported value.

Results

Colorado River Water Entering the LCRB (SN 1–3)

River water entering the LCRB was sampled at the Colorado–Utah state line, Cisco (Utah), and at Lee's Ferry, Arizona (Fig. 1, Table 1). Figure 3 shows that the $\delta^{18}O$–δD pairs of river water upstream of Glen Canyon Dam (SN 1,2) plot on or near the Global Meteoric Water Line (GMWL, see Craig 1961). The average $\delta^{18}O$ and δD value is –16.2 and –122‰, respectively. Note that these data were collected during the high-flow 1984–1987 period (USBR 2000) and may be depleted in ^{18}O and deuterium compared to water from other times.

Lower Colorado River Water (SN 3–11)

Water below Glen Canyon Dam (Lee's Ferry) diverges from the GMWL along an evaporation trend (Fig. 3). Figure 4 illustrates the temporal and spatial variability in the δD values of river water. $\delta^{18}O$ values were not determined for many of these samples. The δD values are arbitrarily grouped by decade and plotted with respect to distance (km) downstream of Glen Canyon Dam. Most samples were taken downstream of Hoover Dam (575 km) in areas that experience extreme evaporation. Several data points in Fig. 4 are offset slightly for plot clarity.

Colorado River Tritium Data

Compiled tritium data from several river locations are plotted against time in Fig. 5. Under normal conditions, the sample location should not affect a river tritium value because the transit time of water released from Hoover Dam to Imperial Dam is estimated to be less than 10 days (Bruce Williams, USBR engineer, personal communication 1999). Further, tritium is a conservative tracer; changes in tritium content due to evaporation are small relative to measurement errors. Tritium levels declined exponentially until about 1990 before leveling off at about 11 TU (1998–2002).

Topock Marsh and Surrounding Shallow Groundwater (SN 12–20)

Figure 6a is a $\delta^{18}O$–δD plot of surface-water samples from Topock Marsh (SN 12–15). Each sample site represents a quadrant of the marsh. Recent (1996–1998) Colorado River water sampled at nearby Needles (SN-7) is also plotted. The marsh is clearly subject to strong evaporation (~2 m/year; Guay 2001). A regression of these data defines the Topock Marsh Evaporation Line (TMEL), a reference used throughout this work.

Figure 6b shows $\delta^{18}O$–δD data for shallow groundwater from the flood plain around Topock Marsh. Represented are four shallow monitoring wells (SN 16–19) and 3-Mile Lake (SN-20), which is an isolated seepage lake recharged by groundwater (i.e., river water). A comparison of Fig. 6a, b shows the relationship of contemporary river water, evaporated river water, and shallow groundwater.

Southern Mohave Valley Groundwater (SN 21–35)

Figure 7 shows the isotope composition of other groundwater samples from southern Mohave Valley in relation to recent Colorado River water (1996–1998). Also depicted are the approximate $\delta^{18}O$–δD values for winter and summer rain in Needles, California (Friedman et al. 1992) and two composite rainfall event samples.

SN-21 is a private residential well located 300 m east of the marsh on an older alluvium terrace. The Refuge irrigation well (SN 22) is located 200 m east of the river, but is used infrequently. SN-23 is a residential well and SN-24 is a high-yield irrigation well, but both are situated on the modern flood plain and within a few hundred meters of the river or irrigated fields. All four samples plot along the TMEL.

Table 1 Colorado River isotope data and sample information

Site number (SN)	Local identifier	Sample date	Data source	River kilometer below Glen Canyon Dam	δ^{18}O ‰	δD ‰	Tritium unit (TU)
1	Colorado–Utah State line	12/04/84	USGS[a]	-	–16.5	–123	
		01/24/85	“	-	–16.0	–119	
		03/20/85	“	-	–16.6	–125	
		04/03/85	“	-	–16.3	–125	
		07/10/85	“	-	–17.1	–125	
		11/05/85	“	-	–16.4	–122	
		03/25/86	“	-	–16.3	–121	
		05/13/86	“	-	–16.4	–123	
		07/15/86	“	-	–16.7	–122	
		08/19/86	“	-	–16.0	–118	
		10/29/86	“	-	–16.1	–121	
		12/16/86	“	-	–16.5	–122	
		02/25/87	“	-	–16.3	–121	
		04/21/87	“	-	–16.5	–123	
		06/23/87	“	-	–16.7	–123	
		08/25/87	“	-	–15.5	–116	
2	Cisco, UT	11/19/84	“	-	–16.4	–121	
		03/19/85	“	-	–16.1	–119	
		04/22/85	“	-	–16.1	–116	
		05/20/85	“	-	–16.4	–120	
		07/23/85	“	-	–16.0	–118	
		09/03/85	“	-	–15.9	–119	
		11/19/85	“	-	–16.4	–121	
		01/22/86	“	-	–16.4	–120	
		03/24/86	“	-	–16.0	–120	
		05/19/86	“	-	–16.2	–120	
		06/23/86	“	-	–16.6	–121	
		08/19/86	“	-	–15.8	–118	
		11/20/86	“	-	–15.8	–118	
		03/25/87	“	-	–15.9	–118	
		04/20/87	“	-	–15.6	–116	
		05/21/87	“	-	–16.4	–120	
		06/25/87	“	-	–16.0	–117	
		07/22/87	“	-	–15.9	–118	
		08/19/87	“	-	–15.9	–118	
3	Lee’s Ferry, AZ	11/07/84	“	8	–14.7	–113	
		01/04/85	“	8	–14.9	–117	
		04/12/85	Friedman[b]	8		–120	
		05/08/85	USGS[a]	8	–15.6	–119	
		06/11/85	Friedman[b]	8		–118	
		07/03/85	USGS[a]	8	–15.1	–115	
		09/03/85	“	8	–15.2	–115	
		10/20/85	Friedman[b]	8		–114	
		11/05/85	USGS[a]	8	–15.1	–113	
		01/08/86	“	8	–15.0	–115	
		05/09/86	“	8	–15.3	–116	
		07/02/86	“	8	–15.0	–114	
		08/27/86	“	8	–14.8	–114	
4	Lake Mead (inflow)	10/04/80	(Robertson 1991)	483	–12.9	–106	
		10/05/84	Friedman[b]	483		–115	
		03/19/85	“	483		–115	
		10/19/85	“	483		–115	
		03/22/96	Eastoe[c]	483	–10.8	–93	13.7
		1997	Wyman[d]	483	–12.7	–102	
5	Lake Mead (outflow)	10/04/84	Friedman[b]	576		–107	
		04/01/85	“	576		–109	
		07/02/85	“	576		–107	
6	Laughlin, NV	1991	Wyman[d]	687	–12.6	–98	
		1991	“	687	–12.7	–98	
		1992	“	687	–12.4	–101	
		1993	“	687	–12.0	–98	
		1995	“	687	–12.0	–99	
		1997	“	687	–12.5	–99	

Table 1 (continued)

Site number (SN)	Local identifier	Sample date	Data source	River kilometer below Glen Canyon Dam	$\delta^{18}O$ ‰	δD ‰	Tritium unit (TU)
7	Needles, CA	07/08/94	Eastoe[c]	730	–12.0	–93	16.4
		09/01/94	“	730			16.0
		10/22/94	“	730	–11.8	–99	16.6
		06/19/98	(Guay 2001)	730	–13.1	–103	11.7
	Needles, CA (south of)	08/05/96	“	735	–12.3	–96	
		01/22/97	“	735	–12.2	–98	
		05/15/97	“	735	–12.6	–100	
		09/25/97	“	735	–12.8	–99	
		12/30/97	“	751	–12.6	–98	
		04/15/98	“	751	–13.0	–99	
8	Parker Dam (outflow)	10/03/80	USGS[e]	817	–12.5	–104	
		04/28/93	Eastoe[c]	817			14.1
		07/09/94	“	817	–11.6	–92	16.7
		08/03/95	“	817	–10.9	–90	14.1
		04/01/98	“	817	–12.8	–101	12.7
	Parker, AZ	09/30/84	Friedman[b]	840		–110	
		10/05/84	“	840		–113	
9	Imperial Dam (inflow)	10/04/80	(Robertson, 1991)	1,047	–12.5	–103	80
		11/12/97	USGS[e]	1,047	–12.1	–100	
		05/14/97	“	1,047	–12.1	–98	
		02/12/97	“	1,047	–12.0	–98	
		12/17/97	“	1,047	–12.2	–100	
		12/18/97	“	1,047	–12.0	–96	
		08/20/97	“	1,047	–12.2	–97	
		08/26/97	“	1,047	–12.2	–100	
		11/13/97	“	1,047	–12.0	–99	**331,441,716,613, 531,428,347,291, 250, 211,181,151, 132,114,97,83,79, 69,58,48,39,34,28**[g]
		02/18/97	“	1,047	–12.0	–96	
		05/29/97	“	1,047	–12.1	–100	
		06/26/97	“	1,047	–12.3	–98	
10	Imperial Dam (outflow)	1965–1987	USBR[f]	1,049			
		05/11/02	Eastoe[c]	1,089			11.0
11	Mexicali Valley	12/16/74	(Payne et al. 1979)	1,110	–12.2	–101	177
		12/16/74	“	1,163	–12.2	–99	174
		12/16/74	“	1,165	–12.2	–98	
		12/16/74	“	1,167	–12.0	–99	
		04/30/76	“	1,110	–12.3	–99	
		05/31/76	“	1,110	–12.1	–99	

[a] USGS, Tyler Coplen, personal contact (fax data), Reston, VA, +1-703-6485862, 3 June 1998. Database is USGS-NASQAN, sampling sites corresponding to in-house Site 841 (Cisco, UT), Site 206 (CO-UT State line), and Site 130 (Lee’s Ferry, AZ)

[b] Irving Friedman, personal contact (fax data), USGS Lakewood, CO, +1-303-2367888, 10 Feb 1998

[c] Christopher Eastoe, Dept. of Geosciences, Laboratory of Isotope Geochemistry, Univ. of Arizona, +1-520-6211638

[d] Richard Wyman, Final report to Mohave County Water Authority, Wyman Engineering Consultants, Boulder City, NV, +1-702-2931098, 10 Nov 1997

[e] USGS, Cheryl Parten, personal contact (fax data), USGS national water information system, Phoenix, AZ, +1-602-3793088, 1997–1998

[f] USBR, James Setmire, personal contact email data (e-mail: jsetmire-ibr3sc@ibr3gw80.lc.usbr.gov), USBR, CA, +1-909-6955310, 2 Sept 1999. Fig. 29 in Setmire et al. (1993) plotted 1977–1988 data

[g] Bold text includes Colorado River water tritium values for consecutive years (1965–1987)

The three municipal supply wells of Needles (SN 25–27) are located along the western margin of the modern flood plain. The wells are cased to about 19 m but screened to 39 m below the ground surface. Five samples from these wells plot near or to the lower left of average recent Colorado River. Also annotated are the tritium concentrations measured in four samples, which range from 0.9 to 28.4 TU.

Only two rain events were sampled during this study (SN-28). The isotope results “bracket” the average winter rainfall value. Individual precipitation events most likely vary widely in $\delta^{18}O$ and δD, but mixing in groundwater attenuates the variability. This phenomenon is well documented in the Tucson basin (Kalin 1994).

Water from two springs (SN 29,30) and an artesian well (SN-31) discharge several hundred feet above the river and therefore cannot derive from river water. These, along with four other well samples from Warm Springs and Sacramento Wash drainage areas (SN 32–35), cluster in the domain of local winter precipitation and are isotopically distinct from mainstream Colorado River water.

Table 2 Surface-water and shallow groundwater isotope data and sample information. Italics are the estimated values

Site number (SN)	Local identifier	Sample date	Data source	Surface-water (SW), ground-water (GW)	δ^{18}O ‰	δD ‰	Well type	Approx. surface elevation (m m.s.l.)	Static water elevation (m m.s.l.)
12	Topock Marsh (north dike)	08/05/96	(Guay 2001)	SW	–10.4	–87			
		05/15/97	“	“	–12.4	–95			
		09/25/97	“	“	–12.5	–97			
		12/30/97	“	“	–8.5	–77			
		04/15/98	“	“	–12.7	–98			
13	Topock Marsh (5-Mile NE)	05/15/97	“	“	–12.4	–97			
14	Topock Marsh (Beal ditch)	09/25/97	“	“	–9.2	–82			
		04/15/98	“	“	–9.4	–81			
15	Topock Marsh (outlet)	08/01/96	“	“	–4.4	–59			
		01/26/97	“	“	–2.5	–41			
		05/15/97	“	“	–7.6	–75			
		09/25/97	“	“	–6.9	–72			
		12/30/97	“	“	–7.0	–70			
		04/15/98	“	“	–7.4	–71			
16	Monitoring Well 1	05/15/97	“	GW	–8.5	–80	2” PVC	140	138
		12/30/97	“	“	–8.2	–75			
		04/15/98	“	“	–8.3	–75			
17	Monitoring Well 2	05/15/97	“	“	–10.8	–95	“	140	138
		12/30/97	“	“	–10.9	–91			
		04/15/98	“	“	–11.0	–97			
18	Monitoring Well 3	05/15/97	“	“	–11.3	–95	“	140	139
		12/30/97	“	“	–10.9	–90			
		04/15/98	“	“	–10.9	–84			
19	Monitoring Well 4	05/15/97	“	“	–12.7	–102	“	*140*	138
		12/30/97	“	“	–12.4	–98			
		04/15/98	“	“	–11.4	–94			
20	3-Mile Lake	08/02/96	“	GW/SW	–10.4	–89			
		01/26/97	“	“	–11.8	–95			

Discussion

Earlier isotope data sets from the LCRV (Payne et al. 1979; Robertson 1991; Wyman 1997) have characteristics similar to those presented in this study. One notable difference is that the evaporation trend in earlier studies plots below the TMEL. Nonetheless, all the studies have identified, where present, the same groundwater sources and their mixtures. As with this study, the source designations have been based principally on the relative plotting positions of δ^{18}O–δD pairs, but were supported to varying degrees by tritium, hydrologic, and geochemical data.

Colorado River Water Entering the LCRB

The δ^{18}O–δD values of river water upstream of Lake Powell at present, and probably in the recent past, plot close to the GMWL (Fig. 3). This plotting position is the signature of upper basin snowmelt that has undergone little evaporation. It is significant because some groundwater samples in the LCRV plot near this position (see Payne et al. 1979; Wyman 1997). Local snowfall might produce similar values, but such events are rare. “Older” river water was probably recharged during spring floods before the closure of Hoover Dam in 1936 (USBR 2000). Thus the residence time of some groundwater near the flood plain is expected to be more than 70 years, which is also confirmed by tritium data (see below).

Lower Colorado River Water

Below Glen Canyon Dam, the δ^{18}O–δD values of river water increase to the right of the GMWL along an evaporation trend (see Figs. 3 and 6a). The slope of the line is typically between 5 and 6 (Robertson 1991; Setmire et al. 1993). A statistical regression of available δ^{18}O–δD pairs for the river (SN 3–11) and Topock Marsh (SN 12–15) yields slopes of 5.6 and 5.1, respectively.

Data in Fig. 4 suggest several trends despite obvious gaps. First, the two-decade range of δD at certain locations, e.g., below Parker Dam (817–840 km) and above Lake Mead (483 km), was about 25‰. One cause was the mid-1980s high flow period (USBR 2000), where isotopically depleted melt-water from the upper basin apparently filled the entire river system. Extreme local runoff events, such as flooding of the Bill Williams River (1993, 1995) and Gila River (1984), could possibly have increased the range. The evaporative losses in Lakes Mead and Powell appear to cause the δD value to increase by about 5 to 7‰ in each lake. Conversely, for periods of less than a decade, the variability in δD at certain locations (e.g., SN-6) has been quite small (<10‰). It is speculation, but large variability appears to be caused by

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Table 3 Isotopic data for southern Mohave Valley groundwater and rainfall. Italics are estimated values

Site number (SN)	Local identifier	Sample date	Data source	Ground-water (GW) rainfall (R)	$\delta^{18}O$ ‰	δD ‰	Tritium unit (TU)	Well type	Approx. surface elevation (m m.s.l.)	Well depth meters below grade	Static water elevation (m m.s.l.)
21	Campbell Well	04/15/98	(Guay, 2001)	GW	–9.0	–81		Domestic	*186*	*37*	
22	Refuge Farm Pump	08/04/96	“	“	–12.4	–96		Irrigation	*140*	*36*	*134*
23	Claypool Well	08/01/96	“	“	–13.9	–104		Domestic	*142*	*11*	137
24	Chesney Well	08/02/96	“	“	–13.5	–101		Irrigation	*142*	*15*	134
25	City of Needles Well #8	12/12/97	“	“	–13.8	–99		Public	*145*	38	
	City of Needles Well #8	06/19/98	“	“	–12.8	–99	15.2	“			
26	City of Needles Well #11	12/12/97	“	“	–13.9	–106	0.9	“	*145*	91	
	City of Needles Well #11	06/19/98	“	“	–13.8	–100	18.3	“			
27	City of Needles Well #12	06/19/98	“	“	–12.6	–98	28.4	“	*145*	91	
28	Rainfall, Needles	01/12/97	“	R	–10.4	–79					
	Rainfall, Needles	09/25/97	“	R	–9.2	–58					
29	Red Spring	01/12/97	“	GW	–9.3	–70			*274*		
30	Klinefelter Well/Spring	12/12/97	“	“	–10.7	–80	<0.6	Domestic	*366*		
31	Warm Springs Artesian Well	04/15/98	“	“	–9.8	–71		“	*274*	*287*	*280*
32	Sacramento Wash Well	04/15/98	“	“	–10.0	–72		“	*244*		
33	Golden Shores Well #2	08/05/96	“	“	–9.1	–68		Public	*219*	*152*	
34	Topock Well	04/15/98	“	“	–9.9	–74		“	*168*		
35	Golden Shores Well #1	04/15/98	“	“	–9.1	–68		“	*189*	*146*	

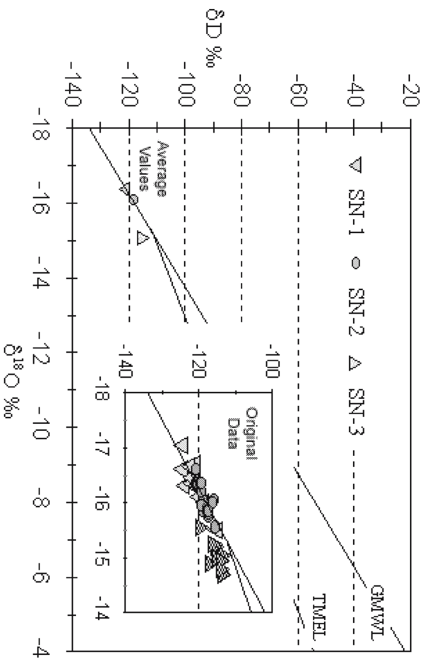

Fig. 3 Plot of average and original $\delta^{18}O$–δD pairs (1984–1987) in river water entering the Lower Colorado River Basin (data sources given in Table 1)

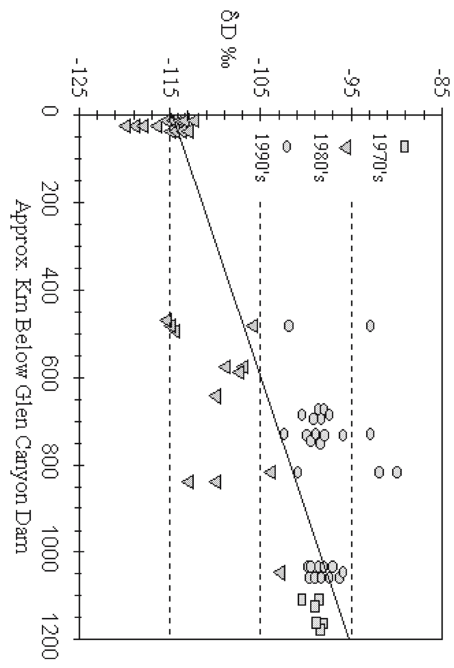

Fig. 4 Colorado River δD values (1974–1998) sorted by decade and plotted by river-kilometer below Glen Canyon Dam. Note, some nearly identical values have been shifted slightly (<±0.5‰ and ±15 km) for better illustration (data sources given in Table 1). An approximate trend line is added for reference

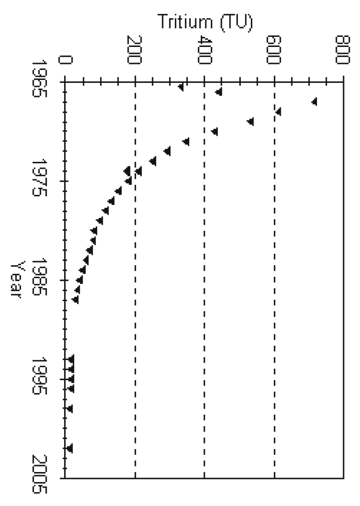

Fig. 5 Tritium concentrations (1965–2002) in lower Colorado River samples. Data sources and locations are given in Table 1

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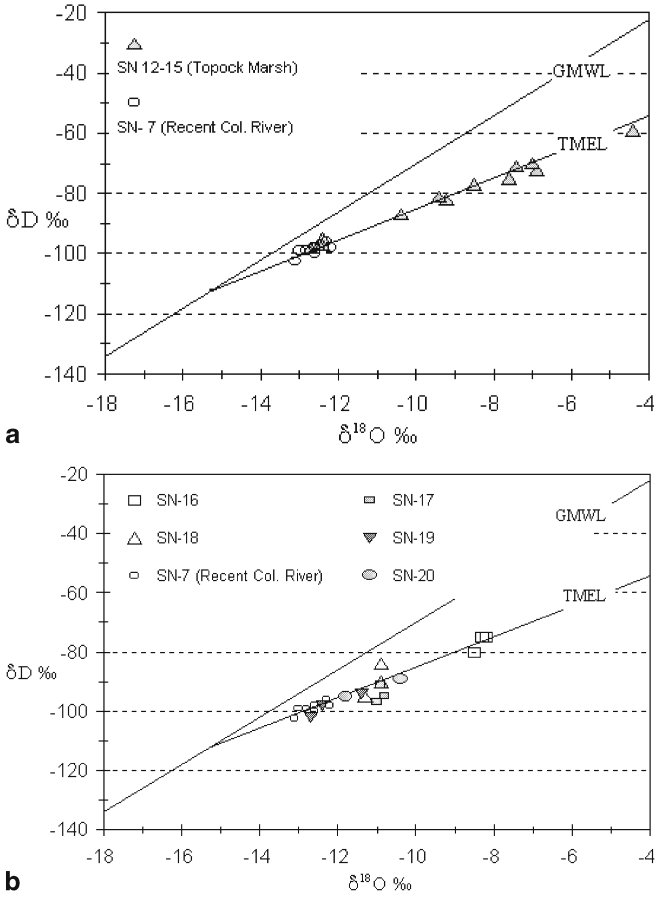

Fig. 6 **a** Plot of δ^{18}O–δD pairs (1996–1998) in Topock Marsh and nearby Colorado River. Regression of evaporated marsh-water samples (*triangles*) defines the Topock Marsh Evaporation Line (TMEL) with slope 5.1. **b** Plot of δ^{18}O–δD pairs (1996–1998) in the shallow groundwater near Topock Marsh (Table 2). SN 16–19 are monitoring wells. SN-20 is a seepage lake (see text). Recent Colorado River water (SN-7) added for reference

infrequent high flow events, while river management or seasonal evaporation may control smaller variability. Nonetheless, Colorado River water is isotopically distinctive because of its evaporation trend.

Colorado River Tritium

The 2002 river-water sample indicates a river tritium value near 11 TU (Table 1). The average annual tritium in Tucson precipitation has been about 5 TU since 1992, indicating complete removal of bomb tritium from the atmosphere (Eastoe et al. 1997). The lagged decrease in Colorado River tritium probably results from the retention of bomb tritium in Lakes Powell and Mead, which store about 5 years of river discharge (USBR 1996).

More significantly, tritium behaves as a conservative tracer, meaning its movement is not slowed or decreased in concentration by interaction with the solid phase and is not produced in the soil (Phillips 1994). Thus, if the tritium content of groundwater is near 11 TU, it suggests recharge by recent river water. Conversely, if the tritium concentration is negligible (<1 TU), the water pre-dates the atmospheric detonation of thermo-nuclear devices, which is, before 1950. A few groundwater samples have tritium levels that exceed the levels in today's river water (e.g., SN-27); these waters are probable mixtures that contain some bomb-induced tritium.

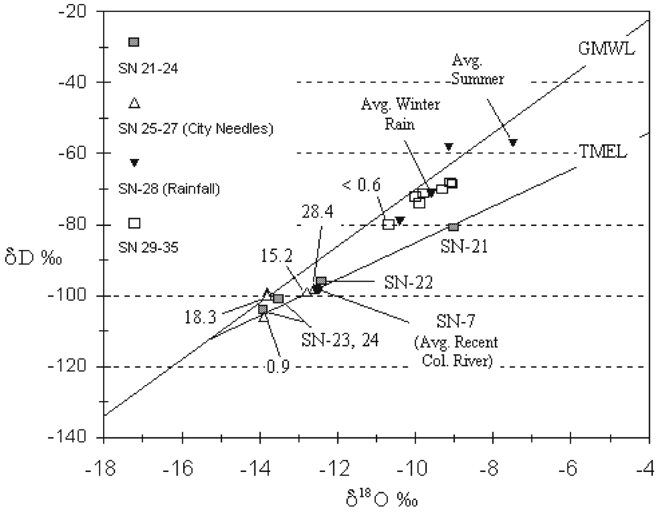

Fig. 7 Plot of δ^{18}O–δD pairs (1996–1998) in groundwater and rainfall events in southern Mohave Valley (Table 3). The average value for recent Colorado River water (SN-7) and estimates of winter and summer rain in Needles (after Friedman et al. 1992) are plotted for reference. City of Needles wells (*open triangle*) and SN-29 are annotated with tritium concentrations (TU). Note SN-33 has been offset from SN-35 for plotting purposes

Topock Marsh and Surrounding Shallow Groundwater

The Colorado River is essentially the only source of inflow into Topock Marsh (Owen-Joyce 1987; Guay 2001). Figure 6a clearly shows that as marsh (i.e., river) water is evaporated, the samples plot along an evaporation line (TMEL) that passes through the field of recent river water. Values of δ^{18}O and δD increase in the direction of flow from the inlet (SN-12) to the outlet (SN-15) during each sampling period (e.g., 5/15/97).

The majority of groundwater samples from shallow monitoring wells (SN 16–19) lie on or near the TMEL, suggesting an evaporated river-derived source (Fig. 6b). This is not surprising given their shallow depth and location between the river and marsh. Evaporation of groundwater occurs in low-lying seepage areas and as a result of capillary rise in the fine-grained alluvium. Alternatively, these data may indicate recharge by evaporated marsh-water. Plant transpiration does not appear to deflect δ^{18}O–δD pairs off the TMEL (see Busch et al. 1992). Guay (2001) noted significant water uptake by phreatophytes in the vicinity of SN-16 and SN-18.

Points lying below the TMEL cannot be derived from contemporary marsh or river water; these probably represent the contribution of earlier river water with lower initial δ^{18}O and δD. The SN-18 sample (4/15/98) plots above the TMEL because recent rain had entered the well through a leaky well-cover. SN-20 samples from 3-Mile Lake confirm a recent river source that is isotopically similar to the less evaporated inlet waters at Topock Marsh (SN-12).

Southern Mohave Valley Groundwater

Marsh and recent river water are the likely source water at SN-21 and SN-22, respectively. This result was unexpected at SN-21 because the well owner estimated the well bottom to be above the marsh elevation. SN-23 and SN-24 contained water that is comparatively depleted in ^{18}O and D. These samples are interpreted as river-water mixtures, probably containing a less evaporated river water, possibly recharged when the area was inundated for several weeks during the 1983 flood.

The City of Needles wells (SN 25–27) had isotope values that suggest variable source waters. SN-27 resembled recent river water in plotting position, but contained some residual bomb tritium (28.4 TU), indicating a mixture with older, post-1960 river water. Both samples from SN-26 were relatively depleted in ^{18}O, again suggesting a mixture with "older" river water. Perhaps more significant, the summer sample had a tritium level (18.3 TU) at or slightly above river water, but the winter sample indicated a pre-bomb (0.9 TU) river water source. The SN-25 summer δ^{18}O–δD pair and tritium content (15.2 TU) typified mid-1990s river water, yet the winter plotting position (δ^{18}O= –13.8‰, δD= –99‰) was again suggestive of a mixture. These sites were also inundated during the 1983 flood. The composition of Needles well-water may be influenced seasonally by the river elevation. Overall, groundwater within the modern flood plain probably has been overprinted by generations of river water and complex mixtures have resulted.

Water from four well or spring sites (SN 29–32) clearly originated from local precipitation. All sites are located ≥8 km from the modern flood plain, and, most importantly, their water elevations are significantly (>100 m) above the adjacent river elevation (~ 139 m above m.s.l.). Further, the δ^{18}O–δD pairs cluster in the domain of winter precipitation as estimated by Friedman et al. (1992). In the case of SN-30, the negligible tritium content (<0.6± 0.3 TU) suggests a pre-bomb age. Other wells (SN 33–35) located nearer the river also appear to be recharged by local precipitation. The Topock Well (SN-34) stable isotope values (δ^{18}O= –9.9‰, δD= –74‰) were unexpected in an active pumping well so close to (<200 m) the river, and its specific conductance (1,900 µS/cm) value was typical of more saline groundwater from the flood plain.

By combining all the data and interpretations from the isotope studies in the LCRV, and using data of Smith et al. (1992) and Friedman et al. (1992) for modern precipitation and groundwater in southeastern California, a recurring data pattern emerges. Figure 8 shows the data "fields" that indicate the relative plotting position of δ^{18}O–δD values for waters in the LCRV. This simple interpretive framework includes plausible and commonly observed water types and reflects the relatively uncomplicated hydrology of this and other desert river systems; that is, a river whose features include a dominant upper basin source (snowmelt), few contributing rivers, mixing and evaporation in large reservoirs, and isotopically dissimilar local precipitation (usually rainfall).

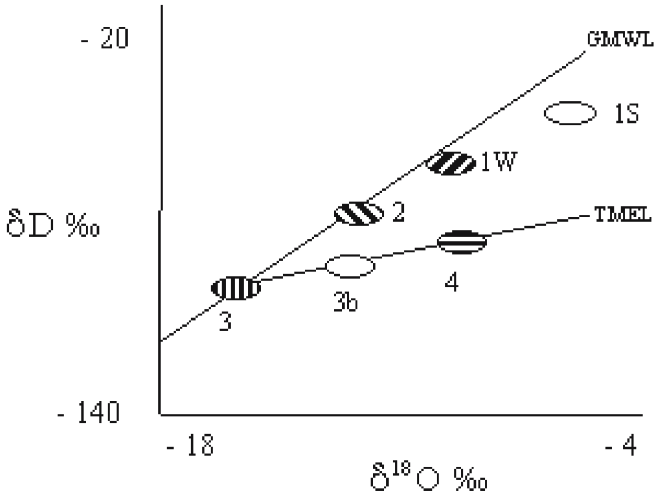

Fig. 8 Schematic δ^{18}O–δD plot showing the proposed fields of different groundwater types in Mohave Valley and other locations along the LCRV: *Field 1* modern precipitation (*1S* summer rain, *1W* winter rain); *field 2* ancient precipitation or fossil water; *field 3* "older" and upper basin river water; *field 3b* mixture of 3 and 4; *field 4* recent river water

Field 1. Local precipitation

Figure 8 depicts the fields of winter (1W) and summer (1S) precipitation in a Mohave Valley location. The actual plotting positions will vary with latitude and elevation. Since both winter and summer rain undergoes significant evaporation, their fields are offset slightly from the GMWL. 1W is significant because winter rainfall is generally the source of tributary recharge in the LCRV (Smith et al. 1992). Therefore, the isotopic make-up of waters from wells and springs away from influence of the Colorado River should have δ^{18}O–δD values that cluster near 1W. The age of tributary water can be readily indicated as pre- or post-bomb using the tritium content.

Field 2. Ancient local precipitation or "fossil water"

Smith et al. (1992) noted that the majority of southeastern California groundwater was considerably depleted in deuterium relative to the lightest (winter) precipitation. They hypothesize that such water most likely originated as late Pleistocene precipitation. Pleistocene- to Holocene-aged waters have been identified in other locations in the Southwestern USA (Davisson and Criss 1993; Phillips 1994). Groundwater with apparent ^{14}C ages of Pleistocene age in Sacramento Valley is depleted in ^{18}O by ~2‰ relative to the local mean precipitation values (Davisson and Criss 1995). In the LCRV, late Pleistocene river water was probably isotopically lighter than what is here designated as pre-bomb (probably pre-dam) river water, but we have no data confirming its presence in Mohave Valley. Nonetheless, this field represents a plausible water type.

Field 3. Upper basin river water (older river water)
Field 3 represents the relatively unevaporated upper basin river water entering the LCRB. Before control structures were emplaced (pre-1936), annual floods recharged the river aquifer system with waters of this kind. Groundwater that plots in field 3 and have a negligible tritium concentration are interpreted as older river water, possibly pre-dam. Field 3b represents a commonly observed mixture (e.g., Payne et al. 1979).

Field 4. Recent Lower Colorado River water
Field 4 represents evaporated recent river water from the LCRV. This field exhibits temporal and spatial variability. The evaporation trend has a slope of 5 to 6. As discussed above, most of the ground- and surface-waters in Mohave Valley, especially within the modern flood plain boundary, can be explained in terms of field 4 and in some cases field 3. Field 4 waters are expected to have tritium concentrations near 11 TU.

Conclusion

Stable hydrogen and oxygen isotopes and tritium can establish the origin of groundwater in the Lower Colorado River Valley (LCRV). Isotope data, especially when supported by geochemical and hydrologic data, can identify mainstream water and locally recharged (tributary) water. The unusual robustness of isotope data from the LCRV derives from the river basin's physical geography and modern hydraulic controls. The groundwater sources identified in this study — locally recharged rainfall (tributary water), "older" Colorado River water, and recent river water — concur with previous studies. Precise age determination of older river water and tributary water will require more complex analytical techniques. Mixtures of all groundwater types are common, but criteria can be established that estimate the percentages of various water sources in a sample.

Wells outside the flood plain probably represent a comparatively small consumptive use of river water, but the large number of well owners do represent a political force that might oppose the accounting surface method and leave a gap in river water accounting. Disagreements over water accounting have led to protracted legal battles between LCRB states. At a minimum, well owners will want to determine whether their well actually withdraws mainstream water. Without isotope data, the accounting surface falls short because it can only demonstrate the physical potential for water movement from the river towards the well. Conventional geochemical data are useful but rarely provide a direct indication of a water's source. Isotope data can and do resolve water resource disputes. In addition, long–term monitoring of isotope values in groundwater will signal basin-scale shifts in the boundary between tributary– and river–derived groundwater. Such information could be used to promote water conservation and resource planning in the rapidly growing river communities. The analytical costs and interpretive criteria need further evaluation. For now, though, isotope data appear to provide an alternative, or at the very least, a supplement to the hydraulic approach being proposed by the Bureau of Reclamation.

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