



Ground-water is the Ultimate Source of the Salt Creek Pupfish Habitat, Death Valley, U.S.A.

A.H. Jahren[★] & K. L. Sanford[†]

[★]*Department of Earth and Planetary Sciences, The Johns Hopkins University, Baltimore, MD 21218, U.S.A.*

[†]*Geology Department, Georgia State University, Atlanta, GA 30303, U.S.A.*

(Received 10 January 2001, accepted 18 October 2001)

We report $\delta^{18}\text{O}$ and δD stable isotope compositions of water collected at several sites in northern Death Valley, including the Salt Creek pupfish (*Cyprinodon salinus* M.) habitat in Mesquite Flat basin. Various theories exist concerning the source of water for Salt Creek, including snowmelt and precipitation, as well as contribution from ground-water. A comparison of Death Valley waters to the Global Meteoric Water Line indicated that none of the rain or snow samples are reasonable candidates for habitat source water; however, all of the ground-water sampled could serve as the source water for the progressively evaporating pupfish habitat sites.

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Keywords: Death Valley; pupfish; GMWL; deuterium; 18-oxygen

Introduction

Salt Creek pupfish (*Cyprinodon salinus*) are one of several distinct pupfish species that inhabit the Death Valley area, and whose existence is threatened by the disruption of the local hydrologic cycle. All Death Valley *Cyprinodon* species are formally listed by the U.S. Department of the Interior as either extinct, endangered, threatened or nominally stable as a result of protective measures. The Devil's Hole (*C. diabolis*) and Jackrabbit Spring (*Empetrichthys merriami*) pupfish provide sobering examples: the exclusive breeding ground of the *C. diabolis* is an exposed shelf of a ground-water spring in the Ash Meadows area of southwest Nevada. Because of intense mining of ground-water for agricultural purposes and the resultant drop in water-table levels in the 1960s, the numbers of Devil's Hole pupfish decreased by 50%, plunging their status to endangered species and resulting in the extinction of the nearby Jackrabbit Spring pupfish. Since this time, habitat protection provided by the Supreme Court water rights decision of 1976 (Deacon & Williams, 1991) has resulted in *Cyprinodon* repopulation of the area, with large populations of *C. nevadensis* present in Jackrabbit and Big Springs (Williams & Sada, 1985).

*Corresponding author.

Appropriately timed water availability is critical to the pupfishes' breeding and survival, despite the fact that the endemic pupfish are adapted to extreme conditions such as elevated temperatures, high salinities, and variable dissolved oxygen availability. In contrast to the Devil's Hole habitat, the source of water for the Salt Creek habitat is not clear: many theories exist concerning the source of water for the perennial Salt Creek, including snowmelt and precipitation for the mountainous areas of the northwest arm of Death Valley (Soltz & Naiman, 1978), or alternatively that the sloping Mesquite Flat intersects the ground-water table near Salt Creek Hills, allowing the ground-water to collect on the surface and form the creek pool (Hunt *et al.*, 1966). Because the source of water is not known, water use at the nearby facilities of the Furnace Creek Visitor Center, including maintenance of golf courses and swimming pools, poses an unknown threat to the Salt Creek pupfish. The Salt Creek pupfish are able to tolerate more extreme temperature variations than any other pupfish species (Miller, 1981) making them perhaps the most eurythermal and euryhaline fish species on earth. Their conservation is mandated for the preservation and study of their unique physiology, as well as for the maintenance of fish biodiversity in desiccated regions: studies of pupfish mitochondrial DNA have revealed only two divergent clades of pupfish, one of which has been isolated to the habitats of Death Valley (Echelle & Dowling, 1992). This study employed $\delta^{18}\text{O}$ and δD stable isotope analyses of water collected over an elevation gradient of 2800 m in the northern Death Valley in order to determine all potential sources of water in the Salt Creek pupfish habitat.

Study area

Death Valley National Monument, located in southeastern California, is well known as the hottest and driest location in the continental United States. Death Valley received an average annual rainfall of 5.95 cm between the years of 1961 and 1993 (Grasso, 1996). Death Valley is also well known for its elevation extremes: Telescope Peak resides at an elevation greater than 3353 m above sea level, whereas Badwater Basin is at 86 m below sea level, making it the lowest elevation in the United States. During the Pleistocene epoch, the two main structural basins of Death Valley were connected via overland water channels. Overflow of glacial lakes created a series of interconnected drainage pathways that eventually reached major waterways such as the Colorado and Columbia Rivers, which flowed into the Pacific Ocean (Soltz & Naiman, 1978). The Pleistocene interconnected system of lakes and rivers within Death Valley allowed aquatic organisms, including pupfishes, to freely move throughout the valley. The termination of the most recent pluvial period was marked by climatic warming to temperatures exhibited in this region today. As a result of this warming, many of the waterways and lakes throughout the Death Valley area evaporated and the remaining water became isolated habitats for those organisms that survived. Separation and isolation became a physical barrier to interbreeding, causing pupfish to evolve the distinct physiological and morphological characteristics observed today.

Salt Creek and its pupfish population are located in one of Death Valley's major drainage basins; the Salt Creek watershed drains an area approximately 5700 km² located in the north-west sector of Death Valley (Soltz & Naiman, 1978). Salt Creek channel is only approximately 1.52 m wide and approximately 9 cm deep, originating in Mesquite Flat, which slopes approximately 2.6 m/km⁻¹ towards the south. The Mesquite Flat basin is separated from the saltpan basin via the Salt Creek Hills, which are uplifted impermeable rock beds of Tertiary formation (Hunt *et al.*, 1966). Over time, Salt Creek has cut a waterway through the Salt Creek Hills to drain into the

Middle Basin. The source of water for Salt Creek is unknown, as discussed earlier, but must be either from the atmosphere in the form of precipitation, the ground via springs, or some combination of these.

During the winter, Salt Creek swells to its maximum volume and flows for 3–6 km along the Death Valley floor, allowing a large population of Salt Creek pupfish to migrate into this new addition to their habitat. Soltz & Naiman (1978) state that a minimal estimate of this springtime population of pupfish is close to 1 million. However, when summertime temperatures influence the area, the stream evaporates at its southern tip; by late summer flow in Salt Creek is restricted to approximately 1 km below its headwaters. The summer number of Salt Creek pupfish drops into the low thousands and those who survive this constriction live in an overcrowded habitat (Soltz & Naiman, 1978). Because the pupfishes' annual cycle involves such extreme changes in population, summer water shortages could easily impact the population and decrease already low numbers.

The Salt Creek pupfish is eurythermal and euryhaline (Minckley *et al.*, 1991), able to tolerate temperature conditions ranging from 0°C to 40°C (Miller, 1981) and chloride concentrations from 0.24% to 5.85 % (w/v) (Hunt *et al.*, 1966). Salt Creek experiences gradients of chloride concentrations and total dissolved solids (ranging from 0.6% to 13.0% (w/v)) from its headwaters south towards the saltpan (Hunt *et al.*, 1966). The Salt Creek pupfish populate the entirety of Salt Creek, demonstrating their tolerance of the entire observed range of conditions, making them the most tolerant of all pupfish species. It is the Salt Creek pupfish's extreme tolerance of environmental conditions that keeps it from being listed as an endangered species: *C. salinus* is considered stable but rare due to limited distribution (Minckley *et al.*, 1991). However, massive declines in population have been observed for most of Death Valley's pupfish species. Removal of ground-water has been directly linked to species endangerment and extinction, as discussed earlier. In order to ascertain the potential threat posed to Salt Creek pupfish populations by local water use, it is critical to understand the link between the ground-water reservoir and the surface Salt Creek Channel.

According to compiled USGS results (Planert & Williams, 1995) the ground-water for all of the Death Valley region is discharged from hydraulically linked carbonate rocks, resulting in a system that originates in Nevada and is continuous for approximately 403 km. The system diverges into two distinct pathways at Lincoln County, NV, with two-thirds of the water flowing towards Muddy River Springs (approximately 75 km NE of Las Vegas, NV) and one-third flowing towards Ash Meadows and Death Valley (approximately 110 km NW of Las Vegas, NV). Ground-water in Death Valley travels through basin-fill sediments and intersects the land surface in springs, such as those sampled at Furnace Creek on the east side of the Armargosa Mountain Range near Highway 190. The warm springs of this area are Nevares Spring, Texas Spring, and Travertine Spring and may connect to the ground-water system via the Furnace Creek fault zone located on the west side of Death Valley (north of Furnace Creek Wash and Highway 190). The discharge from Travertine Spring, which is sequestered for use in Furnace Creek Ranch's agricultural project, exhibits high concentrations of bicarbonate ions and is quite similar in chemical composition to the large warm springs in the Armargosa Desert, east of the Armargosa Mountain Range in western Nevada (Hunt *et al.*, 1966). This suggests that the source of the spring water in the Ash Meadows area also supplies the Furnace Creek springs. Therefore, if the Salt Creek pupfish habitat is supplied by water from the Furnace Creek spring system, pumping in Ash Meadows or Travertine Spring may affect water availability in the Salt Creek habitat.

It has been claimed that since precipitation cannot account for the discharge rates observed at springs in Death Valley, the springs must rely upon a ground-water source (Soltz & Naiman, 1978); for example, McLean Springs lies just north of Salt Creek

Hills, and might be considered a likely candidate for the source of Salt Creek. However, the major aquifer that underlies the entire Mohave Desert Area exhibits the mean residence time of as high as 22,000 years, as inferred from ^{14}C dating (Battey *et al.*, 1999), arguing against extensive surface discharge. Additionally, the large area of the Salt Creek drainage basin, the lack of intercepting vegetation, and the extreme elevation of local features within that basin suggest that precipitation and runoff might constitute an important contribution to the Salt Creek, particularly when wetter periods are required to promote dispersal and population mixing of pupfish (Dunham & Minkley, 1998). This study was designed to use the stable isotope value of local waters to assign potential contributors of water to the Salt Creek pupfish habitat.

Methods

Field methods

Water samples were taken at 13 sites in Death Valley, spanning an elevation gradient of 2800 m and including the Salt Creek pupfish habitat. The location of each sampling site is shown in Fig. 1 and listed with elevation in Table 1. All sampling was performed during December of 1996 in order to assess all potential sources of contribution to Salt Creek during its period of maximum volume. Field sampling was performed in duplicate or triplicate at each site (replicates are designated as 'A', 'B' or 'C'), with all replicates taken within a 10 m distance of one another in order to characterize field variability. Liquid water and snow from the sites were sampled into 20 ml borosilicate vials with minimal headspace and sealed with Teflon-coated caps. All samples were refrigerated prior to laboratory analysis in order to minimize isotopic exchange in any included headspace, and to prevent microbial growth. Elevation at each site was determined from location on USGS topographic maps with contour intervals of 200 ft and validated with a hand-held altimeter.

Sites 1–4 were located along the major pupfish habitat of Salt Creek, at an elevation of about 50 m below sea level. At the time of sampling the creek ranged from 1 to 4 m across, but never more than 0.5 m in depth. Abundant grasses and shrubs (especially *Eriogonum* sp.) were located at the water's edge, and the water was flowing slightly toward the south-east. No pupfish were observed in the habitat, which was expected because December is included in the winter period of dormancy. One of the sites (site 2) exhibited active gas percolation, but all Salt Creek sites exhibited clear water and temperatures comparable to ambient air conditions ($\sim 18^\circ\text{C}$).

Sites 5 and 6 were located on ground-water springs directly south of Salt Creek. Site 5 was Travertine Springs, ~ 60 m above sea level, near the Death Valley Ranger Station and Indian Village. The travertine spring exhibits elevated temperature ($\sim 21^\circ\text{C}$ at the time of sampling), and abundant vegetation, but no salt crystals or algal growth can be observed in the area. Site 6 was Tule Spring, near Badwater Basin, at the lowest elevation sampled, ~ 70 m below sea level. Water sampled from Tule Spring was lukewarm ($\sim 19^\circ\text{C}$) and stagnant, with an intense smell of hydrogen sulfide; nevertheless, water samples were free of algal matter and other detritus.

Site 7 was located at a ground-water seepage along a road-cut in Wildrose Ranger Station at ~ 1200 m above sea level. This sample probably incorporated collected snowmelt and precipitation runoff from local slopes, but may have an additional ground-water component. The place sampled was an actively flowing creek, about 20 cm wide, exhibiting extensive algal growth and no salt crystals; temperature of the water was comparable to ambient air conditions ($\sim 15^\circ\text{C}$).

Sites 8–13 were taken from snow accumulation along an elevation transect of Roger's Peak. Sites 8–12 represented sampling of early winter snow events, while

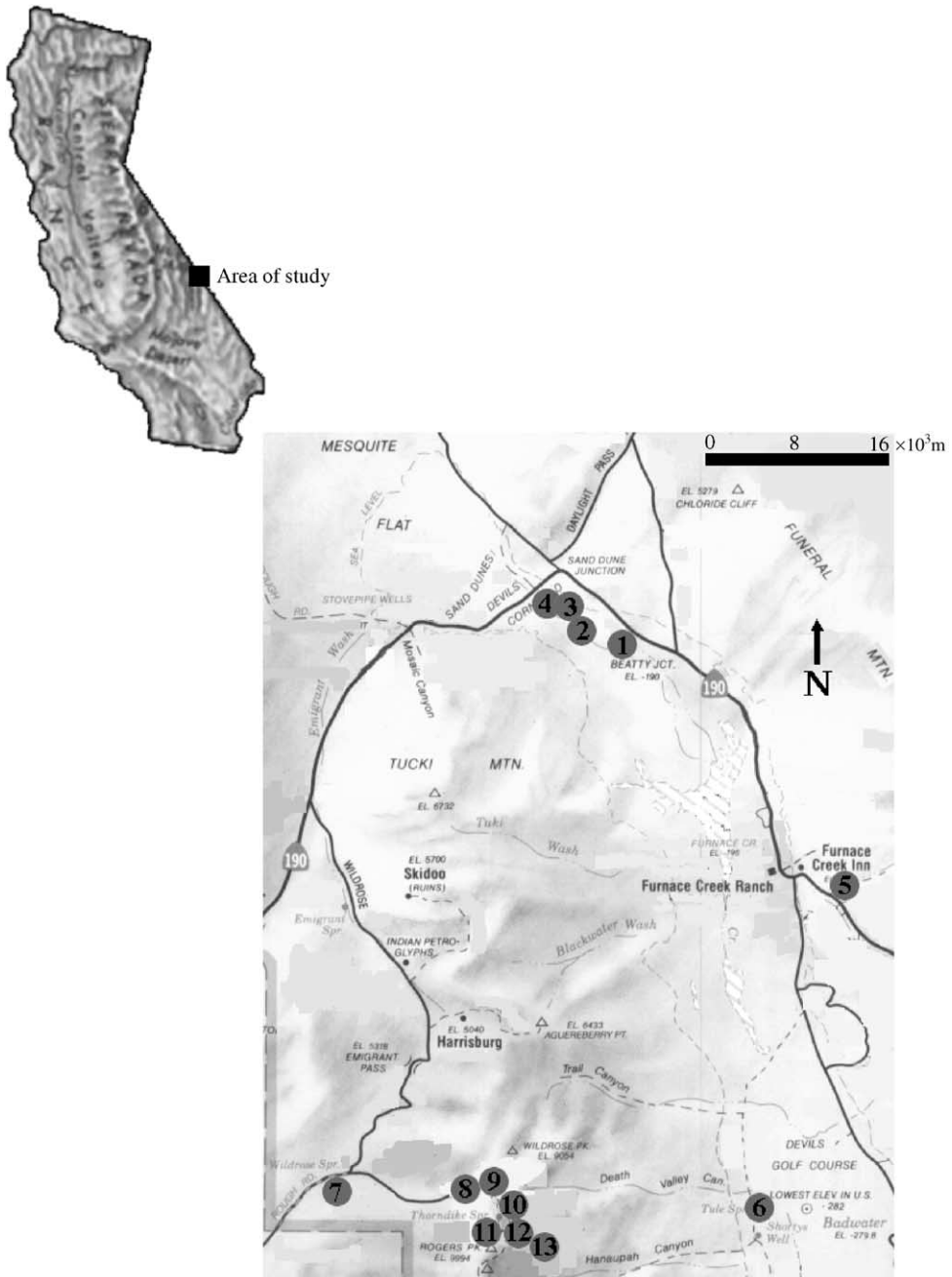


Figure 1. Map of the field area showing sampling sites. Numbered sites correspond to designations listed in Table 1.

sample 13 represented recent snow accumulation at the highest altitude site. Early winter snow accumulation was differentiated from recent accumulation at site 12/13 via the presence of a sublimation ice crust separating the two layers of accumulation. At no place in the Roger's Peak transect was snow accumulation greater than 50 cm.

Table 1. *Isotopic value of water from study sites*

Site number	Site description	Elevation (m)	$\delta^{18}\text{O}_{\text{VSMOW}}$ (‰) $\pm 0.1\text{‰}$	$\delta\text{D}_{\text{VSMOW}}$ (‰) $\pm 3.0\text{‰}$
1A	Pupfish Habitat I	-79	-9.4	-90
1B		-79	-9.6	-92
2A	Pupfish Habitat II	-61	-11.7	-99
2B		-61	-11.6	-100
2C		-61	-11.4	-99
3A	Pupfish Habitat III	-30	-12.1	-108
3B		-30	-11.8	-107
4A	Pupfish Habitat IV	-15	-12.6	-107
4B		-15	-12.2	-103
5A	Travertine Hot Spring	61	-13.6	-107
5B		61	-13.6	-105
5C		61	-13.3	-104
6A	Tule Spring	-70	-13.4	-105
6B		-70	-13.4	-103
7A	Wildrose Road	1219	-14.2	-111
7B	Runoff	1219	-14.2	-109
8A	Snow	1951	-10.6	-66
8B		1951	-10.4	-66
9A	Snow	2134	-9.5	-62
9B		2134	-10.1	-68
10A	Snow	2316	-10.4	-72
10B		2316	-10.6	-78
11A	Snow	2438	-10.1	-66
11B		2438	-10.1	-74
12A	Snow, profile bottom	2743	-10.9	-67
12B		2743	-10.3	-66
13A	Snow, profile top	2743	-13.9	-119
13B		2743	-14.8	-125

The sampling strategy described above was intended to incorporate water samples from all potential sources of input to the Salt Creek, and to include samples of the pupfish habitat. Sites 5 and 6 were collected in order to characterize potential ground-water input, while sites 7–13 were collected in order to characterize runoff from high elevation. A transect on Roger's Peak was sampled because of easy access to high elevations via roads and hiking paths. We acknowledge that the transect sampled drains toward the west, and not toward the pupfish habitat, but the eastern slope was not accessible during December of 1996. We believe that this is a minor impact on the study, since the entire field study is small in area (all sites are circumscribed by a circle of radius 50 km) the high elevations in question are not subject to differing storm inputs. In addition, water from several localities within the Salt Creek pupfish habitat (sites 1–4) were collected.

Laboratory methods

Liquid water samples were prepared for measurement of oxygen isotopic composition via equilibration with CO_2 of known composition and subsequent measurement of the

post-equilibration CO_2 (Epstein & Mayeda, 1953). Liquid water samples were prepared for measurement of the hydrogen isotopic composition by reacting $\sim 3 \mu\text{l}$ of water with purified Zn in an evacuated pyrex tube at 500°C to yield hydrogen gas (Coleman *et al.*, 1982). Measurement of stable isotope ratios was performed on a Micromass Optima stable isotope mass spectrometer.

All isotope values are reported in the delta notation:

$$\delta = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000(\text{‰})$$

where the standard is VSMOW for $R = {}^{18}\text{O}/{}^{16}\text{O}$ and D/H ; the precision associated with preparation of gases and measurement on the mass spectrometer is $\pm 0.1 \text{‰}$ for $\delta^{18}\text{O}$ values and $\pm 3.0 \text{‰}$ for δD values.

Results

It has been demonstrated by the analysis of a large number of meteoric waters collected across a broad range of latitudes that the $\delta^{18}\text{O}$ and the δD values of unevaporated surface water are linearly related according to the following relationship:

$$\delta D = 8(\delta^{18}\text{O}) + 10 \quad (\text{Craig, 1961}).$$

The only surface waters that do not plot upon this Global Meteoric Water Line (GMWL) are from closed basins undergoing progressive evaporation, leading to $\delta^{18}\text{O}$ and δD values that plot along an evaporation trajectory away from the source water (usually having slope approximately equal to 5). Evaporation also serves to decrease the *d-excess* value as defined by Dansgaard (1964)

$$d = \delta D - 8(\delta^{18}\text{O})$$

resulting in a decrease of the *y*-intercept value as the evaporation process differentially affects the *D* and ${}^{18}\text{O}$ isotopes in water.

The isotopic values of waters sampled in this study are listed in Table 1 and plotted against the GMWL in Fig. 2. Data generated by this study are supplemented with $\delta^{18}\text{O}$ and δD value determinations made on 6-month integrated precipitation samples taken at Death Valley during 1985 and 1986 and published as part of an extensive survey of the isotopic composition of precipitation in South-eastern California (Friedman *et al.*, 1992). With the exception of snow collected at sites 8–12, none of the waters sampled coincided with the GMWL, indicating that waters at sites 1–7, including the pupfish habitats, are subject to active evaporation. Deviation from the GMWL shown by winter precipitation is imparted by a kinetic effect during the formation of ice from supercooled water vapor (Jouzel & Merlivat, 1984).

According to the evaporation trajectory indicated by the isotopic composition of the pupfish habitats, none of the rain or snow samples are reasonable candidates for habitat source water. However, all of the ground-water samples, including the springs, could potentially serve as the source water for the progressively evaporating pupfish habitat sites. A best-fit linear regression through the $\delta^{18}\text{O}$ and δD value of the pupfish habitats, the springs, and the ground-water (sites 1–7 of this study) yielded the following relationship:

$$\delta D = 3.5(\delta^{18}\text{O}) - 59.5 \quad (R = 0.87; R^2 = 0.76)$$

with slope of similar magnitude to most observed evaporation trajectories. For example, Yang *et al.* (1997) have reported a slope = 3.62 for Badwater salt pan brines in Death Valley. The evaporation trajectory of pupfish habitats suggests that both the low elevation springs of Death Valley as well as the cumulative integrated high-elevation runoff (represented by site 7) serve as source water for the progressively evaporating pupfish habitats. Considering frequent park observations

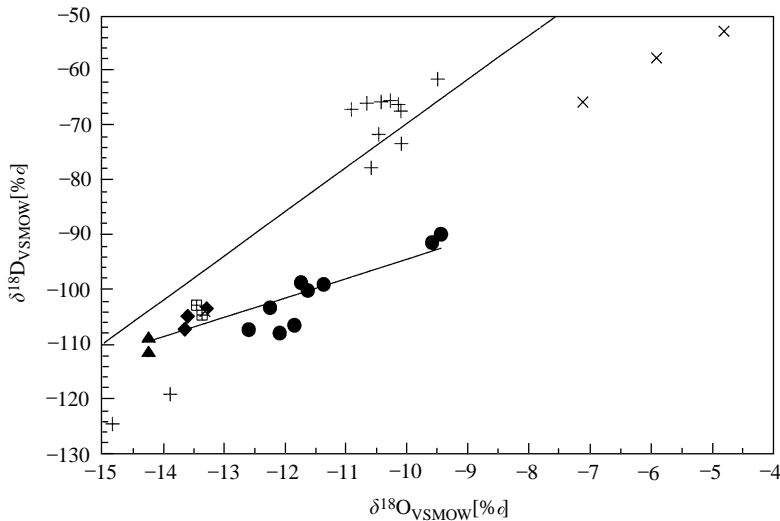


Figure 2. The isotopic values of waters sampled in this study plotted against the Global Meteoric Water Line (GMWL) and including a best-fit (sites 1–7) evaporation trajectory. (●) Pupfish Habitats (1–4); (◆) spring (site 5); (⊞) spring (site 6); (▲) ground-water (site 7); (+) snow (site 8–13); (—) $\delta D = 8\delta^{18}O + 10$ (MWL); (·) rain (Friedan, 1992); (—) $\delta D = 3.5\delta^{18}O - 59.5$ ($R = 0.87$).

regarding the sporadic and limited flow of runoff at site 7 and similar locations, low elevation springs must be considered as major inputs to the evaporating pupfish habitats.

Nonetheless, we wish to emphasize the important ecological role that very small amounts high-elevation runoff may play in maintaining the pupfish habitat. It has been shown that emigration during times of overpopulation serves regulate overall pupfish numbers, keep mortality low and promote overall health in the community (McMahon & Tash, 1988); emigration is only possible during brief precipitation periods that create connecting temporary waterways (Dunham & Minckley, 1998).

In order to further investigate the specific possibility of the Travertine spring system as a source water for the Salt Creek pupfish habitat, the *d-excess* values of sites 1–5 were plotted against site elevation in Fig. 3. The Travertine spring system intersects with the surface at an elevation of 60 m above sea level and is part of the Furnace Creek spring system, which connects Travertine springs to Texas, Salt, Stovepipe Wells and Triangle springs in Mesquite Flat to the north as well as connecting it to Tule and Ash Meadows springs to the south. The discharge from Travertine Spring is actively sequestered for use in Furnace Creek Ranch's agricultural project as well as for use at the Indian Village and Ranger Station of Death Valley National Monument.

Under the hypothesis that the Furnace Creek spring system serves as a source for the Salt Creek pupfish habitat, we envision spring discharge at relatively high altitude which then proceeds down the elevation gradient of the Salt Creek channel, as its *d-excess* value decreases due to progressive evaporation. The data presented in Fig. 3 bear out this relationship: *d-excess* values decrease by nearly 20‰ down an elevation gradient of 140 m from Travertine springs sampling site through the pupfish habitats. For comparison, evaporation from the Great Lakes (calculated to comprise between 4.6% and –15.7% of the downwind atmospheric water content) has been observed to result in a *d-excess* value decrease of 3–4‰ in the Lakes relative to other surface water (Gat *et al.*, 1994), indicating that the Salt Creek pupfish habitat is extensively evaporated compared to other fish habitats in North America.

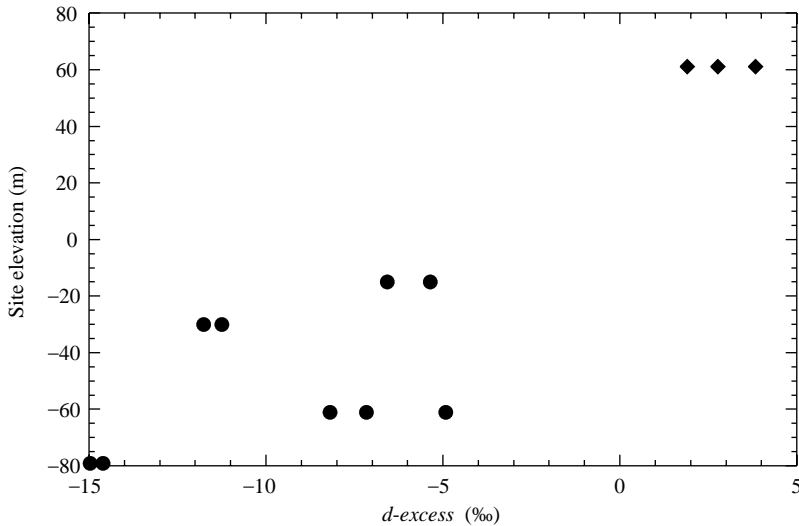


Figure 3. *d-excess* values of sites 1–5 plotted against site elevation. (●) Pupfish Habitats (1–4); (◆) Spring (site 5).

Discussion

This study reveals the Furnace Creek spring system as the most likely source of water in the Salt Creek pupfish habitat, and further indicates that this source is extensively evaporated to a subvolume of its initial contribution. These results also imply that accession of Furnace Creek spring water for various Death Valley National Monument uses poses a threat to the Salt Creek pupfish in reducing the source water for this habitat. At present, the Furnace Creek Springs provides the vast majority of water used for park facilities: 1.4 million gallons per day are taken from this spring system in order to maintain an 18-hole golf course, the park's Visitor Center and campgrounds, as well as the Timbisha Indian Community (Black & Veatch, Consulting Engineers, 2000). As part of the Energy Policy Act of 1992 which requires that Federal agencies reduce energy consumption, a published recommendation has been made to Death Valley National Park to reduce annual water consumption by 6% (EPA, 2000). Since Furnace Creek contributions represent more than 80% of the total fresh water productions in Death Valley National Monument, there are no circumstances in which this recommendation could result in a substantial (i.e. more than 5%) reduction in water removal from Furnace Creek Springs. A long-term study (1972–1997) of the Devils Hole pupfish (*C. diabolis*) population size in Ash Meadows showed that annual maximum population size is positively correlated with water volume of the immediate habitat: populations were seen to increase by 100% in response to a 10 cm change in water level, and this effect persisted many years after crisis recovery (Andersen & Deacon, 2001). This would suggest that a 5% increase in the Furnace Creek reservoir would not dramatically increase Salt Creek pupfish populations, and consideration of more stringent measures is warranted to save this vulnerable population with low genetic diversity from extinction (Duvernell & Turner, 2001). Other efforts to conserve the pupfish habitat have centered around building a boardwalk over Salt Creek in order to restrict the impact of hikers and fish-watchers; this study suggests that curtailment of Furnace Creek spring system pumping and access is warranted as well.

We are grateful to H.A. Loaiciga for bringing the pupfish habitat to our attention and for field assistance during December of 1996; and to W.M. Hagopian for laboratory assistance. S. Butterworth and the National Park Service were helpful in directing us toward water-use statistics for Death Valley National Monument. F.J. Longstaffe, G.K. Meffe, J.P. Montoya and G. Mora provided useful comments on an early version of this manuscript, as did two anonymous reviewers.

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