



REPORT

Informing future management decisions by comparison of the largest freshwater spring in the southeastern Mojave Desert with groundwater quality from downgradient wells, Mojave Trails National Monument, USA

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Abstract

Springs are one of the most vital components of desert ecosystems and an essential element in the cultural traditions and heritage of indigenous peoples. Bonanza Spring on the flank of the Clipper Mountains is the largest freshwater spring in the Eastern Mojave Desert, California, USA and lies in the Mojave Trails National Monument. Like many isolated springs in the arid southwestern United States, it can be vulnerable to changes in climate, vegetative changes (particularly those associated with the encroachment of non-native species), and lowering of local piezometric surfaces due to groundwater extraction and pumping wells. There are proposals to export groundwater from this area to urban and suburban areas in southern California, making the potential relationship and hydrogeologic connectivity between Bonanza Spring and agricultural (Cadiz) irrigation wells a resource management concern. In this study, the similarity or dissimilarity of the chemistry and physical properties of groundwater issuing from Bonanza Spring versus Cadiz agricultural wells in the lower Fenner Watershed and Bristol/Cadiz Basin, located over 22 km (13.7 miles) to the southwest and approximately 400 m (1,315 feet) lower in elevation, is considered through a series of concurrent sampling and analysis of groundwater chemistry and isotopic content. Specifically, spring and well water in the Cadiz agricultural area were sampled and analyzed for over a year's time, also involving evaluation of aqueous physical properties and related biological attributes in the spring ecosystem. Dissimilarities in water quality were found between spring and well waters, suggesting no or poor hydraulic connection between the two.

Keywords Desert springs · Water quality · Mojave Desert USA · Trace elements · Stable isotopes

Introduction

The long-term sustainability of desert springs is a topic of great interest in the scientific community. In this study, possible connections between groundwaters from a major desert spring and an agricultural well field were examined by using chemical and isotopic indicators. Springs are one of the most vital parts of a desert ecosystem and an essential element in Native American cultural traditions and heritage in the southwestern United States (Greeley 2017; Kreamer

et al. 2015; Stevens and Meretsky 2008; Rea 2008). The long-term sustainability of these springs can be impacted by several factors including: climate change, geological changes that would change subsurface hydraulic conductivity, vegetative changes particularly those associated with the encroachment of non-native species, and lowering of local piezometric surfaces due to groundwater extraction and pumping wells (Parker et al. 2021; Danielopol et al. 2003; Shepard 1993). Desert springs have been key to human evolution, migration, and dispersal (Cuthbert et al. 2017) and are of critical importance to the groundwater dependent ecosystems (GDEs) they support (Stevens et al. 2021; Springer et al. 2008). Water sources in desert environments are characteristically far apart and therefore springs often serve as refugia for a diversity of species (Kreamer et al. 2024). The chemistry of springs and well-water has often been used to determine the ability of groundwater to support local

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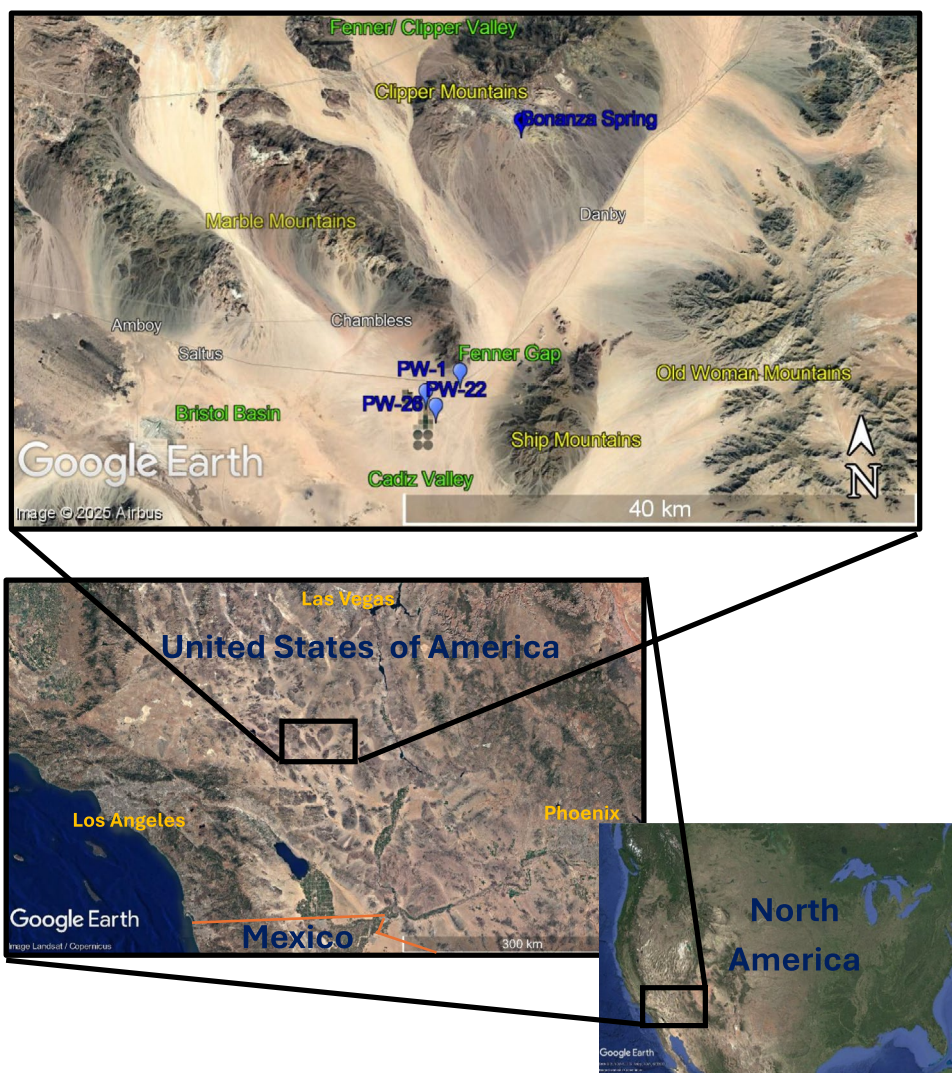
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vegetative and animal communities, and to evaluate suitability for irrigated agricultural and industrial use (Masoud et al. 2022). In order to understand spring sustainability, groundwater chemistry and isotopic values have been used to ascertain hydrogeologic connectivity of aquifer systems, as hydrologic tracers to help determine groundwater flow paths and average subsurface residence times, recharge locations and elevations, and the overall vulnerability of springs to groundwater diminishment (Johannesson et al. 1997, 1996; Davisson et al. 1999; Asante et al. 2018; Cantonati et al. 2020; Cook 2020).

The largest spring in the eastern Mojave Desert, Bonanza Spring, is located at latitude 34.68° and longitude -115.40° , approximately 18.9 km (11.75 miles) northeast of Chambless, California in the eastern Mojave Desert (Fig. 1). The spring is 648 m above mean sea level or MAMSL (2,125 ft above mean sea level or FASL) and is located on the southwestern flank of the Clipper Mountains, which rise to 1,410 MAMSL (4625 FASL). The Clipper Mountains and

Bonanza Spring are within the federally protected Mojave Trails National Monument under the administration of the U.S. Bureau of Land Management (BLM) in San Bernardino County, California, USA. It is one of the few natural water sources in the area and has historical value to local Native American culture (BLM 2024a). Early reconnaissance of the area was done by the U.S. Geological Survey (Mendenhall 1909; Thompson 1921, 1929). In more recent decades much more attention and extensive field work has been done on the hydrogeology and geology in the Clipper Mountains and surrounding areas, much of it associated with the potential for future water development (Moyle 1967; Freiwald 1984; Sass et al. 1994; Davisson 2000; Davisson and Rose 2000; Metropolitan Water District of Southern California 2001; Theodore 2007; CH2M Hill 2011; Santa Margarita Water District 2012; Andy Zdon and Associates Inc. 2016; Kenney and Foreman 2018a; Zdon et al. 2018; Love and Zdon 2018; Parker et al. 2021). Management and use of water in this fragile desert ecosystem is of great importance and is a topic

Fig. 1 Field study area. Location of Bonanza Spring and Cadiz agricultural area with associated production wells PW-1, PW-22 and PW-26



of great discussion (James 2018). A wide variety of groups are participating in this discussion, such as the U.S. Bureau of Land Management, local Native American tribes, several environmental groups, the California State Legislature (under Senate Bill 307, 2019), and several public and private southern California municipal water suppliers.

There is some controversy as to whether pumping wells south of the Clipper Mountains near the Cadiz farming area could affect spring discharge at Bonanza. There are proposals to export groundwater from this area to urban and suburban areas in southern California, making the potential relationship and hydrogeologic connectivity between Bonanza Spring and agricultural (Cadiz) irrigation wells, a resource management concern. The Cadiz agricultural area is 22 km (13.7 miles) to the south southwest of the spring, at approximately 240 MAMSL (785 FASL), or approximately 400 m (1,315 ft) lower than the spring, with irrigation wells supporting the growth of crops in the Bristol/Cadiz Basin, California. The water table below the Cadiz pumping wells is located even lower in elevation below ground surface. The Cadiz agricultural area contains the nearest active pumping wells, with significant discharge, in the vicinity of Bonanza Spring. It has been hypothesized that groundwater issuing from Bonanza Spring is hydraulically connected to the alluvial, basin-fill, Fenner Valley aquifer north of the Clipper Mountains, but importantly, also to much lower elevations in the Fenner Watershed to the south where the Cadiz farming area is located (Zdon et al. 2018; Love and Zdon 2018). These authors who hypothesize this connection acknowledge the possibility that some of the discharge at the spring comes from higher elevations to the north and long groundwater pathways through the Clipper Mountains. However, these authors also opine that increased groundwater development near the pumping irrigation wells below might influence discharge at the significantly higher Bonanza Spring through a hydrogeologic connection between the two. They state, *“Future groundwater development in the region, should it occur, should be cognizant of the likelihood of a hydraulic connection between the recharge area for Fenner Valley, and Fenner Valley itself with Bonanza Spring”*. The authors further assert, *“Bonanza Spring water temperature is indicative of waters that have been at depths of greater than 750 feet below the spring vent and risen to groundwater surface despite being in such a small catchment.”* This last observation is based on the authors’ reporting a temperature of 27.5 °C (or 81.5°F) for the water at Bonanza Spring (Zdon et al. 2018). The authors’ main reasons for this connection hypothesis are three-fold. They propose: 1. that upgradient water supply from a small, immediately upgradient watershed is not adequate to account for spring discharge and recharge from the immediately higher Clipper Mountains is unlikely, 2. that water temperatures that issue from the spring indicate geothermal upwelling from depth below the

spring, and 3. that a hypothetical, large cone of depression or reduction in hydraulic head that might be created by future groundwater extraction in the area and could possibly impact Bonanza Spring.

Counter-arguments to this hypothesis of hydrogeologic connection exist. The assumption of Zdon et al. (2018), that the Clipper Mountain upgradient source of water to Bonanza would be a small watershed recharge area immediately above and on the flanks of the mountain, is challenged by the mapping of fault systems that extend from the spring up into the higher Clipper Mountain elevations above the spring (Kenney and Foreman 2018b). The most relevant structural fracture zones include deformation by a prominent junction of two faults at Bonanza Spring; one northwest trending fault truncated by another northeast trending fault (Brown et al. 2019). This implies the possibility of a much larger recharge area. Greater precipitation amounts are common at higher elevations in desert areas due to orographic lifting, and the potential for recharge and transport along fault and fracture systems is a potential subsurface flow path, common to many other desert springs. Elevated spring water temperatures can also be associated with groundwater flow along faults, and the Eastern Mojave Desert is particularly known to have a geothermal gradient anomaly (Sass et al. 1994). The contention that there is a geothermal source for Bonanza Spring water also conflicts with additional water temperature data reported for Bonanza Spring with a value of 14.2 °C (57.6°F) (Andy Zdon and Associates Inc 2016). This lower, measured spring water temperature documented by Andy Zdon and Associates Inc. (2016) is less than the yearly average air temperature calculated by Zdon et al. (2018) at 21.0 °C (69.8°F) and is different than the spring water temperature reported by Rose (2017). Lastly, downgradient groundwater extraction would need to reduce hydraulic head with a very large radius of influence to impact the spring.

One major goal of this research was to investigate the similarity or dissimilarity of the chemistry and physical properties of groundwater in Bonanza Spring versus Cadiz wells in the lower Fenner Watershed and Bristol/Cadiz Basin below and to the south. This was done through a series of concurrent sampling and analysis of groundwater chemistry and isotopic content issuing from the spring, and well waters that are both topographically and hydraulically downgradient. The comparison is meant to provide several lines of evidence that would be supportive or contradictory to the premise of Bonanza Spring’s groundwater connection to deeper, lower elevation wells in the Cadiz agricultural area.

Site description

Bonanza Spring lies in the Clipper Mountain Wilderness managed by the U.S. Bureau of Land Management and is part of the Mojave Trails National Monument. This

wilderness has small, isolated springs in mountainous terrain, lenticular mesas, and thin dispersed vegetation in valleys and on alluvial fans. The most prominent peak in a cluster of northeast to southwest trending volcanic mountains is Clipper Peak, bounded by a southerly escarpment. Wildlife in the Clipper Mountains is very dependent on limited sources of water. These animals include bighorn sheep, coyote, ground squirrels, jackrabbits, roadrunners, several species of rodents, varieties of snakes, lizards and other reptiles, and many species of birds including hawks, eagles, falcons, chukar and quail. (BLM 2024b). The area is designated as Critical Habitat for the Desert Tortoise populations, protected under the U.S. Endangered Species Act, Nevada Administrative Code (NAC 50.080), and California Fish and Game Code, Division 5, Protected Reptiles and Amphibians, Article 1. Desert Tortoises (5000–5002).

The climate of the Mojave Desert is generally considered Koppen Class BWk: hot in the summer and cool in the winter, similar to the Chihuahuan Desert to the southeast. It has relatively cooler, higher desert elevations compared with the lower, warmer Sonoran Desert, and a different climate compared to other cold-temperate locations in the Great Basin. The nearest town to Bonanza Spring and Cadiz is Chambless CA, with the average summer high temperature at 36.7 °C (98.1°F) occurring in July. In winter, the average high in December is 13.6 °C (56.5°F) and the average low is 5.8 °C (42.4°F). Like most dry desert climates, the Mojave experiences large diurnal temperature changes. Annual rainfall in Chambless is 113 mm (4.45 in) over an average of 42.3 days (Weather.us.com 2024). The Mojave is the driest desert in North America, and climate change has already increased temperatures in the region over the last decades. The U.S. Geological Survey (Hereford et al. 2005) states, “Recent trends in Mojave Desert precipitation and the Pacific Decadal Oscillation (PDO) suggest that climate of the region may become drier for the next 2 to 3 decades in a pattern that could resemble the mid-twentieth century dry conditions.”

Bonanza Spring is on the southwest flank of the Clipper Mountains, which rise to the north in a series of shallow Tertiary igneous intrusive rocks. These rocks contain many faults, joints and fractures (Kenney and Foreman 2018a; Theodore 2007; Miller et al. 2007) and are underlain by Jurassic thrusting of Precambrian basement over Paleozoic strata. According to Howard et al. (1995) these deeper rocks, represent a plutonic intrusion in a thrust zone at the eastern edge of the Cordilleran Jurassic magmatic arc. Topographically downgradient and south of the spring the surficial geology is a pediment plain of Quaternary alluvial sediments. Compositional data of rocks from the Clipper Mountains were collected and reported by Howard et al. (2005). Bonanza Spring itself appears to have experienced a declining water table through the years. The spring discharge was recorded at about 1.3 m³/min (≈10 gallons per minute)

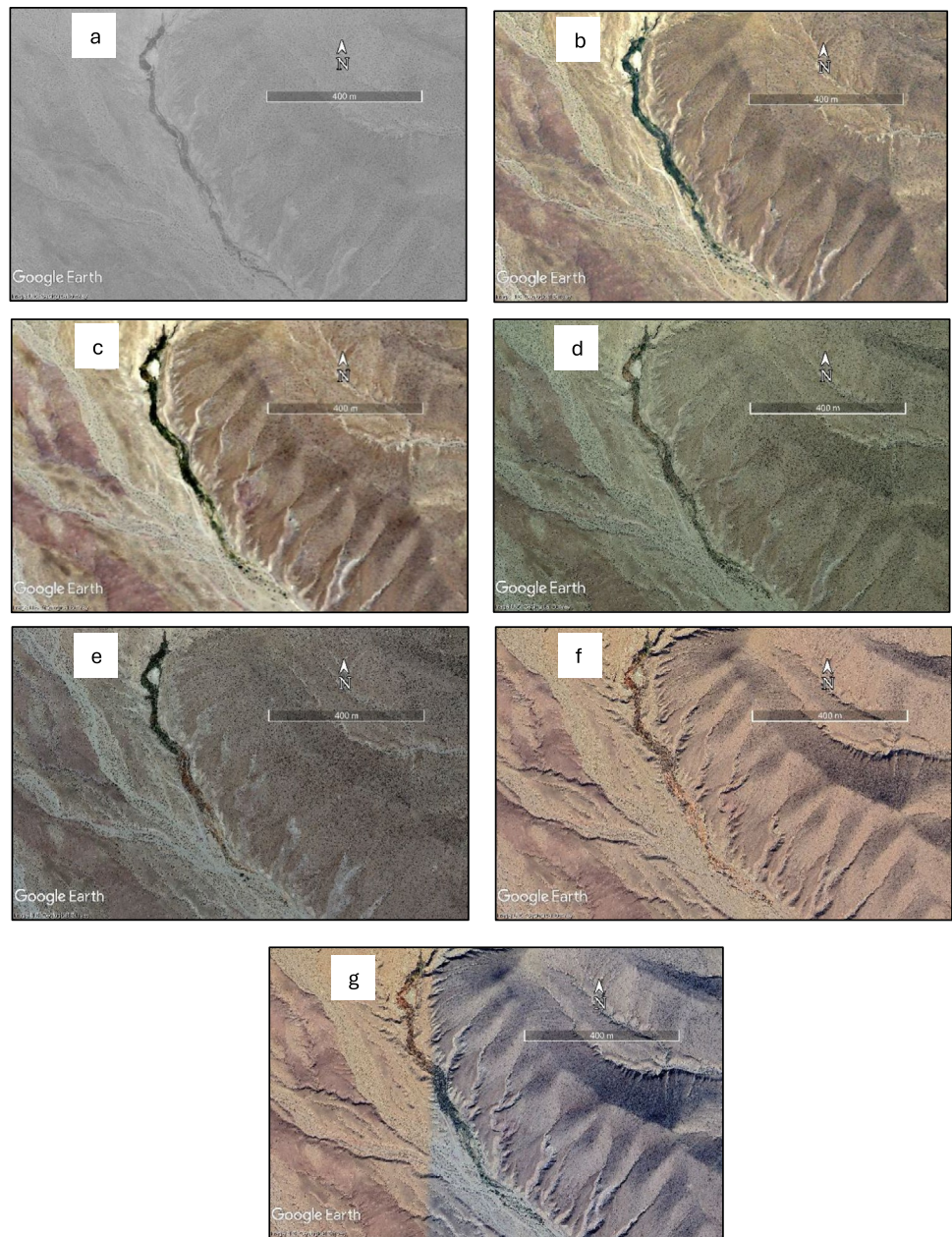
almost 100 years ago and was piped to the small, railroad town of Danby (Thompson 1929), which is approximately twice the flow observed today. The orifice for the spring has lowered in elevation over the years, issuing in 1860 to approximately the 1950s at an elevation of 657 MAMSL (2155 FASL) and decreasing to 648 MAMSL (2125 FASL) from the 1960’s to the present. In March of 2023, the spring orifice collapsed likely due to exceptionally strong storm events, drying up flow at the spring’s uppermost point.

Materials and methods

Between 2022 and 2023, 13 months of sampling were conducted at Bonanza Spring and surrounding wells in the Eastern Mojave Desert. This involved evaluation of aqueous physical properties, chemical characteristics, and related biological attributes. Sampling was monthly over the course of a year, along with a high-frequency, 24-h sampling event. The production wells sampled at Cadiz included PW-1, PW-22 and PW-26, 27N, 27S, 33 and 35 contingent on availability of any particular well, because sampling could only be carried out when pumps were active during scheduled irrigation. These wells were selected due to their geographic proximity to the spring. All Cadiz production wells are in an approximately 2,500 hectare (6178 acre) area. Eventually the number of wells to be sampled monthly was narrowed down due to fewer wells being used for irrigation. The location of the production wells is in the Cadiz Basin, which has an upper aquifer of sands and gravel up to 185 m (600 ft) thick of Quaternary age, underlain by discontinuous clay and silt strata. A deeper, lower permeability aquifer of late Tertiary age contains more fine material than the upper aquifer and can reach a thickness of 550 m (1,800 ft) near the town of Danby (California Department of Water Resources 1967; Metropolitan Water District of Southern California 2001; Brown et al. 2019). The 12 wells in the Cadiz Project have a total capacity of 44.4 million m³ (36,000 acre-ft) per year and typically reach groundwater at approximately 90 m (300 ft) depth, although some wells are as deep as 600 m (2000 ft) (Cadiz 2022). Project data and field photographs are provided in the electronic supplementary material (ESM).

Past Google satellite imagery was reviewed for an initial assessment of vegetative changes at Bonanza Spring and the Clipper Mountains. Figure 2 shows several selected Google Earth Aerial images from the National Agriculture Imagery Program (NAIP) that were used to measure the extent of the riparian zone – the vegetated area around the spring supported by spring water – and to determine the normalized difference vegetation index (NDVI). The NAIP dataset began in 2003 on a five-year cycle before switching to a three-year cycle in 2008. The images were collected by plane at a consistent altitude during the growing season. NAIP

Fig. 2 Satellite imagery of Bonanza Spring. The spring issues at northernmost point and flows southward until it disappears, coincident with the loss of vegetation. **(a)** represents imagery from September 1995, **(b)** December of 2005, **(c)** June 2009, **(d)** March 2014, **(e)** August 2019, **(f)** December 2022, and **(g)** December 2023



photography has data in four spectral bands, and data for Bonanza Spring is available for the years 2005, 2009, 2010, 2012, 2014, 2016, 2018, and 2020. All images were from spring or early summer, from April 25th to June 30th.

The influence of antecedent rainfall on water chemistry in Bonanza Spring was examined to indicate long or short flow paths and the impact of surficial geology, with short flow paths being prevalent when samples show high variability following rainstorms. For this analysis, total rainfall data from the Mid Hills weather stations in the Mojave National Preserve at 35.12317° N, 115.41131° W, with an elevation of 1635.3 m (5365.0 ft), for both the weeks and the months prior to sampling, were used to compare total antecedent

precipitation with chemical concentrations in Bonanza Spring.

Temperature and precipitation data from the nearest weather stations: Mid Hills, Ox Ranch, Amboy Saltus 1 and 2, Mitchell Caverns, the Clipper Mountains, and the Cadiz Valley were compiled. Precipitation data was available for all of these sites, and Table 1 below summarizes the date range for relevant weather and climate parameters available for the sites. The table also shows whether stable isotope data were collected in the precipitation. The Clipper Mountain weather data is derived from precipitation samplers that were checked twice yearly to measure winter and summer rainfall totals and the isotopic composition of these seasonal

Table 1 Weather station data availability in the vicinity of the study area, with information on the collection of stable isotopes of rainwater

Summary of data availability from nearby weather stations					
Station	Latitude	Longitude	Precipitation date range	Temperature date range	Precipitation isotopes
Amboy 1	34.53	−115.70	1966–1981	1972–1993	No
Amboy 2	34.48	−115.74	1972–1993	1972–1993	Yes
Cadiz Valley	34.52	−115.52	2011–present	2011–present	No
Clipper Mountans	36.69	−115.41	2001–2005	None	Yes
Mid Hills	34.56	−115.53	1958–present	1958–present	Yes
Mitchell Caverns	34.93	−115.51	1958–2011	1958–2011	Yes
Ox Ranch	35.20	−115.20	2013–2022	2013–2022	No

rains (Rose 2017). The Amboy Saltus 1 and 2 weather stations, operated from 1966–1989 and 1972–1993, have precipitation and temperature measurements that are included in our compiled dataset (Friedmann et al. 1992). The two Amboy weather stations are separated by 50 m in elevation, and these data show some variation precipitation totals.

Water quality parameters measured in the field were pH, dissolved oxygen (DO), temperature, alkalinity, and electrical conductivity (EC). Field devices were an ItelliCAL pH/temperature meter, a Hach HQ series pH/DO/EC/temperature meter, a CDC401 EC/temperature meter, and a Hach AL-DT 00637–00 alkalinity digital titration field lab. Additional quick field analysis was made with a Hach DREL Complete Water Quality Lab and Meter kit with a DR1900 colorimeter.

Water types are often characterized by major ions in aqueous solutions, and their concentrations can serve to identify the source aquifers of groundwater samples (Yingzhi Li et al. 2020; Sudaryanto and Naili 2018; Vu et al. 2022). Samples of major ions were made with all sampling runs and were analyzed by both ion chromatography (IC) and inductively coupled plasma mass spectrometry (ICP-MS).

Trace elements in groundwater were used to indicate waters of Like or dissimilar provenance. Same-day water samples for trace elements were collected at both Bonanza Spring and Cadiz wells throughout 2022 and early 2023 according to EPA Method 1669. Samples were stored in acid-washed HDPE bottles using the clean hands/dirty hands method following collection in a syringe and filtration through a 45-micron filter in the field (US EPA 2004). After collection, samples were stored on ice within 15 min and taken to the UNLV Las Vegas Isotope Science clean lab for acidification with ultra-pure nitric acid on the same day. Analysis was performed by the UNR Core Analytical Laboratory on a Shimadzu 2030 ICP-MS in kinetic energy discrimination mode. This instrument uses a hydride generator to remove interferences associated with the measurement of arsenic and antimony, two common contaminants of concern.

Principal component analysis (PCA) was applied to the data set. PCA is a multivariate statistical technique that uses dimension reduction to identify and group water samples that have comparable aqueous parameters. PCA can reduce data from n variables to represent the ensemble of similar aqueous concentrations typically in a 2- or 3-dimensional plot. It can also identify dissolved aqueous compounds that are similar or dissimilar in different water samples (Kreamer et al. 1996). Preceding PCA analysis, this method first normalized the data and centered it around 0, preventing major ions from dominating the variance and easing the graphical interpretation (Wilson et al. 2022). Covariance of each parameter with the other parameters was then determined, and a covariance matrix generated. For elements or compounds in the data set with low concentration below the detection limits of analytical chemistry instruments, an alternative to reducing the data set is typically used. Synthetic, non-zero, low concentration data can be simulated, although the way a value for a non-detected compound is simulated varies based on concentrations for that compound in other groundwater sample locations in the complete data set (Farnham et al. 2002). The graphical representations for this study used one of those techniques by assigning concentrations that are half the detection limit for compounds that were originally non-detects. This procedure simulates low aqueous concentrations, while allowing comparison through PCA analysis.

The parameters used for the PCA analysis were As, Ba, Ca, Ce, Dy, Er, Eu, Fe, Gd, Ho, K, La, Mg, Na, Nd, Pb, Pr, Sb, Se, Sm, Tb, Th, Tm, U, Yn, δD and $\delta^{18}O$. The sites analyzed include Bonanza Spring, and Cadiz wells 21 N, 26, 27S, 33 and 35. Input parameters for the spring and well concentrations were the yearly average value for each individual element or parameter. This was done at each site for all measurements for each individual parameter, since strong seasonality was not observed. Analysis was completed using the R programming language's *prcomp* library, and *ggplot* was used for plotting (R Core Team 2018).

Stable isotopes of hydrogen and oxygen were collected monthly for both Cadiz wells and Bonanza Spring, and also at the spring over a 24-h sampling period in October of 2022. The month of October was chosen as a 24-h sampling period to avoid any near-surface evapotranspirative effects of summer heat, or the dilutive effect of higher winter precipitation. Samples were unfiltered and collected in both acid-washed 60 ml HDPE plastic bottles and 40 ml glass vials with no headspace and chilled storage. Analysis was done at the University of Nevada, Las Vegas, Las Vegas Isotope Science Lab (LVIS) with light stable isotope ratio mass spectrometer (IRMS) and peripheral devices. For $\delta^{18}\text{O}$ and δD analyses of water and solids, the lab uses a ThermoElectron Thermal Conversion Elemental Analyzer (TC/EA) operating in continuous flow mode with a He carrier gas. The TC/EA uses a CTC Analytics GC PAL A200S autosampler for sample injections and has been modified with a bottom-feed Helium flow to improve analytical precision. The error range of values for δD and $\delta^{18}\text{O}$ were 1.8 and 0.17‰, respectively. The isotopic data were compared with the Global Meteoric Water Line (GMWL) and a local meteoric water line (Lachniet et al. 2020). The isotopic values were also compared with previously measured values in precipitation by Lawrence Livermore National Laboratories, (LLNL) (Rose 2017).

Results

Past vegetation extent

Accurate measures of the extent and health of the desert spring riparian zones can aid in the identification of changes in the riparian vegetation, and in the case of Bonanza Spring most notably the invasive reed *Arundo donax*. However, no trends for specific species were observed over the time-frame images were available, and results proved inconclusive. From historical aerial observations, flora associated with the spring varied both seasonally and annually, with no discernable correlation with antecedent weather conditions and no observable trends. NDVI is a measure of plant photosynthetic greenness and an indicator of photosynthetic

activity, and allows identification of riparian zones and can be used as a secondary indicator of spring health. Figure 3 shows one example of the NDVI and a false color image for Bonanza Spring for 27 April 2012, with the riparian zone active at that time. Greens represent differences between red and infrared light reflected by a plant, suggesting photosynthetically active plants. The image in Fig. 3 shows green pixels along much of the Bonanza wash. This image was chosen because it indicates dry soil surrounding the spring and therefore does not appear to be influenced by any recent precipitation event.

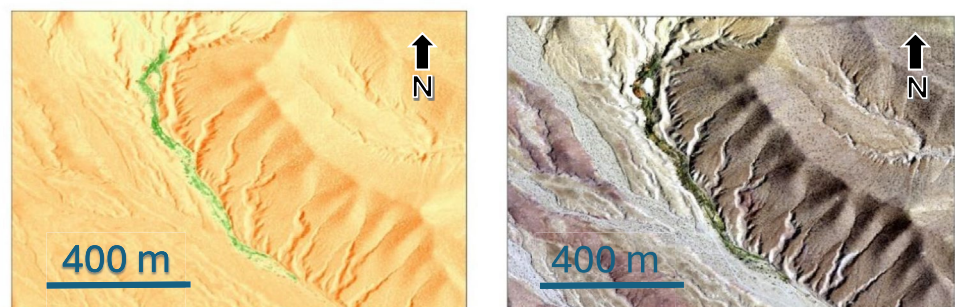
Correlation analyses for elemental spring water concentrations versus antecedent rainfall

Chemical concentrations in Bonanza Spring were compared against antecedent rainfall. There are no strong correlations ($R^2 > 0.50$), but the monthly antecedent rain data shows a slightly stronger positive correlation with aluminum and arsenic. This analysis used the most recent rainfall data available from the Mid Hills weather station from September 2018 – March 2022. Figure 3a below shows the concentrations of the most variable trace metals in the data set versus the total rainfall for the week prior to sampling, and Fig. 4b shows the concentrations of the most variable trace metals in the data set versus the total cumulative rainfall for month prior to sampling.

Ranges of physical and chemical parameters measured in the field

For Bonanza Spring, field parameters showed some variability: electrical conductivity varied between 571–690 $\mu\text{S}/\text{cm}$, temperature ranged from 27.3°–30.1 °C, alkalinity ranged between 147–199 mg/L as CaCO_3 , and pH varied between 7.12–8.04. Cadiz production wells exhibited some variation also: electrical conductivity varied between 413–612 $\mu\text{S}/\text{cm}$, temperature in degrees Celsius differed from 23.3–31.3 °C, alkalinity ranged between 100–175 mg/L as CaCO_3 , and pH varied between 7.14–7.78.

Fig. 3 Examples of NDVI (left) measured around Bonanza Spring and false color image (right). NAIP 27 April 2012



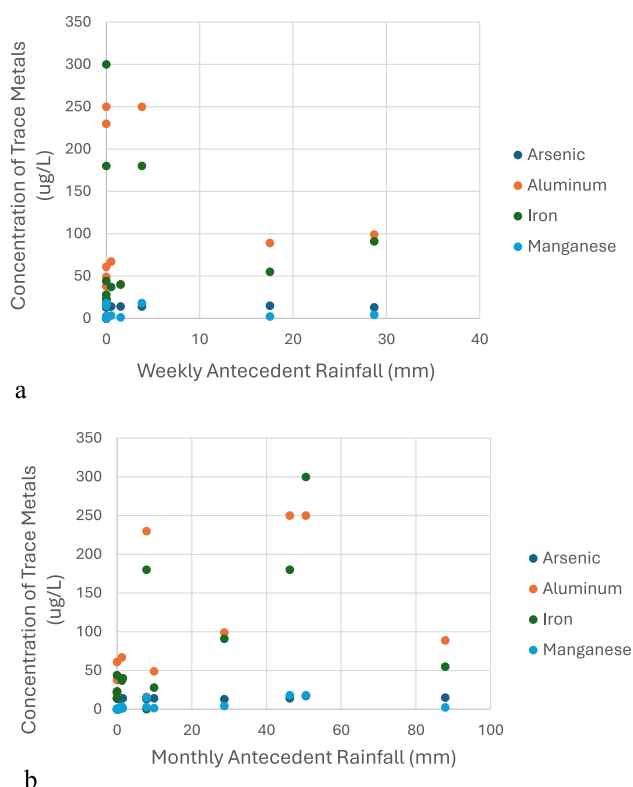


Fig. 4 (a) Concentrations of select trace metals in Bonanza Spring, dependent on total antecedent rainfall for the prior week. (b) Concentrations of select trace metals in Bonanza Spring, dependent on total antecedent rainfall for the prior month

Major ion composition

The major ion chemistry of the groundwater at Bonanza Spring and in the lower Fenner Watershed and Bristol/Cadiz Basin were previously characterized as dominantly Na-HCO₃ type water (Zdon et al. 2018). Well waters in these watersheds and basins show the presence of calcium and magnesium, which are found in much lower relative concentrations at Bonanza Spring, (approximately 10–25% difference). Figure 5 presents a Piper diagram of the major ion chemistry of Bonanza Spring and wells 21 N, 26, 27, 34, and 35 in the Cadiz farming area. These values are taken from average concentrations in the spring and for wells in the lower Fenner Watershed and Bristol/Cadiz Basin aquifers. Two analytical methods were compared in these analyses with most having similar results. Cation concentrations used in this plot come from analysis by ICP-MS, excluding the October 2022 samples that were anomalous. Sodium concentrations from that month were measured at levels much higher than historic values, resulting in an electrical imbalance of 22%. Analysis for these samples was repeated by ion chromatography (IC) with similarly poor electrical balances suggesting contamination of samples from that

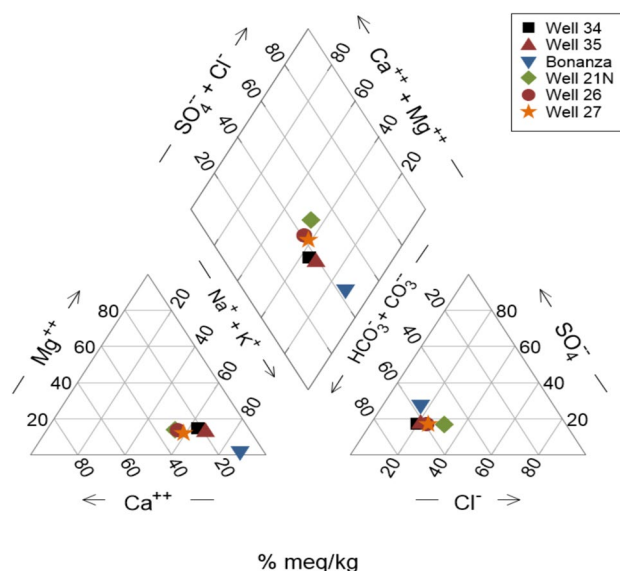


Fig. 5 Piper diagram depicting the composition of the major ions in Bonanza Spring and wells in the Bristol/Cadiz Basin

month, and resulting in exclusion of those results from the data set.. Slightly increased calcium ion concentrations were recorded for all samples with IC analysis compared with ICP-MS—the presence of sulfur in the samples could cause interference with calcium because of peak overlap and erroneously inflate the measurement of calcium by IC. Other measurements of major ion concentrations showed electrical balances of around 2%, and these data are used to produce the Piper diagram in Fig. 5. Data from both measurements are presented in Table S3 of the ESM. These major ion data showing disparity between Bonanza Spring and Cadiz wells are very consistent with the findings of Zdon et al. (2018) despite those authors characterization of Bonanza Spring water as similar in type to groundwater from of Fenner and Cadiz Valleys' basin alluvium.

Trace element concentration and correlation analysis

Water quality at the wells with respect to metal concentrations was generally within drinking water limits established by the U.S. Environmental Protection Agency (EPA). At Bonanza Spring, arsenic was consistently above the EPA Maximum Contaminant Level (MCL) of 10 µg/L with an average concentration of 12.8 µg/L. Well 35 showed arsenic concentrations slightly above the MCL on 28 January 2023 with the two duplicate samples averaging 10.53 µg/L (US EPA 2007).

The covariance matrix is shown in Fig. 6a and compares paired parameters the spring and wells. Figure 6b shows a covariance matrix computed for Bonanza Spring samples

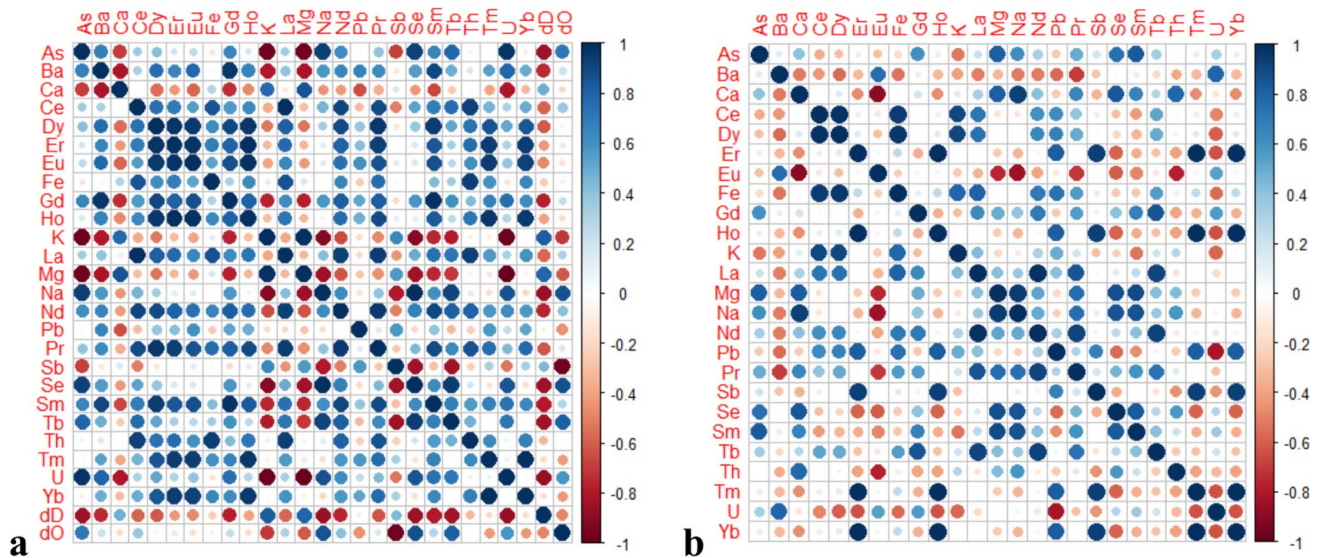


Fig. 6 (a) Covariance matrix used in the PCA, comparing trace element concentrations between the spring and wells using average values over the year of sampling. *Blue intensity* indicates positive covariance, that is the paired elements have similar directional increase or decrease in concentration with time. *Red intensity* indicates paired elements have opposite directional changes in concentration with

time. (b) Covariance matrix of Bonanza Spring comparing samples collected in October 2022 and January 2023. *Blue intensity* indicates positive covariance, that is the paired elements have similar directional increase or decrease in concentrations with time. *Red intensity* indicates paired elements have opposite directional changes in concentration with time

collected between October 2022 and January 2023. Cells in blue represent positive directional trends in aqueous concentration between paired elements while cells in red represent opposite trends. Strong directional relationships are seen between the paired lanthanides Eu, Er, Dy, Gd, Ho, Pr, Yb, and Tm. Other strong positive directional changes exist between As, Se, and U.

Principal component analysis (PCA) showed that the first principal component accounted for 55.5% of the observed variance, and the second principal component accounted for 26.2% of the variance. The third principal component is also considered and represents 15.6% of the variance. These three components account for a cumulative 97.7% of the total variance in the dataset, suggesting that they sufficiently explain the observed chemistries. Table S1 of the ESM shows the percentage of total variance accounted for by each principal component. Relative weights of the parameters included in the principal components are also shown, with larger magnitude eigenvalues indicating a parameter that is significant to the principal component. K-Means clustering was used to determine groupings of water sources. The analysis suggested four cluster centers should be considered, however only cluster 1, containing wells 35, 21 N and 27S, includes multiple sites (Fig. 7). The separation between Bonanza Spring and the wells is preserved in all dimensions considered. The horizontal magnitude on the principal component plots is exaggerated so that equivalent vertical distances represent a smaller difference in chemistry. The PCA clustering

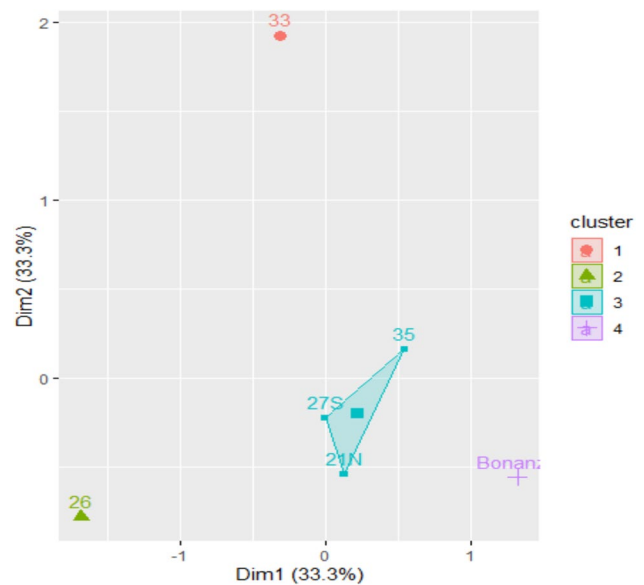


Fig. 7 K-means cluster plot of trace element concentrations using the average values from springs and wells over the year of sampling. Suggests at least three distinct groups, with Bonanza Spring having a dissimilar trace element signatures

of wells can be attributed to their physical proximity to one another and their placement in the same aquifer. Figure 8 is a 3DD plot of the first three principal components. Bonanza Spring stands apart in its aqueous chemical signature. This

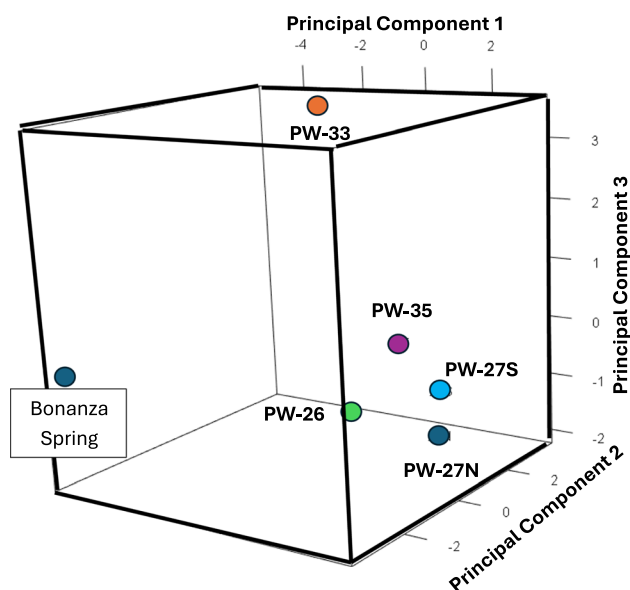


Fig. 8 PCA represented in 3D. Wells 35, 27 s, and 21 N represent a distinct group; Bonanza Spring is unique in chemical composition

3D plot is perhaps the best way to illustrate the significant water quality difference between Bonanza Spring and Cadiz wells, and is evidence to support the idea that these waters originate from different sources with dissimilar flow paths.

Hydrogen and oxygen isotope analysis

Figure 9a shows stable isotopic values of hydrogen and oxygen in well water in the Cadiz farming area collected in this study, water collected at Bonanza Spring in this study and precipitation collected by Lawrence Livermore National Laboratories (LLNL) near Bonanza Spring (Rose 2017). The range of error or uncertainty in analytical results for δD and $\delta^{18}O$ was 1.8 and for 0.17‰, respectively, for spring and well samples. The local meteoric water line suggested in Lachniet et al. (2020) and the linear fit for the precipitation falling on the Clipper Mountains both show a slope lower than the Global Meteoric Water Line (GMWL), suggesting evaporation processes common in desert environments. While Lachniet et al. (2020) present two local meteoric lines, Fig. 9a presents the line representing all of their reported data, not just their partial data set. This local line also best fits the local precipitation measurements at our site. Figure 9b is an expanded view of a portion Fig. 9a showing Linear fits for the wells in orange, and Bonanza Spring in grey and blue. The grey points represent data from the October 2022, 24-h round-the-clock sampling period. There was no periodicity observed in the isotopic values either seasonally or diurnally, so minor variations are likely the result of atmospheric temperature changes and random discrepancies while sampling.

A comparison was conducted between stable isotopes in Bonanza Spring water measured in this study with precipitation isotopes measured by Lawrence Livermore National Laboratories, (LLNL) (Rose 2017). The location of the LLNL precipitation sampler is north of Bonanza Spring about 350 m (1,150 ft) away and at an elevation of approximately 730 MAMSL (2,400 FASL), or about 90 m (300 ft) higher than the spring orifice.

Additional isotopic samples were taken topographically downgradient about 600 m (1,970 ft) from the spring orifice. This was located below the densely vegetated portion of the Bonanza Spring wash, next to the BLM rattlesnake information sign. This location is denoted in some references as Lower Bonanza Spring. In the database for this study, samples in this area are referred to as Alluvial, Below Rattlesnake Sign, and Rattlesnake Sign. Water use by plants, which preferentially uptake lighter isotopes, and evaporation contribute to a heavier isotopic signature downgradient. Figure 10 shows the results of these downgradient samples in blue.

Discussion

Long term groundwater flow paths that provide water to Bonanza Spring may be indicated because no NDVI temporal trends for specific vegetative species were observed. Temporal trends were not apparent over the timeframe for images available for the spring, and there was no discernable correlation with recent, antecedent precipitation (cumulative weekly and monthly rainfall). From historical aerial observations, flora associated with the spring varied temporally, but there were no obvious connections to seasonal or recent meteorological events. The idea that short term meteorologic events were not impactful was reinforced with the lack of correlation between both antecedent weekly and monthly rainfall with aqueous trace metal concentrations at the spring. This evidence of long average residence times for groundwater emerging at Bonanza Spring is supported by the lack of elevated tritium values reported by Zdon et al. (2018).

Similar to some previous studies, water temperatures, that were measured every month and during one 24-h sampling period at the spring orifice, had a small range of temperatures (27.3°C in February 2024 to 30.1°C in October 2023). This does not assume that these groundwater temperatures above average air temperatures represent upwelling geothermal water from more than 750 ft below the spring orifice as stated in Zdon et al. (2018). Elevated spring water temperatures can also be associated with groundwater flow along faults, and the Eastern Mojave Desert in particular is known to have a geothermal gradient anomaly (Sass et al. 1994). This greater regional geothermal gradient would calculate

Fig. 9 **a** Stable isotopes of water. Dark blue points show precipitation isotopes measured by LLNL on the ridge above Bonanza Spring. Green points and purple points show measurements from Bonanza Spring made by Geoscience Support Services Inc. (GSSI) and this study, respectively at Bonanza Spring. Orange points show measurements from Well 22 made by this study. **(b)** Expanded view showing stable isotopes of water measured this study: Bonanza Spring monthly (purple), Bonanza Spring 24-h (light blue), and Cadiz Valley wells (orange)

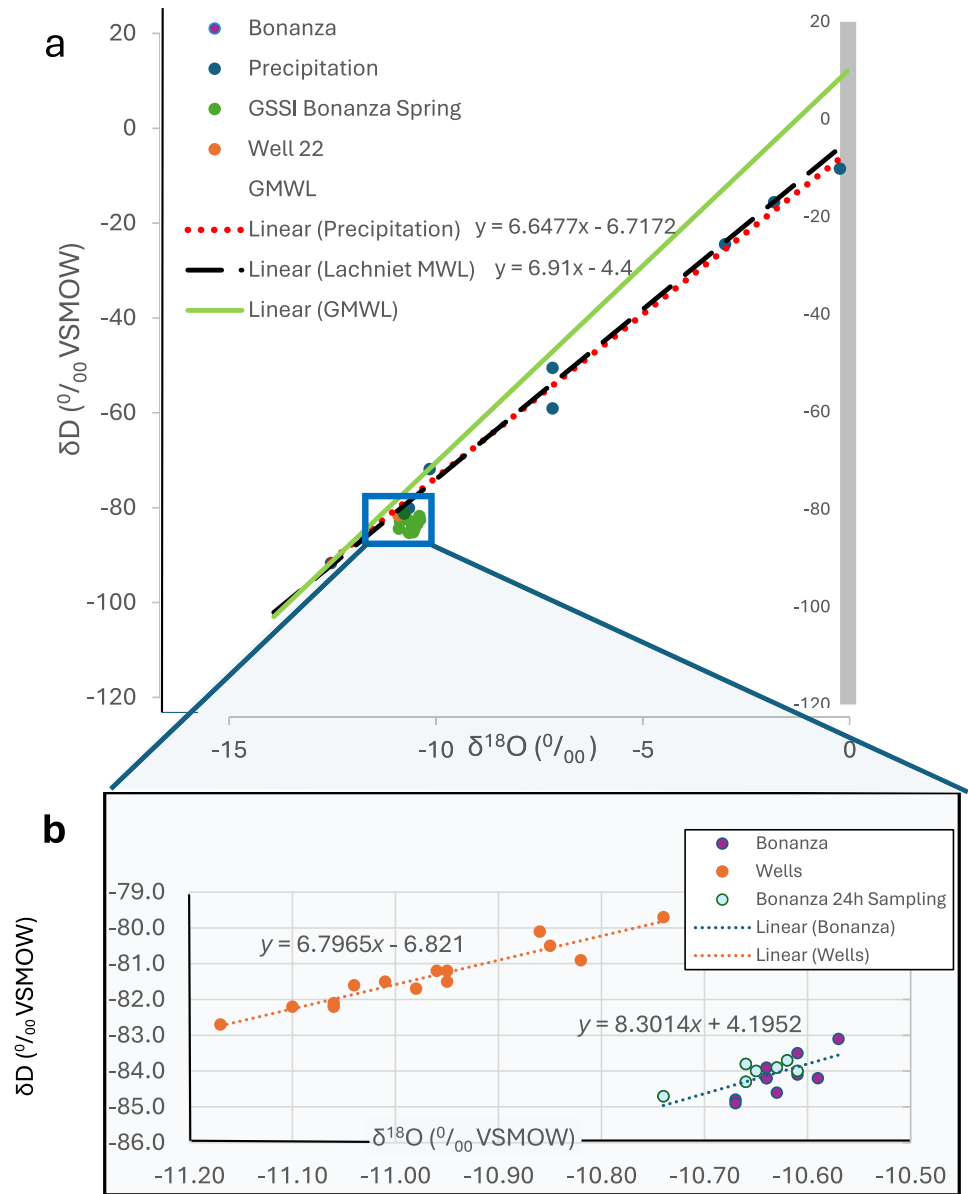
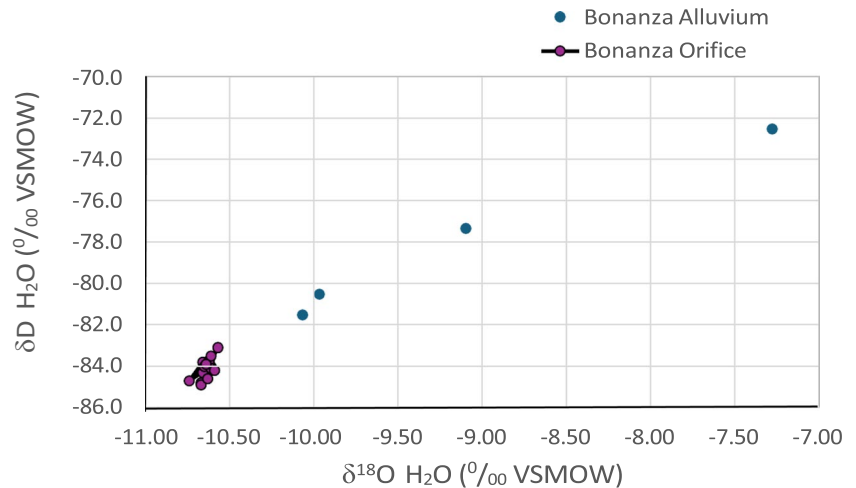


Fig. 10 Stable isotopes of Bonanza Spring Orifice (orange) and Lower Bonanza Wash (blue). The pattern of the Wash isotopes to the right is typical of the effects of downgradient evaporation and transpiration



the depth of geothermal upwelling, if it exists, to be from no greater than approximately 100 m (328 ft) depth. The high stability of temperatures and low variations in stable isotope composition suggests that rapid flow paths do not influence the spring, and baseflow is controlled by matrix flow through micropores. While Zdon et al. 2018 suggests the overlying volcanic material has permeability too low to allow infiltration, structural features, such as the fault trends, could provide areas of higher permeability that allow infiltration to depth and recharge the fractures, faults and micropores (Kenney and Foreman 2018a). The fault trends, which Kenney and Foreman detail, consist of a conjugate fault system and two major faults that intersect at the spring. This fault system extends to the higher elevations of the Clipper Mountains and could be a recharge mechanism for isotopically lighter rainfall. It should be noted that the electrical conductivity of Bonanza Spring was consistently higher than any Cadiz production wells.

Analysis of rainfall data in the Mojave Desert is complicated by the natural unpredictability and variability characteristic of all storms. The Mojave Desert has different meteoric rainfall regions due to the different controls on regional precipitation, complicated by intense convective summer storms which are limited in areal extent. Orographic effects are important influences on total precipitation amounts. Generally, the Western Mojave Desert tends to be drier due to stronger orographic rain shadow effects, while the Southeastern Mojave tends to be wetter. The duration and periodicity of rainfall can also impact these analyses, as sustained rainfall allows greater wetting of the soil and increased recharge to the subsurface.

Flood events, collapse features, and erosional geologic events can have a major impact on spring discharge. Large storms in California had been persistent in late winter of 2023. A period of intense storms in March of 2023 during this wetter than average winter appear to have precipitated a flash flood in the Bonanza Spring drainage system, collapsing the tunnel at the spring orifice, and damming the spring with clasts larger than six inches in diameter. This prevented discharge from the spring's previous point of issuance and appeared to cause dieback of reeds close to the spring's discharge point. The original upgradient orifice did not recover or produce discharge through the end of the project. Of note is that the more deeply rooted cottonwood trees appeared healthy while the shallower rooted *Arundo donax* reeds appeared wilted. These reeds are invasive and are a potential major source of transpiration from the spring system. Previous efforts to remove them from riparian environments have proved unsuccessful due to the longevity of their seeds and rapid maturation (Bell 1997).

Multiple lines of evidence discussed here suggest that Bonanza Spring and the wells in the Cadiz area of the Bristol/Cadiz Basin do not have a subsurface connection or

common source. Most water quality indicators were different between Bonanza Spring and the irrigation well water at Cadiz. On the average, alkalinity values were significantly higher in Bonanza Spring relative to the wells, with the inverse being true of Ca^{2+} ions. These parameters often have an inverse relationships because as the calcium carbonate chemically precipitates, the concentration of carbonate and bicarbonate ions in water typically decreases, producing lower alkalinity values. Electrical conductivity and major ion concentrations were dissimilar particularly with respect to the major cations. Trace elements exhibited the same dissimilarity. The PCA analyses of trace elements showed that the first three principal components explained 97.7% of the total variance in the data set which is indicative of a robust and acceptable analysis and indicated strong difference in aqueous chemical concentrations. There are limitations to the trace element analysis, where additional monitoring of other wells and montane springs further afield could provide interesting and more complete insight into the hydrogeology of the system. The results of the PCA for trace elements suggest that the waters at Bonanza Spring relative to the Cadiz wells are not connected and are evidence to support the idea that these waters originate from different sources with dissimilar flow paths. On the PCA plot (Fig. 8) well 33 appears to be independent from the other grouping of wells in the trace element analysis. Well 33 had the lowest range of electrical conductivity values of any other wells, ranging at least 100 $\mu\text{S}/\text{cm}$ lower than any other well, and more than 250 $\mu\text{S}/\text{cm}$ lower than Bonanza Spring.

Stable isotopes of hydrogen and oxygen also reflected this dissimilarity. The isotopic values at Bonanza Spring show very little variation and great stability with time throughout the study period, providing evidence against rapid infiltration and short average groundwater residence times. Shorter groundwater flow paths to the spring would be expected to result in less groundwater mixing and greater possibility of episodic, varying isotopic ratios in discharge.

Rainfall was found to be isotopically heavier, when comparing stable isotopes in spring water measured during this study with the previous analysis in rainwater collected near the spring by LLNL (Rose 2017). A weighted average of deuterium measured by the LLNL precipitation gauge is reported as -77.4‰ , compared with a lighter average at Bonanza Spring of -84.1‰ . These contrasting isotopic values between rainwater and groundwater can be the result of the input of seasonal precipitation changes and differences in the altitude of rainfall. Particularly in desert climates, isotopically lighter precipitation can be related to winter-dominated seasonal storms, and/or in precipitation falling at higher altitudes, which in turn can give recharging groundwater a lighter signature. In the Basin and Range Province, winter precipitation generally dominates recharge (Neff 2015). Average precipitation in the Mojave Desert

averages between 8.9 cm at lower elevations and 24.5 cm in the mountains annually (3.5 and 10 inches), depending on elevation, with mountains receiving more precipitation (NPS 2024).

The winter of 2022–2023 during the study period was wetter than usual versus the rainfall isotopes which were evaluated several years earlier by LLNL. It was considered possible that the more recent years of precipitation, contributing to spring discharge over this study's period, might be more dominated by isotopically lighter, winter-storm related recharge, compared to the heavier isotopic ratios found in LLNL's earlier precipitation measurements. This would explain why rainfall collected earlier might have a heavier signature than current spring water discharge. However, the average recharge from the earlier winter and summer precipitation for Bonanza Spring was quantified by LLNL using a simple linear mixing model for $\delta^{18}\text{O}$, and this analysis resulted in an estimated contribution of between 95 and 98% from winter precipitation to Bonanza Spring discharge, that is, the light winter rainfall isotopes quantitatively dominated the recorded isotopic fractions (Davisson et al. 1999; Davisson 2000). Therefore, it seems unlikely that the lighter stable isotopes measured in Bonanza Spring (this study) were produced by recent seasonal variation of winter precipitation in just the last few years, as compared to the earlier, isotopically heavier precipitation record by Rose (2017) that was calculated to be highly winter-dominated.

Another, more likely possibility is that lighter stable isotope ratios of oxygen and hydrogen observed in Bonanza Spring, relative to nearby LLNL rainfall measurements, could be associated with precipitation and aquifer recharge at higher altitudes. Friedman et al. (2002) studied the impact of elevation changes on stable isotopes in Great Basin precipitation by analyzing the Linear regression between weather stations separated by more than 400 m within 50 km of each other. This resulted in a slope between -5 and -10‰ per km for δD . Because the precipitation measurements were made by LLNL just above the spring, and the Clipper Mountains rise several hundred meters higher to the north, one possible interpretation would be that groundwater recharge supporting the spring's discharge originates from higher average elevations in the Clipper Mountains. This would also indicate Bonanza Spring water is not recharged solely from the small watershed immediately above the spring cited in Zdon et al. (2018), and not from lower elevations in the lower Fener Watershed or Bristol/Cadiz Basin. Previous analysis of faulting and fracturing in the Clipper Mountains supports the interpretation that recharge originates at higher elevations. The highest elevations considered within the recharge area by Aquilogic Inc. (Brown et al. 2019) are approximately 487 m (1600 ft) higher than the placement of the LLNL precipitation gage. The Clipper Mountains north of both the spring and LLNL precipitation measurement site rise an

additional 680 m (2,225 ft) higher and would likely result in even lighter isotopic rainfall values higher up the mountain. Using an average linear relationship of -0.28‰ $\delta^{18}\text{O}$ per 100 m elevation gain (Poage and Chamberlain 2001) this would represent up to a -1.9‰ $\delta^{18}\text{O}$ difference at the top of the Clipper Mountains compared to Bonanza Spring. The stable isotopic values of precipitation measured immediately above Bonanza Spring measured by LLNL varied widely. These elevation-related Rayleigh isotopic distillation processes could account for the isotopic differences between the average isotopic values in precipitation and those lighter values measured at the spring. However, this could be outweighed at any one time by isotopic fractionation due to temperature variation and desert meteorological conditions.

There are other possible explanations for these data differences between the range of LLNL rainfall isotopic values and the lighter, more consistent values at Bonanza Spring. This, for example, could be a result of the evaporation of precipitation samples before collection by LLNL staff. While this LLNL data suggests the precipitation isotopes falling on the Clipper Mountains are heavier than those found discharging at Bonanza Spring, the slope of the precipitation values, measured by LLNL and plotted as δD vs. $\delta^{18}\text{O}$, falls below the global meteoric water line, suggesting some evaporation has occurred that would artificially enrich the heavy isotopes. Another potential explanation for the data differences between the range of LLNL rainfall isotopic values and the lighter, more consistent values at Bonanza Spring could be the small size of the LLNL data set. Only five summer and four winter precipitation measurements were made, so individual precipitation events could vary greatly and thus bias the overall interpretation of the data.

In the lower reaches of Bonanza Wash, water use by plants, which preferentially uptake lighter isotopes, and evaporation contribute to a heavier isotopic signature down-gradient. Of note is that surface water discharge downstream in the wash appears to be controlled by evapotranspiration, drying up during the summer and flowing when the temperature is cool enough to allow water emerging at Bonanza Spring to flow further before disappearing into the wash.

Conclusions

Between 2022 and 2023, over a year of sampling was conducted at Bonanza Spring and agricultural wells in the Eastern Mojave Desert. This involved evaluation of aqueous physical properties, chemical characteristics, and related biological attributes. Sampling was monthly over the course of a year, along with a high-frequency, 24-h sampling event. Historical vegetative patterns reviewed from aerial imagery showed no trends or consistent seasonal changes. Likewise, there was no correlation of the spring's aqueous

geochemistry with cumulative amounts of antecedent weekly or monthly rainfall.

Analysis of data revealed distinct differences between water quality attributes for major ions, trace elements, and isotopic values between spring and well water. This agrees with data observed and some of the conclusions in previous studies (Zdon et al. 2018). Specifically, there is supporting evidence developed here that recharge for Bonanza Spring originates at higher elevations to the north, and groundwater emerging from the spring has experienced long travel times beyond monthly or seasonal influences. Although spring discharge and hydrochemistry associated with these long groundwater residence times are not influenced by recent weather events, this may not hold for geological changes associated with surface flash flooding, damming the spring orifice. Alterations in the spring orifice and point of groundwater issuance changed dramatically late in the study in 2023, resulting in observable changes to the discharge amount, location, and in the spring's vegetative community that is dependent on flow. Principal component analysis indicated that trace element concentrations showed significant dissimilarities between Bonanza Spring water versus Cadiz well water. This is supportive evidence for lack of a hydrogeologic connection over the approximately 22 km (13.7 miles) of distance of separation and 400 m (1,312 ft) of elevation difference between the two locations. Comparison of stable isotope samples showed spring water to be isotopically lighter than historical values of isotopes in local precipitation, suggesting a higher altitude recharge source for the spring than its immediately upgradient, small watershed. This included the possibility of groundwater recharge higher up in the Clipper Mountains above Bonanza Spring, and groundwater movement through higher fractured hard rock to its spring discharge point. This contribution to spring flow from recharge to the Clipper Mountain massif is very possible but does not rule out the possibility of additional contribution to discharge from further north. Isotopic enrichment of heavier isotopes several hundred meters topographically downgradient from the spring orifice to "Lower Bonanza Spring" was observed here and was in agreement with previous studies. It is likely due to evaporative and transpirational fractionation along the course of the wash. There is not supportive isotopic evidence of hydrogeologic connection between Bonanza Spring and Cadiz wells.

According to multiple Lines of evidence, Bonanza Spring receives groundwater from recharge areas to the north and at higher elevation, has isotopic enrichment effects traveling on the surface for several hundred meters below the spring orifice, and is chemically distinct from water in wells from the Cadiz farming area approximately 22 km (16.7 miles) to the south and 400 m (1,312 ft) lower in elevation. Based on the distinctly dissimilar hydrochemical concentrations of major ions and trace metals, and from the observed differing

stable isotopic ratios of hydrogen and oxygen, there is not supporting evidence of a hydrogeologic connection between Bonanza Spring and Cadiz wells.

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Author Contributions Luke Stevens served as primary author and Principal Scientist. He directed the bulk of the field work, logistics, field and laboratory analysis, and statistical analysis and interpretation of results. David Kreamer was the Principal Investigator, served as Luke's M.S. thesis advisor on this project, contributed and advised in the field, was responsible for obtaining and managing funding to support the research effort, and was secondary author.

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Data Availability All supporting data and field photographs are available in the electronic supplementary material (ESM).

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