THE HISTORY OF WATER IN BEARS EARS NATIONAL MONUMENT, SOUTHEASTERN UTAH

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ABSTRACT

On December 28, 2016, President Barak Obama created Bears Ears National Monument on 1.35 million acres in southeastern Utah, primarily to protect the archaeological heritage of the Basketmaker (0-700 AD) and Ancestral Puebloan (700-1300 AD) cultures. One of the primary archaeological questions in the Bears Ears area is the cause of the migration of the Ancestral Pueblo from southern Utah to the Rio Grande valley of New Mexico about 1300 AD. Climate change, especially long-term drought, is often invoked as a cause, but understanding migration involves combining the occurrence of climate change with the resilience of the ecosystem and social system. The objective of this study was to assess the resilience of the ecosystem in the Bears Ears area, specifically the persistence of groundwater sources in the event of a long-term drought. The objective was addressed by collecting water samples from 36 springs and measuring stable isotope compositions and concentrations of the anthropogenic gas CFC in order to determine the sources and residence times of groundwater. Stable isotope compositions indicated that 47% of springs are recharged by fall rains, 36% by snowmelt or spring rains, and 17% by late summer monsoon rains. Analysis of CFC concentrations indicated that groundwater residence times ranged from 24-64 years with a mean of (42 ± 12) years, and with 28% of springs having residence times > 50 years. The above results suggest an exceptionally resilient ecosystem in which considerable groundwater sources would persist after a drought that lasted for several decades. A pattern is emerging in which characteristic petroglyphs seem to be associated with more persistent (residence time > 50 years) springs. These petroglyphs belong to the Glen Canyon Linear Petroglyph Style that was created by the Western Archaic culture and may date as far back as 6000 BC.

INTRODUCTION

On December 28, 2016, President Barak Obama created Bears Ears National Monument on 1.35 million acres in southeastern Utah (Fig. 1), primarily to protect the archaeological heritage of the Basketmaker (0-700 AD) and Ancestral Puebloan (700-1300 AD) cultures. (Ancestral Puebloan is the current preferred term and is equivalent to Anasazi.) One of the primary archaeological questions in the Bears Ears area is the cause of the migration of the Ancestral Pueblo from southern Utah and the Four Corners region to the Rio Grande valley of New Mexico about 1300 AD. Climate change, especially long-term drought, is often invoked as a cause, but understanding migration involves combining the occurrence of climate change with the resilience of the ecosystem and social system (Plog, 2008; Stuart, 2014). Other studies have focused on social inequality and the investment in non-productive infrastructure as elements of a non-resilient social system (Stuart, 2014).

The objective of this study was to assess the resilience of the ecosystem in the Bears Ears area, specifically the persistence of groundwater sources in the event of a long-term drought. The objective was addressed by collecting water samples from springs and measuring stable isotope compositions and concentrations of the anthropogenic gas CFC in order to determine the sources and residence times of groundwater. This study has built upon previous work on springs (Hoglander et al., 2016; Coles-Ritchie, 2017) and hydrogeology (Avery, 1986; Otton et al., 2010) in the Bears Ears area, as well as studies on archaeological geology in the area (Agenbroad, 1975a-b; Lipe and Matson, 1975). We are not aware of any previous work on stable isotopic compositions or CFC concentrations of springs in the Bears Ears area. The political and legal battles that have ensued since the presidential proclamation will not be discussed in this paper.

MATERIALS AND METHODS

Fieldwork was carried out in July 2015, June 2017, and July 2017. The USGS (2018) database, National Geographic (2008, 2013) maps, and information provided by Grand Canyon Trust and the Ute Mountain Ute Tribe were used to locate 36 flowing springs throughout Bears Ears National Monument (Table 1a, Figs. 2-7). In most cases, the flow from the springs was too diffuse to measure the discharge. However, for 12 springs, nearly all of the flow had been channeled through man-made pipes, and discharge was measured in triplicate by timing the flow into a 5-gallon bucket (Table 1b). Nine additional springs were marked as non-flowing because insufficient water was present for sample collection (Table 2, Figs. 2, 8, 9, 10a-b). For example, at the time of observation, Rock Spring (Site No. 37, Table 2, Fig. 8) was nothing more than muddy hoof prints, and Red House Spring (Site No. 38, Table 2, Fig. 9) was only a field of salt. Castle Ruins (Site No. 43, Table 2, Figs. 10a-b) had a non-flowing spring in the sandstone overhang and dry impact impressions could be seen in the floor of the cave. Of course, it could have been possible to map numerous “unnamed” non-flowing springs. The unnamed spring at Site No. 44 (Table 2) was mapped because of its association with a prominent archaeological site. The positions of all springs were measured with the Garmin eTrex 10 GPS Receiver and elevations were determined by comparison with Google Earth images.

Water samples were collected from all springs in 125-mL glass vials for measurement of stable isotopes of hydrogen and oxygen. Stable isotopes were measured in three aliquots per sample bottle using the Los Gatos Research Liquid Water Isotope Analyzer at Utah Valley University for Site Nos. 1-16, and using the Picarro Cavity Ringdown Spectrometer at the University of Utah for Site Nos. 17-36 (Table 1b). The local meteoric water line was constructed using monthly estimates for stable isotopic compositions for precipitation obtained from the

Online Isotopes in Precipitation Calculator v. 3.1 (Welker, 2000; Bowen et al., 2005; IAEA/WMO, 2015; Bowen, 2017) at the average position and elevation of all flowing springs (Table 1b, Fig. 11). Water samples were assigned to recharge months by comparison with the local meteoric water line or sub-parallel evaporation lines branching from the local meteoric water line (Fig. 11).

Water samples were collected in triplicate in 500-mL glass bottles from Sites No. 1-17 and Site No. 29 for measurement of CFC concentrations (Table 1c). All samples were collected directly from the water source using copper tubing and a glass syringe in order to avoid contamination with plastic (Fig. 5). Concentrations of CFC-11, CFC-12 and CFC-113 were measured at the Dissolved and Noble Gases Lab at the University of Utah. The conversion of concentrations to residence times required knowledge of the recharge elevation and temperature. The recharge elevation was assumed to be equal to the elevation of the spring (Table 1a). The recharge temperature was assumed to be equal to the average air temperature at the spring at the assigned recharge month, which was estimated using the average monthly temperature for 1981-2010 at the weather station at Natural Bridges National Monument (Fig. 2; NOAA-NCEF, 2018), and adjusting for the difference in elevation between the weather station (1983.6 m) and the spring using the standard environmental lapse rate of 6.49 °C/km (Table 1b; ICAO, 1993). The mean residence time for groundwater emerging from a spring was calculated as the mean of the residence times that were calculated from CFC-11, CFC-12 and CFC-113 concentrations (Table 1c).

At Site Nos. 17-36, water temperature, pH, dissolved oxygen, oxidation-reduction potential, and electrical conductivity were measured on-site using the Hach HQ30d Portable pH, Conductivity, Optical Dissolved Oxygen (DO), ORP, and ISE Multi-Parameter Meter (see list of probes in Table A1). At the same sites, unfiltered water samples were collected in duplicate in 500-mL polyethylene bottles. All samples were analyzed for nitrate, sulfate and phosphate using the Hach DR-2800 Portable Spectrophotometer (Table A1). Three aliquots from each sample bottle were further analyzed for As and 15 heavy metals (Tables A2-A3) by digestion using the MARS 6 Microwave Reaction System, followed by analysis with the PerkinElmer Optima 8000 ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometer). Since samples were not filtered, As and heavy metal concentrations should be regarded as total, rather than dissolved concentrations. The above results were not analyzed further as the objective of the study changed after the field season in 2015. The results are included for completeness in the Appendix (Tables A1-A3).

RESULTS

A comparison of the stable isotopes of groundwater emerging from springs in Bears Ears with the local meteoric water line and its sub-parallel evaporation lines shows that the groundwater is derived from local precipitation, rather than from regional groundwater flow. All springs could be assigned to only five recharge months, which were April, May, August, October and November (Table 1b, Figs. 11, 12). Grouping the months by precipitation seasons in which April and May correspond to snowmelt or spring rains, August corresponds to late summer monsoon rains, and October and November correspond to fall rains, showed that 36% of springs were recharged by snowmelt or spring rains, 17% were recharged by late summer monsoon rains, and 47% were recharged by fall rains (Fig. 12). It should be noted that there are other possible interpretations for the 10 springs that plotted off the local meteoric water line (Fig. 12). For example, any spring could be connected with a more depleted portion of the local meteoric water line by drawing a longer and steeper evaporation line. Such an evaporation line would correspond to a longer period of evaporation into a more humid atmosphere. However, the shorter sub-parallel evaporation lines indicating shorter periods of evaporation into an atmosphere with roughly constant relative humidity throughout the year are a simpler interpretation.

The residence time for groundwater emerging from springs ranged from (24.1 ± 22.3) to (63.9 ± 11.3) years, with a mean for all springs of (41.8 ± 12.1) years, where the uncertainty is the standard deviation of the nine estimates of residence time, corresponding to the three measurements each of CFC-11, CFC-12 and CFC-113 concentrations (Table 1c, Fig. 13). Five out of 18 springs (28%) had mean groundwater residence times exceeding 50 years. Moreover, all of these long (> 50 years) residence times should be regarded as underestimates. At Site Nos. 1 and 10, one of the triplicates had no detectable CFC-11, resulting in a minimum residence time of 77.5 years, and one of the triplicates had no detectable CFC-113, resulting in a minimum residence time of 74.5 years (Table 1c). At Site Nos. 2, 8 and 12, all of the triplicates had no detectable CFC-113, resulting in a minimum residence time of 74.5 years (Table 1c). One of the triplicates at Site No. 10 also had no detectable CFC-11, so that its mean groundwater residence time of (41.8 ± 32.3) years is also an underestimate.

Although there was some positive skew, the groundwater residence times were roughly normally distributed, which allowed the use of the ANOVA and posterior Tukey comparison statistical tests. According to the single-factor ANOVA, there was a statistically significant difference ($P = 0.009$) between the mean groundwater residence time for springs recharged by late summer monsoon rains ((30.6 ± 6.5) years) and both the mean groundwater residence time for springs recharged by snowmelt or spring rains ((48.3 ± 11.2) years) and the mean groundwater residence time for springs recharged by fall rains (45.5 ± 9.1) years). Further use of the posterior Tukey comparison showed that the difference in mean groundwater residence times between springs recharged by snowmelt or spring rains and springs recharged by fall rains was not statistically significant ($P = 0.66$). Correcting for the underestimations of residence times at six of the sites would increase the positive skew, but would not affect the conclusions of the above statistical tests.

A remaining problem is how to take into account the groundwater residence times of the nine non-flowing springs (Table 2). Presumably, these springs flow only seasonally at most and, thus, have groundwater residence times less than a year. Adding nine springs with residence times of less than one year to the histogram of groundwater residence times (Fig. 13) would create a profoundly bimodal distribution. Of course, adding all of the innumerable “unnamed” springs where there was evidence of previous water flow, as mentioned earlier, would create even more of a bimodal distribution. The most likely interpretation of the bimodal distribution is that the non-flowing and flowing springs arise from different populations, for example, from springs with hydraulic pathways above and below the water table, respectively. On that basis, the non-flowing springs were not included in calculating the statistics of groundwater residence times. It should be noted that all fieldwork occurred between recharge seasons in June and July (Fig. 12), so that it was unlikely to mistake seasonal springs for perennial springs.

Figs. 3-7 show flowing springs illustrating the range of groundwater residence times, recharge seasons, evaporation times, and discharge measurements. Pine Spring (Site No. 2, Fig. 3) has the oldest groundwater ((63.9 ± 11.3) years) and is recharged by snowmelt or spring rains with negligible evaporation after precipitation (Tables 1a-c, Fig. 11). An unnamed spring that promotes the growth of a hanging garden (Site No. 7, Fig. 4) has a groundwater residence time of (57.3 ± 17.1) years and is recharged by fall rains with significant evaporation after precipitation

(Tables 1a-c, Fig. 11). Another unnamed spring (Site No. 14, Fig. 5) has a younger groundwater residence time of (27.0 ± 18.6) years, and is recharged by late summer monsoon rains with negligible evaporation after precipitation (Tables 1a-c, Fig. 11). CFC concentrations were not measured for Duck Lake (Site No. 19, Fig. 6) or Crystal Spring (Site No. 25, Fig. 7). Duck Lake is recharged by snowmelt or spring rains with significant evaporation after precipitation, which is consistent with its large surface area (Table 1b, Fig. 11). At all of the above sites, spring discharge was too diffuse for measurement. However, spring discharge was measured as 4.75 L/min at Crystal Spring (Site No. 25, Fig. 7), which is recharged by fall rains with negligible evaporation after precipitation (Tables 1a-b, Fig. 11).

DISCUSSION

The above results for groundwater residence times (Table 1c, Fig. 13) suggest an exceptionally resilient ecosystem in which significant groundwater resources would persist after a mega-drought (usually regarded as lasting more than 20 years) and even after a drought that persisted for half a century. Moreover, since groundwater recharge occurs in three seasons (Fig. 12), significant groundwater resources would most likely persist even after a considerable change in the seasonality of precipitation. On this basis, the cause of the collapse of the Ancestral Puebloan civilization in the Bears Ears area should be sought not simply in the occurrence of climate change, but in the social response to climate change, as argued forcefully by Stuart (2014). If these results could be generalized to other groundwater-fed forest ecosystems in the Southwest, it could imply a positive outlook for these forest ecosystems in response to the current anthropogenic climate change. Of course, the impact of overgrazing on the health of springs must also be taken into account (Fig. 8).

While carrying out the fieldwork for this study, a surprising pattern emerged in which characteristic petroglyphs were found to be associated with the springs with longer (> 50 years) groundwater residence times. These petroglyphs belong to the Glen Canyon Linear Petroglyph Style, which was created by the Western Archaic culture, who were the hunters and gatherers who inhabited the Bears Ears area prior to the Basketmaker culture (Schaafsma, 1980). The characteristic features of these petroglyphs include concentric circles, mountain sheep, deer, and plant motifs (Fig. 15a), rabbit-eared anthropomorphs (Fig. 15b), and anthropomorphs with long tentacle-like arms (Fig. 15c). The beginning of this art genre has been dated between 2000 BC and as far back as 6000 BC (Turner, 1971). The reasons why these particular petroglyphs were created is quite a difficult question, and the interpretation of prehistoric art can resemble a game with no rules. However, the significance of any particular art form that is associated only with the most persistent groundwater sources suggests that the hunters and gatherers must have known which were the most persistent groundwater sources. In accordance with scholarly practice, we have not published the exact coordinates of rock art.

CONCLUSIONS AND FUTURE WORK

The chief conclusions of this study can be summarized as follows:

1) Groundwater residence times of springs in Bears Ears National Monument range from 24-64 years with a mean of (42 ± 12) years, and with 28% of springs having residence times > 50 years.
2) The above results suggest an exceptionally resilient ecosystem, so that explanations for the collapse of the Ancestral Puebloan civilization should be sought in the social, rather than the hydrologic response to climate change.

3) Characteristic petroglyphs associated with the more persistent (residence time > 50 years) springs were created by the hunters and gatherers of the Western Archaic culture, so that knowledge of the long-term persistence of water sources in Bears Ears may date as far back as 6000 BC.

Since the precipitation record for the Four Corners area is well known from dendrochronology (Plog, 2008; Stuart, 2014), this study raises the possibility of using both the precipitation and the persistence of groundwater sources to create a series of paleo-hydrographic maps for the duration of the Ancestral Puebloan occupation (700-1300 AD) of the Bears Ears area. Such maps could potentially be combined with botanical data to create an accompanying series of paleo-vegetation maps for the same area. These maps could yield considerable insights into Ancestral Puebloan history as a sequence of social responses to changes in the availability of water and edible plants. One of the central problems in the creation of these maps would be understanding the circumstances under which currently ephemeral streams such as White Canyon Creek (Fig. 2) would transition between permanent and ephemeral. We are not aware of any current research on this problem.

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Table 1a. Flowing Springs in Bears Ears: Site Information

Site No.	Name[1]	Sampling Date[2]	Latitude[3] (°N)	Longitude[3] (°W)	Elevation[4] (m)
1	Dog Tanks Spring	6/9/2017	37.56211	109.73632	1869
2	Pine Spring	6/9/2017	37.55211	109.80328	2010
3	Maverick Spring	6/9/2017	37.61089	109.87915	2393
4	Todie Spring	6/10/2017	37.48311	109.92849	1938
5	Collins Spring	6/10/2017	37.43753	110.17312	1540
6	unnamed	7/18/2017	37.51111	109.92528	1906
7	unnamed	7/18/2017	37.46867	109.81630	1757
8	Ruin Spring	7/20/2017	37.50169	109.52316	1648
9	Irish Green Spring	7/21/2017	37.42664	110.34175	1661
10	unnamed	7/22/2017	37.43029	109.93467	1952
11	unnamed	7/22/2017	37.40861	109.95504	1959
12	unnamed	7/22/2017	37.40850	109.95552	1957
13	unnamed	7/22/2017	37.40874	109.95632	1951
14	unnamed	7/22/2017	37.40889	109.95646	1949
15	unnamed	7/22/2017	37.40902	109.95655	1949
16	unnamed	7/22/2017	37.40912	109.95656	1949
17	unnamed	7/9/2015	37.82850	109.82846	2309
18	unnamed	7/9/2015	37.82800	109.75983	2572
19	Duck Lake	7/10/2015	37.81171	109.73261	2255
20	unnamed	7/10/2015	37.79111	109.73096	2174

21	Poso Spring	7/10/2015	37.78191	109.76618	2600
22	Poso Spring	7/10/2015	37.78327	109.76581	2594
23	North Notch Spring	7/10/2015	37.76186	109.77612	2620
24	unnamed	7/10/2015	37.86022	109.78451	2610
25	Crystal Spring	7/10/2015	37.88147	109.81453	2619
26	Big Spring	7/10/2015	37.84527	109.85156	2611
27	unnamed	7/10/2015	37.85323	109.86373	2587
28	unnamed	7/10/2015	37.84850	109.74990	2412
29	unnamed	7/10/2015	37.86220	109.76264	2487
30	unnamed	7/11/2015	37.72561	109.81824	2557
31	unnamed	7/11/2015	37.67557	109.82691	2540
32	Twin Springs	7/11/2015	37.67583	109.87942	2622
33	unnamed	7/11/2015	37.65879	109.83113	2541
34	unnamed	7/11/2015	37.88486	109.75887	2467
35	unnamed	7/11/2015	37.85729	109.73183	2305
36	unnamed	7/11/2015	37.85919	109.72979	2299

[1]All names obtained from USGS (2018), except for Poso Spring, which was obtained from Hoglander et al. (2016).

[2]Month/day/year

[3]Locations measured on-site using Garmin eTrex 10 GPS Receiver and based on WGS (World Geodetic Survey) 84 coordinate system.

[4]Elevations obtained by comparing measured locations with Google Earth.

Table 1b. Flowing Springs in Bears Ears: Discharge, Stable Isotope Compositions, and Predicted Recharge Month and Temperature

Site No.	Discharge[1] (L/min)	δ^2H [2,3] (‰, V-SMOW)	$\delta^{18}O$ [2,3] (‰, V-SMOW)	Recharge Month[4]	Recharge Temperature[5] (°C)
1	N/A	-97.09 ± 0.27	-12.84 ± 0.08	April	8.0
2	N/A	-95.41 ± 0.24	-12.73 ± 0.11	April	8.9
3	N/A	-103.70 ± 0.33	-14.18 ± 0.03	November	6.5
4	N/A	-98.75 ± 0.06	-12.78 ± 0.07	April	8.5
5	N/A	-98.19 ± 0.10	-13.03 ± 0.10	April	5.9
6	N/A	-80.77 ± 0.28	-10.40 ± 0.14	October	10.2
7	N/A	-74.26 ± 0.43	-8.09 ± 0.08	October	9.2
8	2.21	-99.48 ± 0.10	-12.68 ± 0.03	April	6.6
9	2.57	-92.18 ± 0.17	-11.01 ± 0.08	April	6.7
10	N/A	-23.07 ± 0.23	-2.39 ± 0.12	August	21.7
11	N/A	-35.25 ± 0.38	-4.74 ± 0.17	August	21.7
12	N/A	-93.83 ± 0.60	-12.25 ± 0.12	April	8.6
13	N/A	-36.42 ± 0.27	-5.52 ± 0.12	August	21.7
14	N/A	-35.32 ± 0.33	-5.25 ± 0.03	August	21.7
15	N/A	-30.91 ± 0.14	-4.66 ± 0.14	August	21.7
16	N/A	-29.62 ± 0.45	-4.55 ± 0.13	August	21.7
17	47.63	-107.68 ± 0.09	-14.64 ± 0.05	November	6.0
18	N/A	-104.26 ± 0.26	-14.19 ± 0.07	November	7.7
19	N/A	-48.13 ± 0.06	-3.59 ± 0.02	May	16.2

20	10.26	-106.61 ± 0.40	-14.32 ± 0.09	November	5.1
21	0.66	-99.06 ± 0.23	-13.38 ± 0.03	November	7.9
22	11.82	-75.80 ± 0.46	-10.65 ± 0.08	May	18.4
23	N/A	-104.16 ± 0.27	-14.18 ± 0.07	November	8.0
24	N/A	-50.96 ± 0.21	-4.83 ± 0.04	May	18.5
25	4.75	-107.54 ± 0.20	-14.29 ± 0.03	November	8.0
26	1.68	-108.51 ± 0.37	-14.60 ± 0.08	November	8.0
27	N/A	-101.82 ± 0.33	-13.68 ± 0.05	November	7.8
28	4.5	-108.65 ± 0.09	-14.78 ± 0.02	November	6.7
29	N/A	-97.97 ± 0.07	-12.91 ± 0.03	April	12.0
30	1.74	-106.41 ± 0.19	-14.53 ± 0.03	November	7.6
31	1.62	-104.74 ± 0.20	-14.28 ± 0.05	November	7.5
32	N/A	-84.17 ± 0.18	-11.17 ± 0.03	October	14.8
33	N/A	-102.67 ± 0.11	-13.87 ± 0.03	November	7.5
34	4.73	-109.53 ± 0.20	-14.87 ± 0.04	November	7.0
35	N/A	-66.08 ± 0.20	-9.58 ± 0.02	May	16.5
36	N/A	-62.93 ± 0.16	-8.32 ± 0.03	May	16.5

[1]N/A indicates that spring discharge was too diffuse for measurement.

[2]Samples from Site Nos. 1-16 were analyzed using the Los Gatos Research Liquid Water Isotope Analyzer. Samples from Site Nos. 17-36 were analyzed using the Picarro Cavity Ringdown Spectrometer

[3]Uncertainties are one standard deviation based on measurement of three aliquots per sample.

[4]Most likely recharge months were determined by comparison with the local meteoric water line or the probable evaporation lines (see Fig. 11).

[5]Recharge temperatures were determined by using the long-term (1981-2010) normal monthly mean temperature at the closest weather station (Natural Bridges National Monument, elevation = 1983.6 m, see Fig. 2) and adjusting for the elevation of the spring assuming an environmental lapse rate of 6.49 °C/km (ICAO, 1993).

Table 1c. Flowing Springs in Bears Ears: Groundwater Residence Times[1]

Site No.	CFC-11 Residence Time[2] (yr)	CFC-12 Residence Time[2] (yr)	CFC-113 Residence Time[2] (yr)	Mean Residence Time[3] (yr)
1	72.2 ± 5.3[4]	52.3 ± 11.0	67.3 ± 6.3[5]	63.9 ± 11.3
2	71.2 ± 0.3	45.5 ± 0.9	74.5 ± 0.0[6]	63.7 ± 13.8
3	64.3 ± 4.6	34.3 ± 0.4	41.8 ± 4.6	46.8 ± 14.3
4	48.2 ± 11.3	22.0 ± 15.6	37.2 ± 4.0	35.8 ± 15.0
5	42.3 ± 1.9	39.2 ± 1.0	35.2 ± 0.3	38.9 ± 3.3
6	38.5 ± 0.5	34.8 ± 1.3	33.2 ± 0.3	35.5 ± 2.5
7	71.5 ± 8.5[4]	42.8 ± 1.8	57.8 ± 23.7[5]	57.3 ± 17.1
8	42.5 ± 0.5	38.7 ± 4.5	74.5 ± 0.0[6]	51.9 ± 17.2
9	44.3 ± 0.3	43.0 ± 0.5	36.7 ± 0.3	41.3 ± 3.6
10	72.2 ± 4.6[4]	4.0 ± 0.0	49.2 ± 23.4[5]	41.8 ± 32.3
11	61.3 ± 3.8	12.5 ± 14.7	26.5 ± 19.8	33.4 ± 25.1
12	42.0 ± 0.0	37.0 ± 1.0	74.5 ± 0.0[6]	51.2 ± 17.6
13	55.3 ± 4.5	11.7 ± 13.3	26.0 ± 19.4	31.0 ± 22.7
14	46.3 ± 1.3	4.0 ± 0.0	30.7 ± 0.8	27.0 ± 18.6
15	52.2 ± 1.6	16.2 ± 10.6	4.0 ± 0.0	24.1 ± 22.3
16	48.2 ± 1.6	26.2 ± 1.4	4.0 ± 0.0	26.1 ± 19.2
17	45.7 ± 0.6	43.3 ± 0.6	38.7 ± 0.3	42.6 ± 3.1
29	42.0 ± 1.7	35.8 ± 8.1	41.0 ± 11.0	39.6 ± 7.5

[1]CFC concentrations were measured from triplicate sample bottles at the Dissolved and Noble Gases Lab at the University of Utah. Residence time was calculated assuming that the recharge elevation was equal to the spring elevation (see Table 1a) and that the recharge temperature was the average monthly air temperature at the spring for the probable recharge month (see Table 1b).

[2] The uncertainty is the standard deviation of the triplicates.

[3]The mean residence time is the mean of the nine residence times determined from CFC-11, CFC-12 and CFC-113 concentrations. The uncertainty is the standard deviation of the nine measurements.

[4]One of the triplicates had no detectable CFC-11, resulting in a minimum residence time of 77.5 years.

[5]One of the triplicates had no detectable CFC-113, resulting in a minimum residence time of 74.5 years.

[6]All of the triplicates had no detectable CFC-113, resulting in a minimum residence time of 74.5 years.

Table 2. Non-Flowing[1] Springs in Bears Ears

Site No.	Name[2]	Visit Date[3]	Latitude[4] (°N)	Longitude[4] (°W)	Elevation[5] (m)
37	Rock Spring	6/10/2017	37.65841	110.18145	5266
38	Red House Spring	6/10/2017	37.48023	110.18757	5176
39	Junction Spring	7/18/2017	37.51274	109.94101	5945
40	Prehistoric Cave Spring	7/18/2017	37.46111	109.81374	6008
41	Fry Spring	7/21/2017	37.62037	110.14170	5352
42	Green Water Spring	7/21/2017	37.41508	110.36134	5382
43	Castle Ruins	7/21/2017	37.41915	110.35685	5403
44	unnamed	7/21/2017	37.51396	109.66398	5051
45	Navajo Spring	7/23/2017	37.26051	109.67484	4363

[1]At non-flowing springs, insufficient water was present for sample collection.

[2]All names of springs obtained from USGS (2018), except for Castle Ruins, which is the name of the archaeological site where the spring occurs.

[3]Month/day/year

[4]Locations measured on-site using Garmin eTrex 10 GPS Receiver and based on WGS (World Geodetic Survey) 84 coordinate system.

[5]Elevations obtained by comparing measured locations with Google Earth.

APPENDIX

Table A1: Flowing Springs in Bears Ears: On-site Parameters[1] and Oxyanions[2]

Site No.	Temp (°C)	pH[3]	DO[4,5] (mg/L)	ORP[5,6] (mV)	EC[7] (μS/cm)	NO_3 (mg/L)	SO_4 (mg/L)	PO_4 (mg/L)
17	12.3	10.40	6.34	224.7	335	7.25	6	1.95
18	16.9	8.13	7.84	134.1	253	1.95	5.5	0.55
19	13.1	10.63	3.78	172.7	162.8	2.3	5	0.3
20	9.8	7.60	N/A	N/A	560	2.55	43.5	0.35
21	8.1	7.11	N/A	N/A	148.8	2.3	5.5	0.45
22	15.0	7.57	N/A	N/A	150.8	1.9	0	0.45
23	11.4	7.19	N/A	N/A	192	2.25	4	0.6
24	14.0	7.83	6.30	171.4	267	4	150	2.4
25	14.6	9.54	7.12	178.2	494	2.35	22.5	0.25
26	15.0	9.18	7.76	175.2	530	2.2	11	0.35
27	17.3	9.23	6.68	152.5	641	1.9	7	0.5
28	16.5	7.31	5.04	171.7	645	1.8	34.5	0.25
29	21.8	7.81	7.61	167.7	947	2	70	0.25
30	16.3	7.47	7.93	187.9	970	2	4.5	0.3
31	12.0	7.48	5.34	166.6	480	2.45	9.5	0.35
32	21.3	7.12	3.84	154.1	380	2.15	2.5	0.4
33	16.7	7.25	7.10	145.8	585	2.2	27.5	0.25
34	10.8	7.48	N/A	N/A	486	2.1	8	0.35
35	21.7	8.06	N/A	N/A	329	2.05	130	0.4

36	20.9	7.97	N/A	N/A	182.6	2.1	140	0.85

[1]Water temperature, pH, dissolved oxygen, oxidation-reduction potential, and electrical conductivity were measured on-site using the Hach HQ30d Portable pH, Conductivity, Optical Dissolved Oxygen (DO), ORP, and ISE Multi-Parameter Meter.

[2]The oxyanions nitrate, sulfate and phosphate were measured from duplicate samples using the Hach DR-2800 Portable Spectrophotometer.

[3]pH was measured using the Hach IntelliCAL PHC201 Standard Gel Filled pH Electrode.

[4]DO (dissolved oxygen) was measured using the Hach IntelliCAL LDO101 Rugged Luminescent/Optical Dissolved Oxygen (LDO) Probe.

[5]N/A indicates that the parameter was not measured because the probe was unavailable.

[6]ORP (oxidation-reduction potential) was measured using the Hach IntelliCAL MTC101 Standard Gel Filled ORP Electrode.

[7]EC (electrical conductivity) was measured using the Hach IntelliCAL CDC401 Standard Conductivity Probe.

Table A2: Flowing Springs in Bears Ears: Arsenic and Heavy Metals – I[1]

Site No.	Ag (μg/L)	As (μg/L)	Bi (μg/L)	Cd (μg/L)	Co (μg/L)	Cr (μg/L)	Cu (μg/L)	Fe (μg/L)
17	0.0	16.1	0.7	4.3	0.0	1.9	0.0	13.0
18	0.5	31.3	0.1	3.1	0.0	0.2	0.0	38.4
19	1.3	32.0	0.1	3.4	0.0	3.9	0.3	265.7
20	2.5	65.2	0.0	3.9	0.0	1.5	91.3	16.8
21	0.6	27.6	0.0	5.5	0.6	2.2	0.0	80.9
22	0.7	11.0	0.0	2.0	1.2	7.2	0.0	457.9
23	1.2	13.1	0.0	5.6	0.0	5.4	1.8	62.3
24	1.9	30.3	0.0	123.3	0.0	111.7	56.8	9760.9
25	1.8	8.8	0.0	0.4	1.0	7.0	0.0	524.1
26	0.0	21.8	0.0	2.7	2.2	5.1	2.4	23.4
27	0.0	0.0	0.0	4.7	0.0	1.8	39.9	53.8
28	0.0	0.0	0.0	0.7	0.0	1.9	0.0	13.0
29	0.0	67.4	0.1	1.2	0.0	0.0	0.0	48.8
30	0.3	109.3	0.0	1.6	0.0	0.6	0.0	33.7
31	0.2	151.0	0.0	2.2	0.0	2.7	0.0	25.1
32	0.2	63.0	0.0	5.1	0.0	16.8	0.0	1032.4
33	0.0	32.7	0.0	3.2	0.0	3.9	0.0	274.4
34	0.0	261.8	0.2	17.5	0.0	1.2	0.0	14.9
35	0.0	83.9	0.0	11.5	0.0	96.3	6.2	5633.0

36	0.1	49.4	0.0	9.3	0.0	73.0	0.9	4491.0

[1]All elements were measured from duplicate samples with three aliquots per sample by digestion using the MARS 6 Microwave Reaction System, followed by analysis with the PerkinElmer Optima 8000 ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometer). Samples were not filtered prior to digestion.

Table A2: Flowing Springs in Bears Ears: Arsenic and Heavy Metals – II[1]

Site No.	Mn (μg/L)	Ni (μg/L)	Pb (μg/L)	Sb (μg/L)	Th (μg/L)	Ti (μg/L)	U (μg/L)	Zn (μg/L)
17	1.1	1.1	24.4	3.9	0.0	0.2	2.3	1.3
18	0.6	0.7	0.0	1.3	0.0	0.1	1.6	0.2
19	9.4	0.2	0.0	0.2	0.0	0.4	1.1	0.4
20	0.8	0.0	39.5	0.0	0.0	0.0	3.9	0.8
21	6.0	0.3	49.1	0.0	0.0	1.5	1.3	0.1
22	47.4	0.5	0.0	0.0	0.0	0.3	2.3	0.0
23	2.4	4.8	99.9	0.0	0.0	1.0	0.4	3.3
24	893.4	13.0	44.2	0.0	0.0	76.0	74.1	67.5
25	21.1	4.2	43.0	0.0	0.0	9.5	7.1	2.4
26	1.0	5.5	44.3	0.0	0.0	1.1	1.9	1.3
27	1.3	65.6	67.9	0.0	0.0	0.1	7.7	26.3
28	0.0	0.0	32.9	0.0	0.0	0.0	3.1	10.4
29	39.2	0.0	55.7	4.1	0.0	0.1	2.4	829.0
30	1.0	1.5	51.8	0.0	0.0	0.2	0.0	7.4
31	0.9	0.0	13.2	1.1	0.0	0.3	1.0	4.0
32	62.6	6.9	52.1	0.0	0.0	19.2	10.2	4.1
33	4.4	0.0	53.0	0.0	0.0	2.2	6.5	2.0
34	0.5	0.0	63.2	0.0	0.0	0.4	2.2	1.4
35	113.2	5.5	47.6	0.0	0.0	223.2	62.2	12.9

36	77.3	26.3	0.0	0.0	0.0	191.7	43.8	11.4

[1]All elements were measured from duplicate samples with three aliquots per sample by digestion using the MARS 6 Microwave Reaction System, followed by analysis with the PerkinElmer Optima 8000 ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometer). Samples were not filtered prior to digestion.

FIGURE CAPTIONS

Fig. 1 On December 28, 2016, President Barak Obama created Bears Ears National Monument on 1.35 million acres in southeastern Utah, primarily to protect the archaeological heritage of the Basketmaker and Ancestral Puebloan cultures.

Fig. 2 Water samples were collected from 36 flowing springs in Bears National Monument (Tables 1a-c). An additional nine non-flowing springs were mapped (Table 2).

Fig. 3 Based on CFC concentrations, the water emerging from Pine Spring (Site No. 2, Tables 1a-c) had a groundwater residence time of (63.9 ± 11.3) years, where the uncertainty is one standard deviation. The stable isotope composition indicated that the spring is recharged by snowmelt or spring rains with negligible evaporation after precipitation (Table 1b, Fig. 11). Spring discharge was too diffuse for measurement.

Fig. 4 An unnamed spring (Site No. 7, Tables 1a-c) allows growth of a hanging garden. Samuel Nofchissey is collecting a water sample from beneath the sandstone ledge. Based on CFC concentrations, the water emerging from the spring had a groundwater residence time of (57.3 ± 17.1) years, where the uncertainty is one standard deviation. The stable isotope composition indicated that the spring is recharged by fall rains with significant evaporation after precipitation (Table 1b, Fig. 11). Spring discharge was too diffuse for measurement.

Fig. 5 Samuel Nofchissey (left) and Morgan Abbott (right) are collecting water samples at an unnamed spring (Site No. 14, Tables 1a-c) for measurement of CFC concentrations. Based on CFC concentrations, the water emerging from the spring had a groundwater residence time of (27.0 ± 18.6) years, where the uncertainty is one standard deviation. The stable isotope composition indicated that the spring is recharged by late summer monsoon rains with negligible evaporation after precipitation (Table 1b, Fig. 11). Spring discharge was too diffuse for measurement.

Fig. 6 Based on the stable isotope composition, Duck Lake (Site No. 19, Tables 1a-b) is recharged by snowmelt or spring rains with significant evaporation after precipitation (Table 1b, Fig. 11). Spring discharge was too diffuse for measurement.

Fig. 7 Based on the stable isotope composition, Crystal Spring (Site No. 25, Tables 1a-b) is recharged by fall rains with negligible evaporation after precipitation (Table 1b, Fig. 11). Spring discharge was measured as 4.75 L/min.

Fig. 8 Although Rock Spring (Site No. 37, Table 2) is a mapped spring (USGS, 2018), it was found to be nothing but muddy hoof prints.

Fig. 9 Red House Spring (Site No. 38, Table 2) was marked only by a field of salt at the time of observation.

Fig. 10a Castle Ruins (Site No. 43, Table 2) consists of Ancestral Puebloan dwellings beneath a sandstone ledge.

Fig. 10b Although water staining from a spring could be seen beneath the roof of the ledge at Castle Ruins and the imprints of water drops were visible beneath the spring (note pen for scale), no water was flowing at the time of observation.

Fig. 11. A comparison of the stable isotopes of groundwater emerging from springs in Bears Ears with the local meteoric water line shows that the groundwater is

derived from local precipitation, rather than from regional groundwater flow. The most likely recharge months for each spring were determined by comparison with the local meteoric water line or the probable evaporation lines.

Fig. 12. Nearly all recharge of springs in Bears Ears results from snowmelt or spring rains in April and May, late summer monsoon rains in August, and fall rains in October and November.

Fig. 13. The mean residence time for groundwater emerging from 18 springs in Bears Ears is (41.8 ± 12.1) years, where the uncertainty is the standard deviation. These long residence times indicate that springs would remain as persistent water sources even after droughts lasting for several decades.

Fig. 14. According to the single-factor ANOVA test ($P = 0.009$), springs that are recharged by late summer monsoon rains have shorter groundwater residence times than springs that are recharged by snowmelt or spring rains or by fall rains.

Fig. 15a Petroglyphs in the Glen Canyon Linear Petroglyph Style were associated with springs with long (> 50 years) groundwater residence times. The petroglyphs were created by the Western Archaic culture and could date as far back as 6000 BC. Characteristic themes include concentric circles, mountain sheep, deer, and plant motifs.

Fig. 15b Petroglyphs in the Glen Canyon Linear Petroglyph Style were associated with springs with long (> 50 years) groundwater residence times. The petroglyphs were created by the Western Archaic culture and could date as far back as 6000 BC. A characteristic theme is the rabbit-eared anthropomorph visible in the middle left of the photo.

Fig. 15c Petroglyphs in the Glen Canyon Linear Petroglyph Style were associated with springs with long (> 50 years) groundwater residence times. The petroglyphs were created by the Western Archaic culture and could date as far back as 6000 BC. A characteristic theme is the anthropomorph with long tentacle-like arms visible in the middle right of the photo.

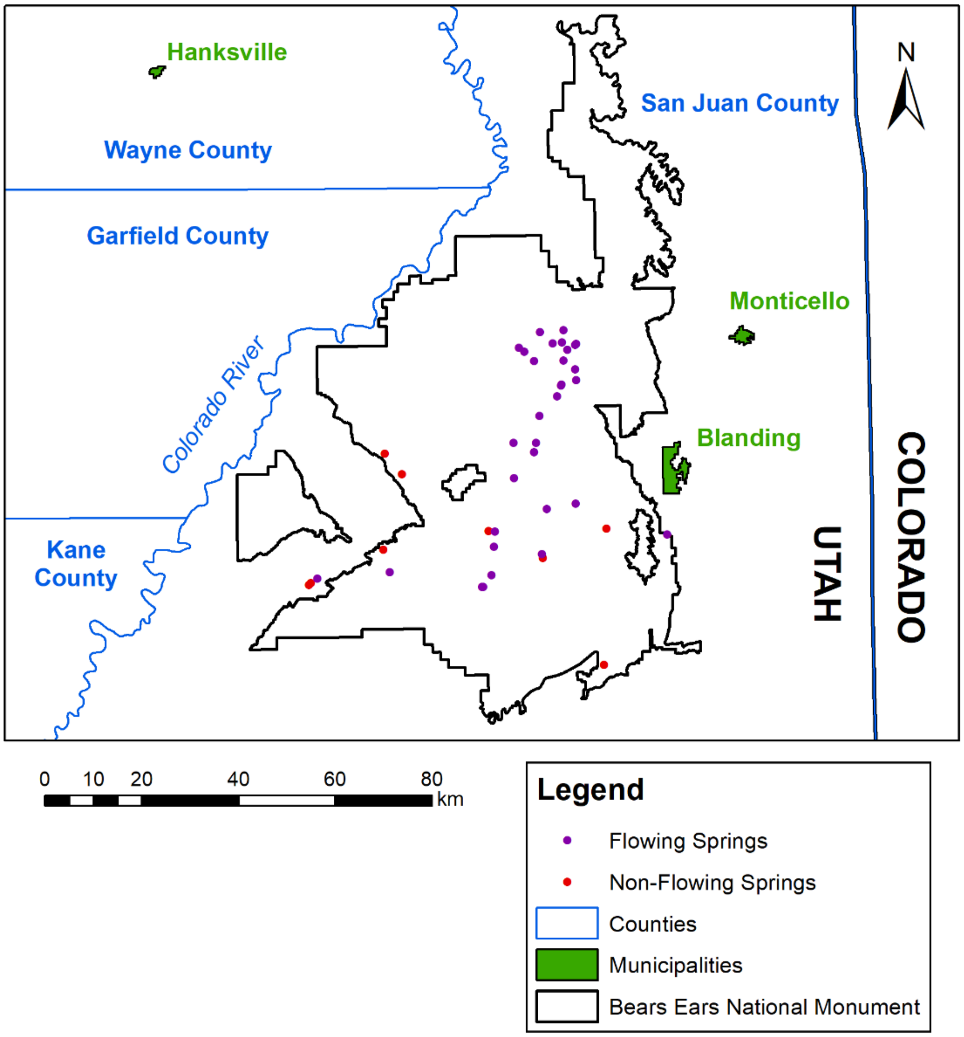
Hanksville
Wayne County
Garfield County
San Juan County
Monticello
Blanding
Colorado River
Kane County
UTAH
COLORADO
N
0
10
20
40
60
80
km
Legend
Flowing Springs
Non-Flowing Springs
Counties
Municipalities
Bears Ears National Monument

Figure 1

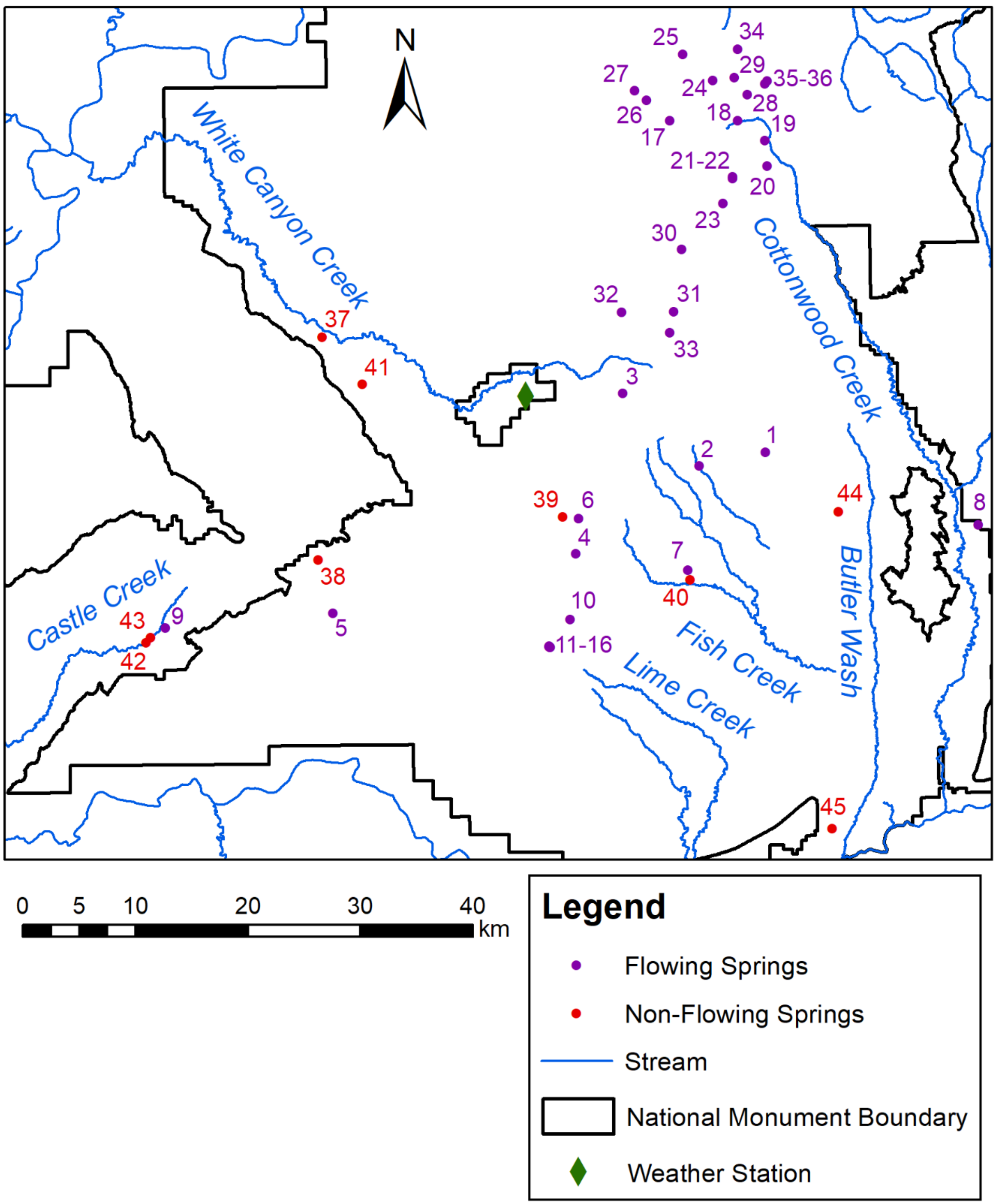
N
White Canyon Creek
Cottonwood Creek
Castle Creek
Fish Creek
Lime Creek
Butler Wash
25
34
29
35-36
27
24
28
26
18
19
17
21-22
20
23
30
32
31
33
37
41
3
2
1
39
6
4
44
8
7
40
38
43
9
42
5
10
11-16
45
0
5
10
20
30
40
km
Legend
Flowing Springs
Non-Flowing Springs
Stream
National Monument Boundary
Weather Station

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10a

Figure 10b

Figure 10b

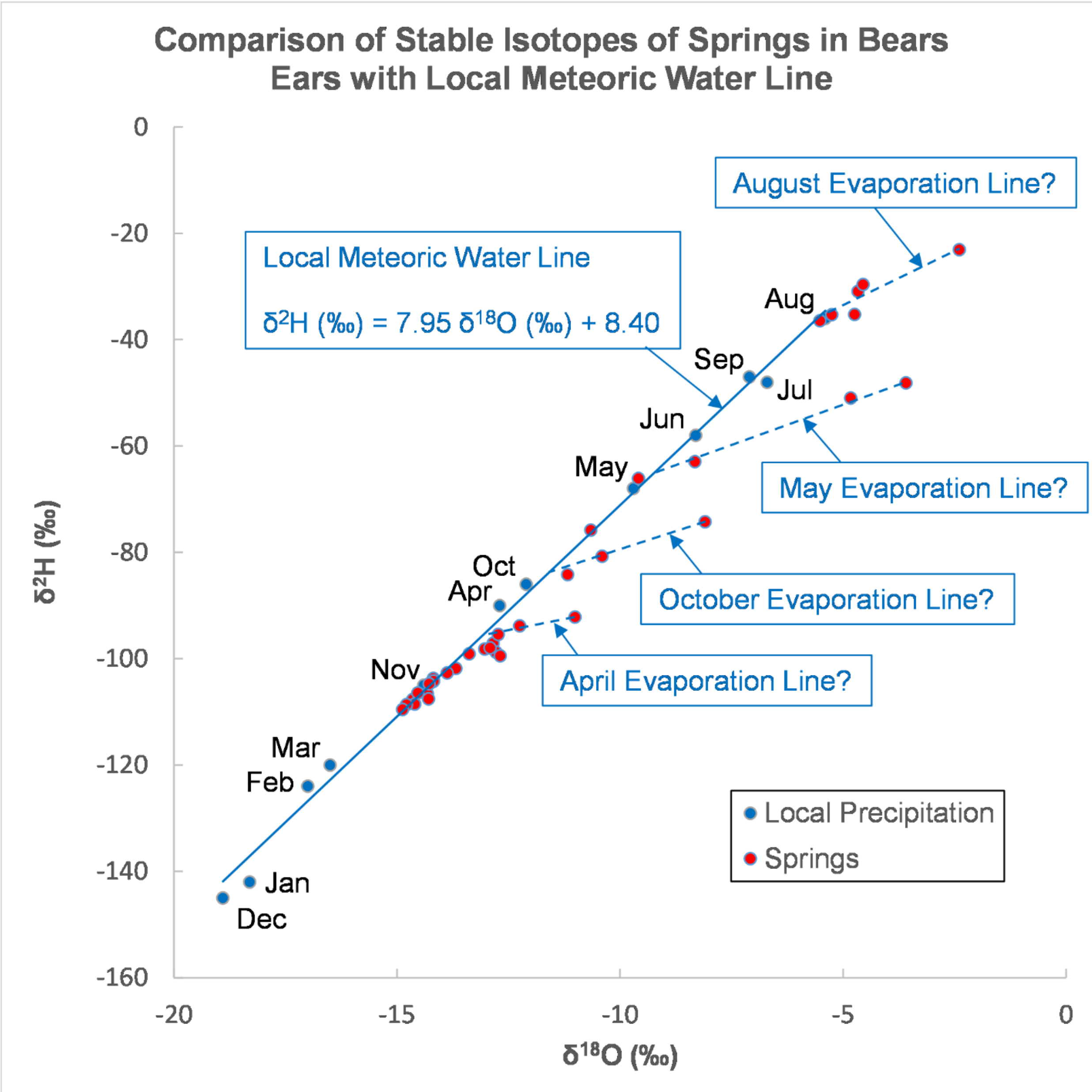
Comparison of Stable Isotopes of Springs in Bears Ears with Local Meteoric Water Line
Local Meteoric Water Line
δ2H (‰) = 7.95 δ18O (‰) + 8.40
August Evaporation Line?
May Evaporation Line?
October Evaporation Line?
April Evaporation Line?
Aug
Sep
Jul
Jun
May
Oct
Apr
Nov
Mar
Feb
Jan
Dec
Local Precipitation
Springs
δ2H (‰)
δ18O (‰)
0
-20
-40
-60
-80
-100
-120
-140
-160
-20
-15
-10
-5
0

Figure 11

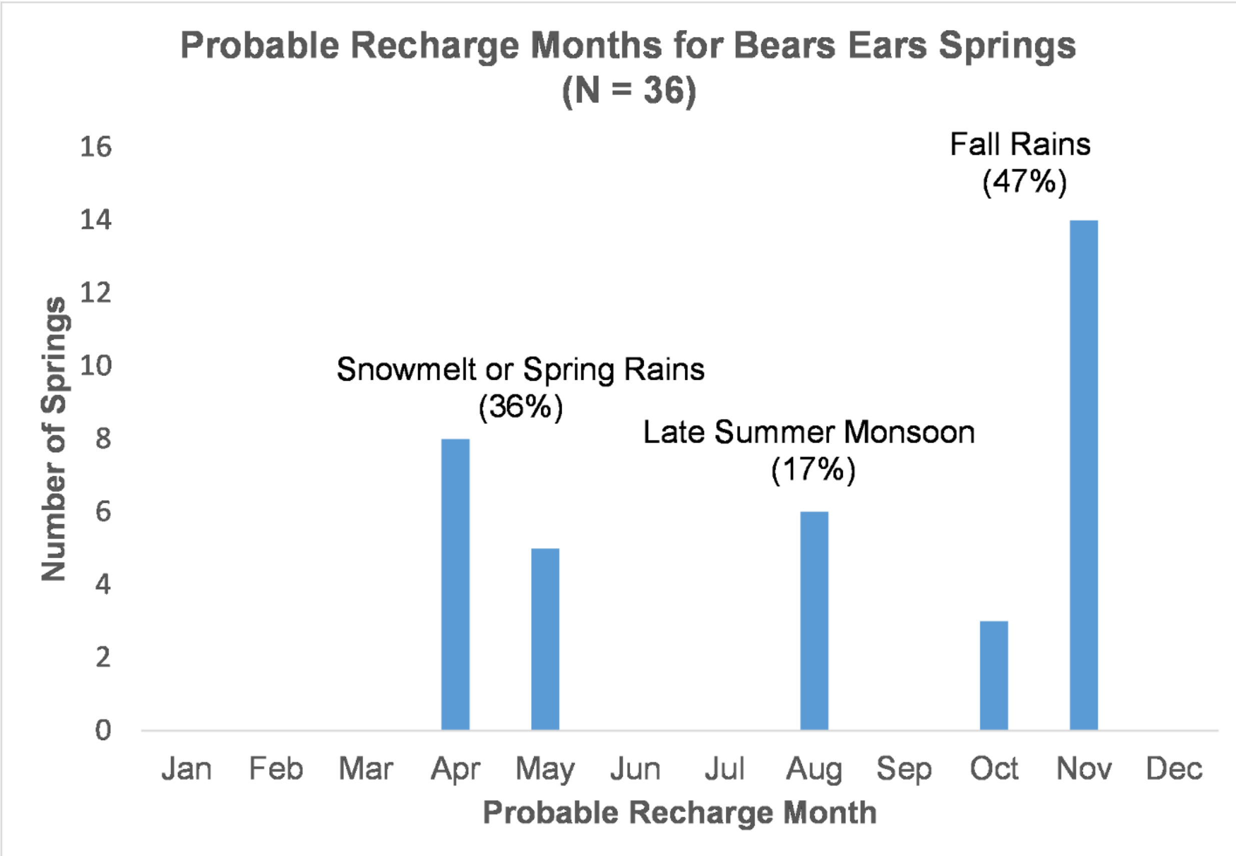
Probable Recharge Months for Bears Ears Springs
(N = 36)
Fall Rains
(47%)
Snowmelt or Spring Rains
(36%)
Late Summer Monsoon
(17%)
Number of Springs
0
2
4
6
8
10
12
14
16
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Probable Recharge Month

Figure 12

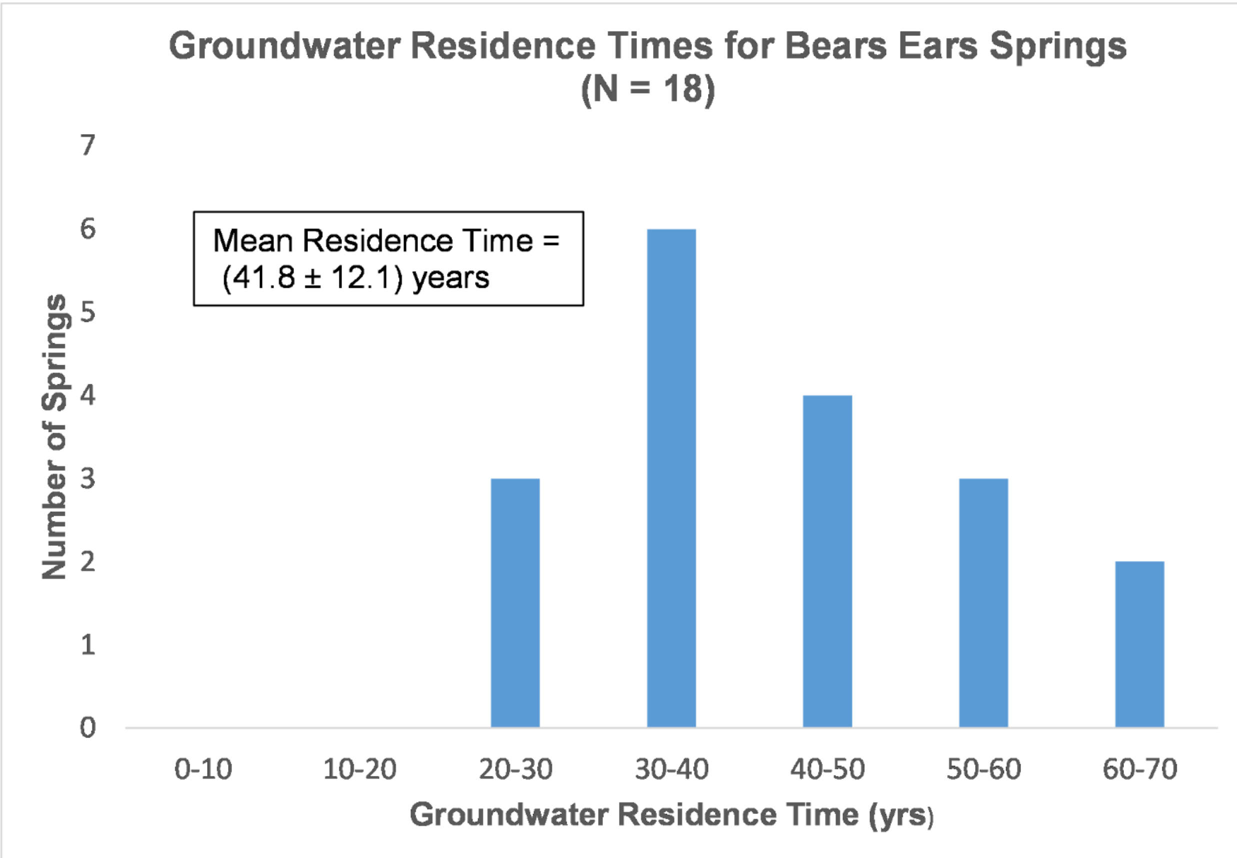
Groundwater Residence Times for Bears Ears Springs
(N = 18)
Mean Residence Time =
(41.8 ± 12.1) years
Number of Springs
0
1
2
3
4
5
6
7
0-10
10-20
20-30
30-40
40-50
50-60
60-70
Groundwater Residence Time (yrs)

Figure 13

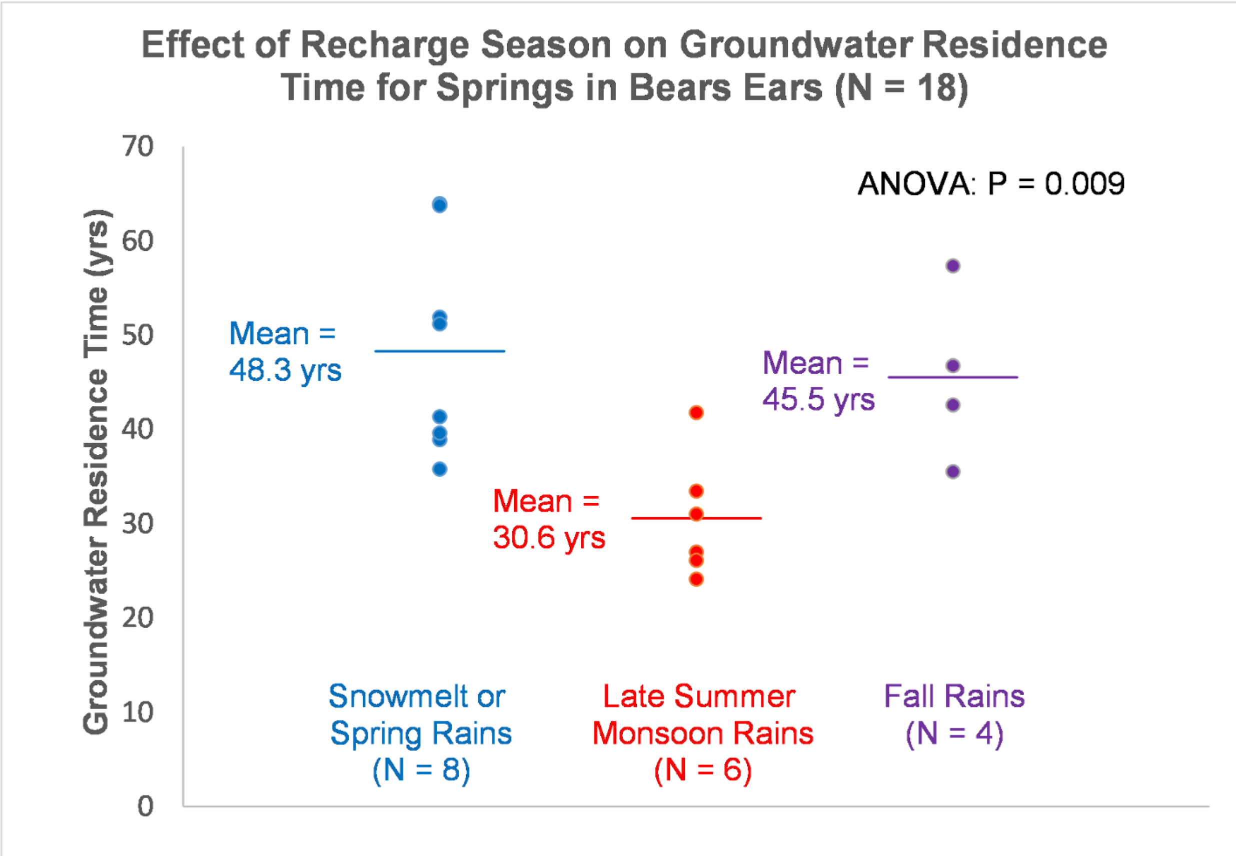
Effect of Recharge Season on Groundwater Residence Time for Springs in Bears Ears (N = 18)
ANOVA: P = 0.009
Groundwater Residence Time (yrs)
70
60
50
40
30
20
10
0
Mean = 48.3 yrs
Mean = 30.6 yrs
Mean = 45.5 yrs
Snowmelt or Spring Rains (N = 8)
Late Summer Monsoon Rains (N = 6)
Fall Rains (N = 4)

Figure 14

Figure 15a

Figure 15b

Figure 15c