

Groundwater Age Dating in and Near Arches National Park, Utah

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Executive Summary

National Park Service (NPS) water managers are concerned about the impact that current and/or future water use will place on water resources within Arches National Park located near Moab, in southeastern Utah. Springs and seeps within Courthouse Wash and Sevenmile Canyon (a tributary of Courthouse Wash), which support hanging gardens, riparian communities, and the baseflow within Courthouse Wash, are connected to the Moab Member of the Curtis Formation aquifer. This aquifer underlies private and state-owned land to the west and northwest of the park boundary (Hurlow and Bishop, 2003). The NPS is concerned about the impacts that current and future groundwater withdrawal from wells adjacent to the park could have on the springs and seeps in Courthouse Wash and Sevenmile Canyon.

The objectives of this study were to determine the age and origin of recharge for waters issuing from four springs in Courthouse Wash and Sevenmile Canyon in Arches National Park, and waters from four wells screened within the Moab Member of the Curtis Formation, Slickrock Member of the Entrada Sandstone, or the Navajo Sandstone aquifers adjacent to Courthouse Wash and Sevenmile Canyon. Noble gas thermometry and stable isotopes were used to estimate the recharge elevation for these waters, and the environmental tracers tritium and chlorofluorocarbons were used to determine the age of

waters within these aquifers.

The age data suggest that the oldest waters are from Archview Campground Well, Dalton Well #2, and Canyonlands Airport Well, located to the north and west of Arches National Park. The noble gas data for these sites indicate that these sites are recharged at predominantly higher altitudes than other sites in the study, which would corroborate longer groundwater flow paths suggested by the older waters at these sites. The noble gas data also indicate that Courthouse Wash Boundary Spring, located north of the other three springs, and Arches Headquarters Well, located at the southern end of the park, also may receive a portion of water that recharges at high altitudes. However, there is an indication of some younger water at both these sites, suggesting that they are receiving a mix of younger and older waters. The apparent ^{14}C ages for these two sites indicates that Courthouse Wash Boundary Spring water is closer in age to the Archview Campground, Dalton #2, and Canyonlands Airport Wells. Although the noble gas data suggest that the Arches Headquarters Well recharges at a high altitude, the age of the water at this site suggests that the well may be capturing a significant portion of younger water following a shorter, more local flow path, which likely recharges at a lower elevation than as indicated by the noble gas data. Most likely, the source waters for Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring are from more local recharge areas, given the younger groundwater ages of these springs.

The stable isotope data do not support the very high recharge elevations indicated by the noble gas data. Waters recharged at higher elevations should have more negative δD and $\delta^{18}\text{O}$ values than measured in the current study. Therefore, the stable isotope data indicate lower recharge elevations than the noble gas data. Further sampling is

needed, however, to resolve this discrepancy.

Introduction

As demand for water continues to increase in the western United States, National Park Service (NPS) water managers are concerned about the impact that current and/or future water use will place on water and water-related resources within the parks. Of particular interest in this study are water resources within Arches National Park located near Moab, in southeastern Utah. Courthouse Wash, located in the southwestern section of the park, is the only (nearly) perennial stream in this part of the park, and supports a stable riparian environment that is critical to the ecology of the park (HurLOW and Bishop, 2003).

Springs and seeps within Courthouse Wash and Sevenmile Canyon (a tributary of Courthouse Wash), which support hanging gardens, riparian communities, and the baseflow within Courthouse Wash, are connected to the Moab Member of the Curtis Formation aquifer. This aquifer underlies private and state-owned land to the west and northwest of the park boundary (HurLOW and Bishop, 2003). The NPS is concerned about the impacts that current and future groundwater withdrawal from wells adjacent to the park could have on the springs and seeps in Courthouse Wash and Sevenmile Canyon. More specifically, the NPS would like to know if withdrawals from existing water wells within the Courthouse Wash-Sevenmile Canyon watershed have the potential to capture groundwater that would otherwise discharge at springs and seeps in Courthouse Wash and Sevenmile Canyon within the park boundary.

To this end, the objectives of this study were to determine the age and origin of

recharge for waters issuing from springs in Courthouse Wash and Sevenmile Canyon in Arches National Park, and waters from wells screened within the Moab Member of the Curtis Formation, Slickrock Member of the Entrada Sandstone, and the Navajo Sandstone aquifers adjacent to Courthouse Wash and Sevenmile Canyon. Noble gas thermometry and stable isotopes were used to estimate the recharge elevation for these waters, and the environmental tracers tritium and chlorofluorocarbons were used to determine the age of waters within these aquifers.

Study Site Description

Water samples were collected from three springs located within the southwestern section of Arches National Park (Courthouse Wash Boundary Spring and Sleepy Hollow Spring in Courthouse Wash, and Poison Ivy Spring in Sevenmile Canyon), one spring located just outside of the Arches National Park boundary in Sevenmile Canyon (Sevenmile Canyon Boundary Spring), three wells located upstream of the park boundary in the Courthouse Wash watershed (Archview Campground Well, Dalton Well #2, and Canyonlands Airport Well), and one well located at the Arches National Park headquarters (fig. 1). The springs sampled are part of the Courthouse-Sevenmile spring system, that supports base flow within Courthouse Wash and other important riparian ecological systems within the park (Hurlow and Bishop, 2003). The source waters for the sampled springs and wells are from three Jurassic age aquifers (from youngest to oldest): the Moab Member of the Curtis Formation, the Slickrock Member of the Entrada Sandstone, and the Navajo Sandstone. Table 1 gives the locations and other field information of the eight sites sampled.

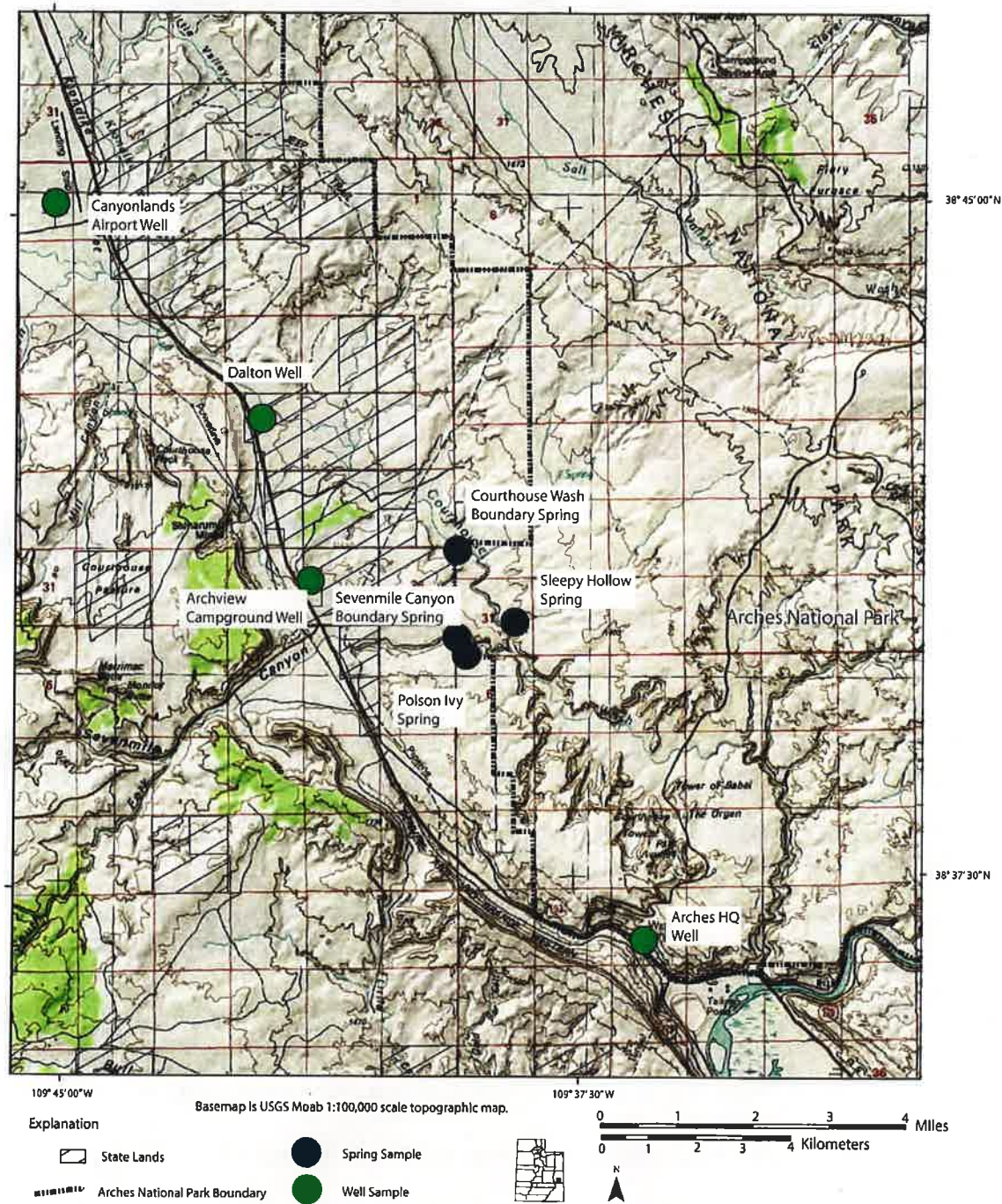


Figure 1. Location map of groundwater sampling sites.

Table 1. Summary of sampling sites.

<i>Sample Site</i>	<i>East¹</i>	<i>North¹</i>	<i>Elevation²</i>	<i>Total Well Depth³</i>	<i>Screen Interval⁴</i>	<i>Source unit⁵</i>	<i>Sample Location</i>
Courthouse Wash Boundary Spring	614206	4282707	1305	--	--	Qa/Jem	pool in wash
Sevenmile Canyon Boundary Spring	617149	4280806	1310	--	--	Base of Jem	below seep
Poison Ivy Spring	617400	4280523	1290	--	--	Base of Jem	below seep
Sleepy Hollow Spring	618436	4281215	1285	--	--	Base of Jem	below seep
Archview Campground Well	614206	4281747	1385	118	100-118	Jes	hose bib near well
Arches Headquarters Well	620919	4274848	1245	52	35-52	Jn	pump house hose bib upstream of flow gage and chlorinator
Dalton Well #2	613025	4285382	1340	152	--	Jcm/Jes	hose bib on well
Canyonlands Airport Well	608463	4290192	1385	366	--	Jes	hydrant next to well on south side of airport taxiway

¹ Coordinates are in meters UTM zone 12N NAD 27 except for Dalton Well #2 which is given in UTM NAD 83

² Elevation of spring or land surface at well site in meters above sea level

³ Well depth in meters below land surface

⁴ Depth of screened interval in meters below land surface

⁵ Geologic unit from which spring issues or in which well is completed; Qa=Unconsolidated alluvium, Jem=Moab Member of the Curtis Formation, Jes=Slick Rock Member of the Entrada Sandstone, Jn=Navajo Sandstone

-- denotes no data

The Moab Member of the Curtis Formation is a pale-orange, gray-orange, pale-yellow-brown, or light-gray, resistant sandstone that forms an unconformable capping surface on many of the Entrada Sandstone cliffs within the area (Doelling, 2000). It is a fine- to medium-grained, calcareous, massive, cliff forming sandstone that weathers to light gray or white, exhibits low angle cross-stratification, and is highly jointed in outcrop (Doelling, 2000). The Moab Member outcrops as northwest-trending jointed benches on

either side of Salt Valley (Doelling, 2000) (fig. 1). The thickness of the Moab Member ranges from 60 to 120 feet within Arches National Park (Doelling, 2000). To the north and northwest of Courthouse Wash and Sevenmile Canyon, the Moab Member aquifer is confined, while to the southwest of Courthouse Wash and Sevenmile Canyon, the aquifer is unconfined (Hurlow and Bishop, 2003).

The Slick Rock Member of the Entrada Sandstone is a massive, red-orange or brown, very fine to fine-grained, calcite and iron-oxide cemented sandstone containing scattered medium to coarse grains (Doelling, 2000). It weathers to form smooth cliffs and bare-rock slopes that are usually striped or banded in color, and may either be distinctly cross-stratified or planar bedded (Doelling, 2000). Most of the arches in Arches National Park are positioned within the unit (Doelling, 2000). The Slick Rock Member is 200 to 350 feet thick within the park (Doelling, 2000).

The Navajo Sandstone is an orange to light-gray, fine-grained, well-sorted, massive, calcite and quartz cemented sandstone that is known for its high-angle cross bedding (Doelling, 2000). The unit was deposited as eolian sands in regionally extensive dune fields that covered the area in the Early Jurassic (Stokes, 1986). The unit is divided into cross-bed sets that are generally 15 to 25 feet thick, the boundaries of which are thought to represent former water table surfaces (Doelling, 2000). The unit also contains localized gray to pink-gray, thin, lacustrine limestone deposits that are interpreted to have developed in oases, playas, or interdune lakes (Stokes, 1991; Doelling, 2000). The formation is 200 to 550 feet thick in the Arches area, and the variation in thickness is due to the fact that the upper surface of the unit is a regional unconformity (Doelling, 2000).

All four springs sampled in this study are sourced in the Moab Member aquifer.

Two of the sampled springs are located in Courthouse Wash (Courthouse Wash Boundary Spring and Sleepy Hollow Spring), and two of the sampled springs are located in Sevenmile Canyon (Sevenmile Canyon Boundary Spring and Poison Ivy Spring). Of the springs sampled in the study, only Courthouse Wash Boundary Spring had a large pool associated with the discharge outlet of the spring, where it emerged between the contact of the alluvium in the wash and the Moab Member (fig. 2). The other three springs sampled emerged as numerous, multi-leveled seeps within alcoves in the canyon walls of Courthouse Wash and Sevenmile Canyon, forming highly vegetated hanging gardens (fig. 2).

The wells sampled in this study lie to the south and/or west of Arches National Park and to the south, west, and/or northwest of the springs sampled. The Arches Headquarters Well is completed in the Navajo Sandstone and the Archview Campground Well and the Canyonlands Airport Well are completed in the Slickrock Member of the Entrada Sandstone. The Dalton Well #2 is completed near the contact between the Moab Member of the Curtis Formation and the Slickrock Member of the Entrada Sandstone. Total well depths ranged from approximately 172 ft (Arches Headquarters Well) to 1200 ft (Canyonlands Airport Well). Most of the wells sampled either had a separate hydrant or a spigot on the well itself for sampling.

Methods

Noble gas thermometry and stable isotopes were used to estimate the recharge temperatures and elevations, and the environmental tracers tritium and chlorofluorocarbons were used to determine the age of waters collected from the eight



Figure 2. Top: Photo of Courthouse Wash Boundary Spring and associated pool. Bottom: Photo of Sleepy Hollow Spring showing multi-level seeps and hanging gardens.

sampling sites.

Using Noble Gases to Determine Recharge Temperature and Elevation

Many of the gases that are dissolved in surface and groundwater originate in the atmosphere, including the noble gases He, Ne, Ar, Kr, and Xe. The solubility of these gases into recharging (fresh) waters depends mostly upon three parameters: temperature, pressure (elevation), and excess air (due to entrapment of air during water table fluctuations). Because the noble gases are non-reactive, and the production of these gases within aquifers is negligible, the concentrations of these gases dissolved within groundwater remain relatively constant as the water moves through the subsurface. Therefore, the dissolved noble gas concentrations within groundwater potentially provide a record of the temperature and elevation at which the water was recharged (that is, when the water was last in contact with the atmosphere, just above the water table). Since the solubility of each gas is uniquely dependent upon temperature, pressure (elevation), and the amount of excess air, it is theoretically possible to solve for each of the three unknowns if the concentrations of at least three different noble gases within the groundwater can be measured. However, this is only possible if perfect measurements of dissolved gas concentrations can be made. Small errors in the data measurements and analysis yield large uncertainties in the derived values of recharge temperature ($\pm 6^\circ\text{C}$), recharge elevation ($\pm 1500\text{ m}$), and excess air (Manning and Solomon, 2003). In dissolved gas studies, when the recharge elevation is known a priori as in studies that use noble gases for paleotemperature reconstructions (Mazor, 1972; Herzberg and Mazor,

1979; Ballentine and Hall, 1999; Aeschbach-Hertig et al., 2000), it is possible to solve for the two remaining unknowns (recharge temperature and excess air). If the recharge elevation is known, it is possible to determine the recharge temperature with an uncertainty of only ± 1 °C (Manning and Solomon, 2003).

To determine all three unknowns using real data some additional information and/or assumptions are needed. Manning and Solomon (2003) have shown that in the Wasatch Mountains in northern Utah, the relationship between recharge temperature and elevation is similar to the atmospheric lapse curve for adiabatic cooling. Air temperature data from meteorological stations near Moab, Utah show that the mean annual temperature in Moab is 13.2 °C and decreases by 6 °C per 1,000 m into the La Sal Mountains. Therefore, if it is assumed that recharge temperature also decreases by 6 °C per 1,000 m, it is possible to solve for recharge temperature, elevation, and excess air for samples in which a suite of noble gases is analyzed (see also studies by Zuber et al., 1995 and Aeschbach-Hertig et al., 1999).

Use of Stable Isotopes

The most common stable isotopes used in groundwater studies are those of hydrogen (^2H or deuterium) and oxygen (^{18}O) as these occur naturally in the water molecule itself. For water samples, $\delta^2\text{H}$ (δD) and $\delta^{18}\text{O}$ values are referenced against Vienna Standard Mean Ocean Water (VSMOW), where δD and $\delta^{18}\text{O}$ values are defined as 0 ‰ (per mil). Fractionation of these isotopes within precipitation depends on a number of factors, including temperature of condensation, and the history (origin and trajectory) of the water mass, and, therefore, waters from different areas will often have

different isotopic “fingerprints”.

Since the isotopic composition of water is temperature dependent, and because there is a relationship of decreasing temperature with increasing elevation, the stable isotopic composition of waters is indirectly a function of elevation. Waters that are recharged at higher elevations become more enriched in the lighter isotopes (i.e. δD and $\delta^{18}O$ become more negative with respect to VSMOW). However, due to the high variability in storm histories, temperature, and other fractionation processes (e.g. evaporation of rain), the isotopic composition of precipitation can vary between different precipitation events, and can even vary within the same precipitation event. In order to use stable isotope data to interpret recharge elevation, a time-series of isotopic composition values within precipitation, and a statistically significant number of groundwater samples in the recharge area must be measured, which was beyond the scope of this study. Therefore, the stable isotope data were used as a general check on the noble gas thermometry. Isotopic trends between the sampling sites were also identified.

Using Chlorofluorocarbons and Tritium as Indicators of Groundwater Ages

Chlorofluorocarbons (CFCs) were first produced in the 1930s, and their production reached a peak in the 1970s and 1980s. It was discovered, however, that the release of these chemicals into the atmosphere was leading to the depletion of the ozone layer and measures were taken to reduce or eliminate the production of CFCs. By 2001, atmospheric CFC concentrations were stable or falling due to regulations imposed by the Montreal Protocol to Reduce Substances that Deplete the Ozone Layer, enacted in 1987,

and subsequent amendments to the Montreal Protocol (Plummer and Busenberg, 2006).

There are three CFCs that are commonly used to date groundwater: CFC-11, CFC-12, and CFC-113. The atmospheric concentrations (atmospheric mixing ratio) of these three CFCs each follows a unique concentration vs. time curve (fig. 3). By assuming that the sampled water was in solubility equilibrium with the unsaturated zone air at the time of recharge, the recharge temperature and elevation are known, and the CFC mixing ratio input function for the area of interest is known (Plummer et al., 2006), one can match the concentrations of CFCs measured in the water sample to a specific recharge year based on the CFC concentration curves. This method, therefore, can be used to date waters that were recharged after the 1940s. For more information on using CFCs to date groundwaters see Plummer et al. (2006).

There are several limitations to the use of CFCs for age dating. First, due to the decline in CFC production, the atmospheric mixing ratio of CFC-11 began declining in 1994. By 2001 it had dropped to approximately the same value as 1989; thus the CFC-11 dates are not unique from the period of 1989 to the present. This same issue exists for CFC-113 starting in 1991. Second, during sampling and analysis, CFC groundwater samples are highly susceptible to “contamination;” that is, the sample contains a CFC concentration that is greater than is possible for a water in solubility equilibrium with air at the time the maximum CFC mixing ratio occurred in the atmosphere (Plummer and Busenberg, 2006), and, therefore, contaminated samples do not yield reliable groundwater recharge dates.

The natural tracer tritium (^3H) was also used to determine the apparent groundwater age using the tritium/helium-3 ($^3\text{H}/^3\text{He}$) dating method. Tritium is a

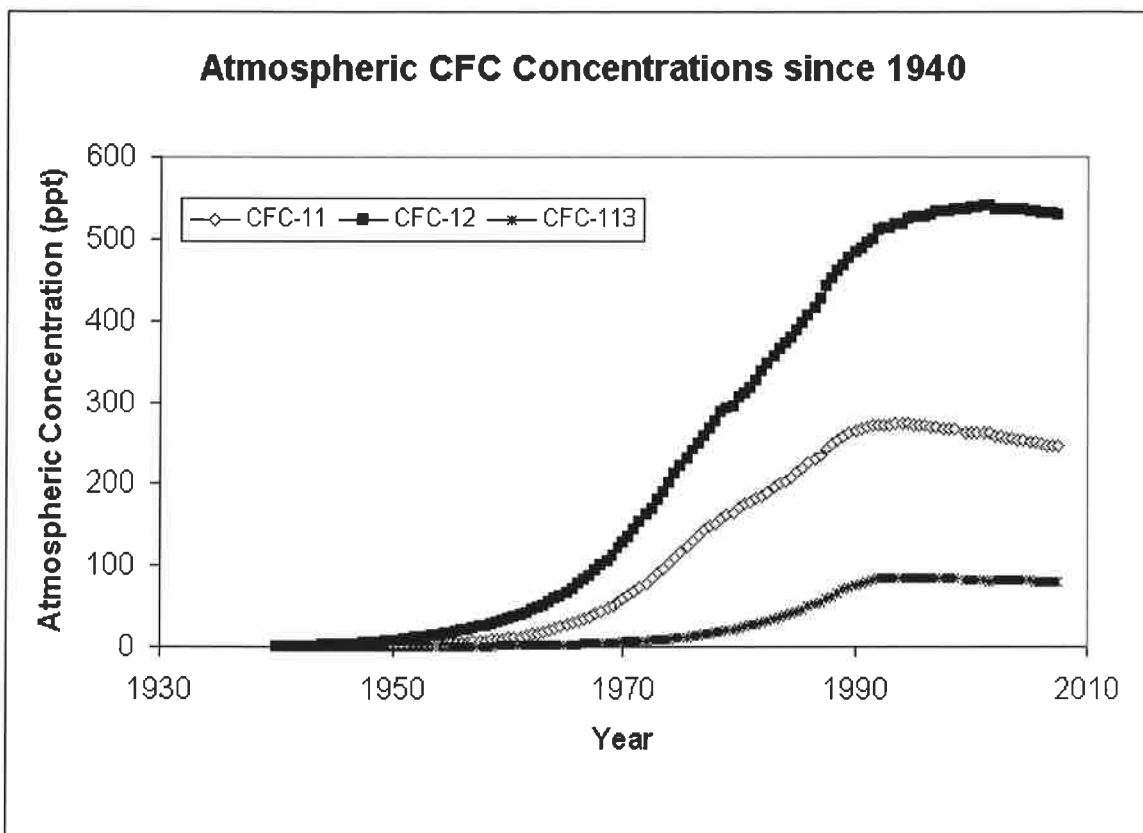


Figure 3. Atmospheric concentrations of CFCs since 1940 for North America.

radioactive isotope of hydrogen that decays to ^3He with a half-life of 12.4 years. Tritium is produced naturally in the atmosphere, and the concentration in precipitation ranges between 6-8 tritium units (TU, where 1 TU is equal to 1 ^3H atom per 10^{18} atoms of ^1H). In the early 1950s and 1960s, above ground thermonuclear testing released large amounts of tritium into the atmosphere, causing tritium concentrations in precipitation over the northern hemisphere to peak at over 1,000 TU. After above ground thermonuclear testing was banned in the early 1960s, concentrations in the atmosphere have been declining, and for the most part have returned to pre-bomb values.

The apparent $^3\text{H}/^3\text{He}$ age of a water sample is defined as:

$$t = \lambda^{-1} \ln \left(\frac{{}^3\text{He}^*}{{}^3\text{H}} + 1 \right)$$

where λ is the tritium decay constant and ${}^3\text{He}^*$ is the ${}^3\text{He}$ concentration from tritiogenic sources. Unlike CFCs, this method requires the measurement of a parent-daughter ratio, and therefore the tritium input function does not need to be known. The ${}^3\text{H}/{}^3\text{He}$ dating method is most suitable for dating relatively young waters, and provides an independent check of age results obtained from CFCs. For additional details regarding the ${}^3\text{H}/{}^3\text{He}$ dating method see Solomon and Cook (2000).

Sampling Methods

Samples were collected for noble gases, tritium, chlorofluorocarbons (CFCs), and for the stable isotopes of hydrogen and oxygen. Measurements of water temperature, dissolved oxygen, and total dissolved gas pressure were also taken in the field. All samples were collected over a five day period from November 9-13, 2007.

At the well sites, at least three well volumes were purged from each well before sampling, with the exception of Dalton Well #2. When the pump was turned on to purge this well, up to three wells at this site may have been pumping simultaneously, and it is unknown what percentage of the discharge was produced by Dalton Well #2 (Bob Beeman, owner of Dalton Wells, personal communication). The wells were sampled as close as possible to the well heads, and before passing through any water treatment, to minimize risk of contamination of the samples (fig. 4).

At the spring sites, risk of some atmospheric contamination was unavoidable at Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring, as samples at these sites could only be collected after the water had fallen from seeps on the



Figure 4. Top: Photo of hose bib used to sample well at Archview Campground.
Bottom: Photo of hose bib used to sample well at Arches National Park Headquarters.



Figure 4 (cont.). Top: Photo of Dalton Well #2 and hose bib used for sampling. Bottom: Photo of Canyonlands Airport Well and hydrant used for sampling.

canyon walls (fig. 2). Therefore, results of samples collected from these springs may not be accurately representing conditions within the aquifer. The only site where this was not an issue was at Courthouse Wash Boundary Spring, which has a large pool at the point of discharge where the samples were collected (fig. 2).

Collection of Noble Gas Samples

At the spring sites, noble gases were sampled using passive diffusion samplers constructed at the University of Utah. These samplers consist of gas permeable silicon tubing attached to a short length of 3/16" outer-diameter (OD) soft copper tubing. The diffusion samplers were submerged in the discharging spring waters for at least 24 hours to allow for the gas in the samplers to equilibrate with the dissolved gases in the water. After equilibration, the samplers were removed and the copper tubing was sealed using a cold-weld crimping device.

Generally, it is best if the diffusion samplers can be submerged near the point of discharge so as to minimize any re-equilibration of the gases within the water with atmospheric gases. The only site where this was possible was at Courthouse Wash Boundary Spring. At the other three spring sites, which emerged as diffuse seeps from the canyon walls, the diffusion samplers were left in either 5 gallon buckets that were used to collect the spring waters below the seeps at Sevenmile Canyon and Sleepy Hollow springs (fig. 5, top), or submerged within a shallow pool that was dug out below Poison Ivy Spring to collect water from the seep (fig. 5, bottom). Because the water was in contact with the atmosphere for a short time while it was falling from the seep to the collection point, there may have been some exchange of gases between the water and the

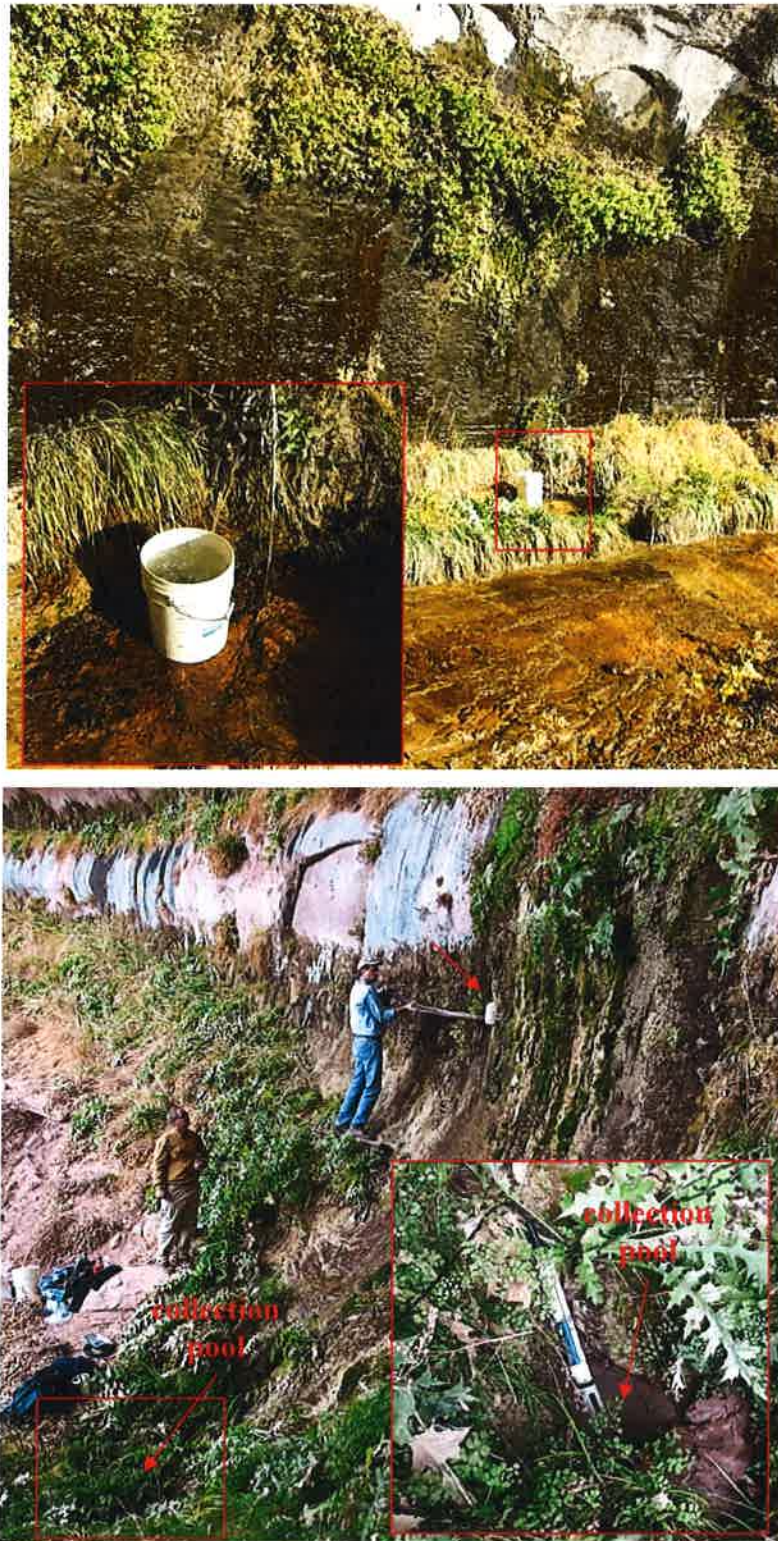


Figure 5. Top: Photo showing example of “bucket collection” method at Sleepy Hollow Spring; same collection method was also used at Sevenmile Canyon Boundary Spring. Bottom: Photo showing location of excavated collection pool at Poison Ivy Spring; also shown is collection of tritium from seep.

atmosphere.

While the most reliable method for sampling noble gases is using the passive diffusion samplers, it was impossible to install these within the wells because they could not be operated continuously for a 24-hour period. Samples for dissolved gases from the wells were collected by directing well discharge through a 21.5" length of 3/8" OD copper tubing. While the tubing was being flushed with the well water, it was lightly tapped so as to force out any air bubbles that may have collected on the inside of the tubing thereby eliminating any trapped air inside the sample. The copper tubes were sealed using pinch clamps before turning off the well.

Collection of Tritium Samples

Tritium samples were collected in 1 L plastic bottles. At all spring sites except for Courthouse Wash Boundary Spring, the bottles were filled beneath the seeps (fig. 5, bottom). As with the noble gases, there may have been tritium exchange with the atmosphere while the dripping water was in contact with the atmosphere before being collected. At Courthouse Wash Boundary Spring, the bottle was filled within the discharge pool. At the wells, the water was pumped directly into the bottles.

Collection of Chlorofluorocarbons

The collection procedure for CFC samples is slightly more involved than that for the other constituents sampled in this study, as contamination of samples by contact with atmospheric air is of great concern, especially for groundwaters which may not have been previously exposed to modern (high CFC concentration) air. Samples were collected

following the procedure put forth by Busenberg et al. (2006). Before sampling, water was either pumped through copper tubing into a five gallon plastic bucket at the well sites, or collected below the seeps in five gallon plastic buckets at Sevenmile Canyon Boundary and Sleepy Hollow Springs. This was not done at Courthouse Wash Boundary or Poison Ivy Springs as these sites either had a natural or excavated pool used to collect the spring water. A one gallon metal paint can was then inserted into the buckets or pools, and both the plastic bucket and metal cans were allowed to fill to overflowing. Four 125 mL glass sample bottles and bottle caps were submerged inside of the metal can. At the well sites, the sample bottles were flushed by placing the copper tubing into the bottom of the bottle (fig. 6, top). At the spring sites, the bottles were flushed by removing water from the bottom of the bottles using a hand-operated vacuum pump (fig. 6, bottom). In this manner, the bottles and caps were flushed with at least 2 L of water prior to collecting the sample. The bottles were sealed with foil-lined plastic caps while still submerged, and were checked to ensure the absence of any trapped air bubbles within the bottles.

Collection of Stable Isotope Samples

Samples for the stable isotopes of hydrogen (^2H or deuterium) and oxygen (^{18}O) were collected in 5 mL glass bottles and sealed with polyseal caps. The polyseal caps eliminate any headspace within the bottles, preventing evaporative fractionation of the sample within the bottle.



Figure 6. Top: Photo showing sampling method for CFCs at well sites. Bottom: Photo showing sampling method for CFCs at spring sites (using hand vacuum pump).

Sample Analysis

Samples collected for noble gases, tritium, and CFCs were analyzed at the Dissolved and Noble Gas Laboratory, Department of Geology and Geophysics, University of Utah (contact: alan.rigby@utah.edu). Samples collected for the stable isotopes deuterium and ^{18}O were analyzed at the Stable Isotope Ratio Facility for Environmental Research (SIRFER), Department of Biology, University of Utah (contact: sirfer@bioscience.utah.edu).

Results and Discussion

The results of the noble gases, tritium, CFCs, and stable isotope analyses are shown in table 2. Also shown are average field measurements of water temperature, total dissolved gas pressure, and dissolved oxygen taken during the collection of the samples. The results have been interpreted in terms of age and recharge temperature/elevation discussed in the following sections. Additional data can be found in the tables in the appendix at the end of the report.

Age

The data shown in table 2 provide several measures of the age of the samples, that is the elapsed time between recharge and sample collection. The first is the tritium data. Apparent $^3\text{H}/^3\text{He}$ ages for Sevenmile Canyon Boundary, Poison Ivy, and Sleepy Hollow Springs appear to be very recent (approximately 0 years), while Courthouse Wash Boundary Spring is slightly older (>19 years). All of the wells sampled, except Arches Headquarters Well, show apparent $^3\text{H}/^3\text{He}$ ages that are older than the springs (at least

Table 2. Results of noble gases, tritium, CFCs, stable isotopes, and field measurements of the groundwater.

	<i>Courthouse Wash Boundary Spring</i>	<i>Sevenmile Canyon Boundary Spring</i>	<i>Poison Ivy Spring</i>	<i>Sleepy Hollow Spring</i>	<i>Archview CG Well</i>	<i>Arches HQ Well</i>	<i>Dalton Well #2</i>	<i>Canyonlands Airport Well</i>
N_2^1	8.7E-01	7.7E-01	8.8E-01	8.0E-01	1.3E-02	1.3E-02	1.4E-02	1.4E-02
$^{40}Ar^1$	9.6E-03	9.5E-3	1.0E-02	9.6E-03	3.4E-04	2.8E-04	3.3E-04	3.3E-04
$^{84}Kr^1$	6.5E-07	6.5E-07	7.0E-07	6.6E-07	4.8E-08	6.1E-08	4.0E-08	4.1E-08
$^{20}Ne^1$	1.9E-05	1.7E-05	1.9E-05	1.7E-05	2.0E-07	1.7E-07	1.8E-07	1.8E-07
$^{129}Xe^1$	2.2E-08	2.2E-08	2.8E-08	2.4E-08	2.8E-09	3.4E-09	3.4E-09	3.4E-09
$^4He^1$	3.6E-05	5.2E-06	5.6E-06	6.0E-06	6.1E-07	1.5E-07	2.9E-07	2.0E-07
R/Ra ²	1.9E-01	7.7E-01	6.4E-01	6.2E-01	1.5E-01	2.8E-01	2.0E-01	2.7E-01
^3H (TU)	0.3	5.9	5.2	8.1	0.2	0.8	0	0.1
±	0.1	0.3	0.3	0.7	0.1	0.1	0.1	0.1
Apparent $^3H/^3He$ age (years)	>19	0	0	0	>103	>11	pre-1950	>88
Mean CFC-11 (pmoles/kg)	0.69	4.08	3.27	3.18	0.25	3.45	1.38	0.06
Mean Recharge Year	1965	1988	1981	1986	1961	1979	1965	1954
# of samples used	4	3	1	2	4	4	3	4
Mean CFC-12 (pmoles/kg)	0.79	1.96	1.08	1.60	0.05	N/A	0.20	N/A
Mean Recharge Year	1970	1991	1976	1987	1951	N/A	1960	N/A
# of samples used	4	2	4	3	3	0	3	0
Mean CFC-113 (pmoles/kg)	0.06	0.36	0.26	0.24	0.03	0.09	0.23	N/A
Mean Recharge Year	1972	1989	1985	1987	1967	1976	1983	N/A
# of samples used	2	4	4	4	3	4	1	0
$\delta^{18}O$ (‰)	-12.7	-12.3	-12.1	-11.2	-12.3	-12.4	-11.9	-12.2
±	0.03	0.26	0.22	0.24	0.09	0.16	0.05	0.21
δD (‰)	-96	-95	-92	-88	-91	-92	-88	-90
±	0.2	3.1	0.8	1.4	0.2	0.6	0.2	0.5
Collection Date	11/11/07	11/11/07	11/11/07	11/11/07	11/9/07	11/12/07	11/13/07	11/13/07
In Situ Water Temp. (°C)	10.5	10.6	14.8	13.4	16.1	19.2	18.4	20.4
Total Dissolved Gas Pressure (atm)	0.80	0.85	0.85	0.86	0.87	0.88	0.86	0.90
Dissolved Oxygen (mg/L)	5.5	9.5	8.4	8.9	3.0	4.0	1.1	1.3

¹Noble gas amounts for spring samples are in mole fractions; noble gas amounts for well samples are in ccSTP/kg.

²R is the $^3He/^4He$ ratio of the sample, and Ra is the $^3He/^4He$ ratio of air (1.384×10^{-6}).

>60 years); the apparent $^3\text{H}/^3\text{He}$ age for Arches Headquarters Well is >11 years.

The apparent $^3\text{H}/^3\text{He}$ ages for the wells and Courthouse Wash Boundary Spring can only be put in terms of a lower limit of the age, as these sites have very low concentrations of tritium which are nearing the detection limits of the equipment used to analyze the samples. For instance, at Dalton Well #2 there was no tritium detected in the sample. The best that can be said is the age of the water pre-dates 1950, but in all actuality it may be much older than any of the other samples, in which at least small amounts of tritium were detected.

Another measure of age is provided by the CFC data. At each site, four samples for CFC-11, CFC-12, and CFC-113 were collected. However, during collection or analysis, a few of the samples became contaminated or could not be measured due to peak interference from other gases. The data from the remaining valid samples for each site were averaged together. Table 2 indicates how many samples were included in determining the average CFC recharge year values. All individual CFC samples are given in table A-1 in the appendix.

With the exception of Courthouse Wash Boundary Spring and Arches Headquarters Well, the CFC ages of the well samples (calculated by subtracting the CFC recharge year from the sample year, 2007) are older than the springs. CFC ages for Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring range between approximately 16 and 31 years. The CFC ages for Courthouse Wash Boundary Spring are slightly older, ranging between 35 and 42 years. Arches Headquarters Well shows the youngest water of the wells sampled with CFC ages ranging between approximately 28 and 31 years, while waters sampled within the other three wells range

between approximately 24 and 56 years. Apparent CFC ages of 40 years and older represent very small concentrations of CFCs and may result from a small amount of contamination during sampling, with the actual age being older than 40 years.

Table 3 shows a comparison between the $^3\text{H}/^3\text{He}$ apparent ages, and the CFC apparent ages. In general, $^3\text{H}/^3\text{He}$ apparent ages are younger than CFC apparent ages for the springs, and except for Arches Headquarters Well, are older than CFC apparent ages for the wells.

There is a large discrepancy between the two methods in dating waters sampled from Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring, with the $^3\text{H}/^3\text{He}$ apparent ages being much younger than the CFC apparent ages. This discrepancy can be explained in two ways. First, the springs may be seeing a mixture of relatively older and relatively younger water. Alternatively, the discrepancy may suggest that there may have been some exchange of atmospheric helium with these samples during collection as the water at these sites was exposed to the atmosphere while dripping from the seeps before entering into the sample container. Helium has a very high diffusion coefficient and can exchange with the atmosphere (thereby resetting the “clock”) significantly faster than CFCs.

The low tritium concentration in the waters of Courthouse Wash Boundary Spring is indicative of much older waters than the given apparent $^3\text{H}/^3\text{He}$ age of 19 years. The CFC data show slightly older water at this site (~35 to 42 years) suggesting there may be water of different ages discharging at the site. The $^3\text{H}/^3\text{He}$ method of dating of mixed age waters will generally give the age of the younger component of the water, even if only a small fraction of the younger water exists within the sample. Similarly, the CFC data

Table 3. Comparison of apparent $^3\text{H}/^3\text{He}$ and CFC ages.

<i>Sample Site</i>	<i>Apparent $^3\text{H}/^3\text{He}$ age (years)</i>	<i>Average CFC-11 age (years)</i>	<i>Average CFC-12 age (years)</i>	<i>Average CFC-113 age (years)</i>
Courthouse Wash Boundary Spring	>19	~ 42	~ 37	~ 35
Sevenmile Canyon Boundary Spring	0	~ 19	~ 16	~18
Poison Ivy Spring	0	~ 26	~ 31	~ 22
Sleepy Hollow Spring	0	~ 21	~ 20	~ 20
Archview Campground Well	>103	~ 46	~ 56	~ 40
Arches Headquarters Well	>11	~ 28	N/A	~31
Dalton Well #2	pre-1950	~ 42	~ 47	~ 24
Canyonlands Airport Well	>88	~ 53	N/A	N/A

show slightly older water at the Arches Headquarters Well (~28 to 31 years) relative to the apparent $^3\text{H}/^3\text{He}$ age of 11 years.

One further indication of age is the R/Ra value of the sample. Lower R/Ra values generally correspond to older groundwater ages. All the wells and Courthouse Wash Boundary Spring have much lower R/Ra values than the other three springs (table 2). In fact, Courthouse Wash Boundary Spring has a lower R/Ra value than all the wells except the Archview Campground Well, suggesting that there is a component of much older groundwater discharging at this site.

The older age of waters from Courthouse Wash Boundary Spring versus the younger ages of the waters from the other springs sampled suggests Courthouse Wash Boundary Springs is being recharged from a different area than the other three springs. The same may be true of the Arches Headquarters Well as the age data for water from this well are younger than that of the other wells.

Recharge Temperature and Elevation

Concentrations of the noble gases are shown in table 2. Recharge temperature was evaluated by assuming a recharge elevation, and then solving an over-determined set of solubility equations representing each of the gases listed in table 2 (except ^4He which is also generated in the subsurface). This results in a value of the recharge temperature and excess air that best fits the observed data for that elevation. A new recharge elevation was then chosen, and the set of solubility equations was re-solved to provide a new best-fit estimate of recharge temperature. This process was repeated several times to produce a family of recharge temperature-elevation solutions for the wells and Courthouse Wash Boundary Spring. These families of solutions are shown in figure 7. The solution curves for each sample are truncated at their discharge elevations (~1200 to 1300 m) since it is highly unlikely that the recharge elevation is lower than the discharge elevation. Thus, the temperature that corresponds to the lowest elevation on these curves represents the maximum possible recharge temperature of each sample. Sevenmile Canyon Boundary, Poison Ivy, and Sleepy Hollow Springs are not shown on this figure as it is assumed that there was some exchange with atmospheric noble gases during collection at these sites, and therefore the noble gas data collected for these springs are not representative of their respective recharge temperature and elevation.

Also shown on figure 7 is a curve that represents the lapse rate curve (i.e. elevation vs. temperature) for recharging water in the La Sal Mountains adjacent to Moab. The slope of this curve is consistent with the atmospheric lapse rate, but the intercept has been adjusted based on information from other investigations of springs around the Moab area (more precisely, Pioneer Spring on the western slope of Spanish

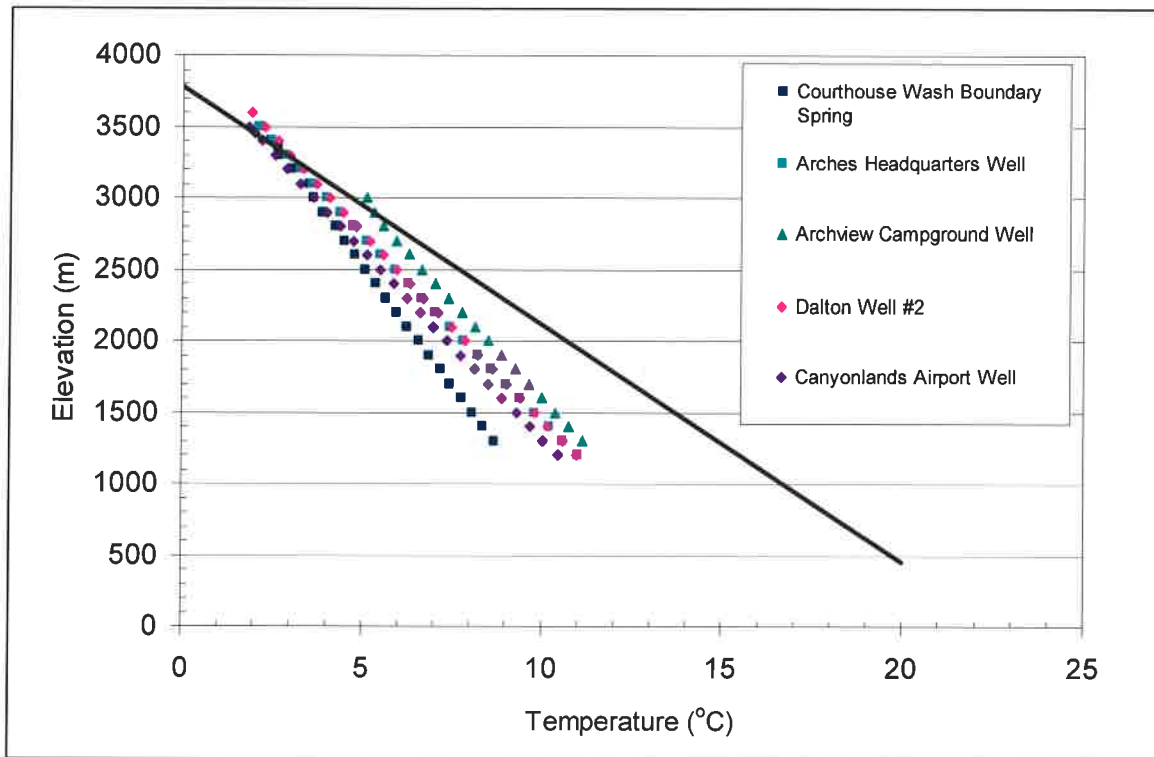


Figure 7. Recharge temperature-elevation solution curves (colored symbols) for samples in study. Also shown is recharge lapse curve for the La Sal Mountains (solid line) located to the east of the Moab area and south of the study area.

Valley).

The most probable solution of recharge temperature and recharge elevation for a sample is the temperature and elevation at the intercept of the sample recharge temperature-elevation pair curves with the recharge lapse curve. For example, the sample solution curve for Courthouse Wash Boundary Spring intersects the recharge lapse curve at an elevation of ~3350 m and a temperature of 2.7 °C. A summary of the most probable solutions of recharge temperature and recharge elevation is given in table 4. It should be noted that the La Sal Mountains lie to the south of the Colorado River, and the river is believed to be a barrier to groundwater flow to the north. Therefore, the recharge lapse curve shown in figure 7 may not be applicable for the sites sampled in the current study.

Table 4. Summary of results of noble gas thermometry for five of the sampled sites (see also fig. 7). Uncertainty associated with recharge elevation is assumed to be at least ± 300 m; uncertainty associated with recharge temperature is assumed to be ± 1 °C.

<i>Sample Site</i>	<i>Probable Recharge Elevation (m)</i>	<i>Probable Recharge Temperature (°C)</i>	<i>Excess Air (ccSTP/g)</i>	<i>Minimum Recharge Elevation (m)</i>	<i>Maximum Recharge Temperature (°C)</i>	<i>Excess Air (ccSTP/g)</i>
Courthouse Wash Boundary Spring Archview Campground Well	3350	2.7	0.0195	1305	8.7	0.0129
Arches Headquarters Well	3300	2.9	0.0017	1245	10.8	0.0002
Dalton Well #2	3300	3.0	0.0027	1340	10.8	0.0012
Canyonlands Airport Well	3450	2.0	0.0028	1385	9.7	0.0012

Due to the lack of meteorological data for areas to the north of Moab, a recharge lapse curve was not developed for the current study. For this reason, maximum recharge temperatures determined using the elevation of the sampling locations (“Minimum Recharge Elevation” column) are also given in table 4. However, it is believed that the recharge lapse curve developed for the La Sal Mountains should not be much different from the recharge lapse curve for areas to the north of Moab.

In a more detailed study, one would want to develop an empirical recharge lapse curve for the area of interest by sampling springs that discharge at various elevations (Manning and Solomon, 2003). The uncertainty in the recharge lapse curve represents the primary uncertainty associated with assigning precise recharge elevations based on

dissolved gases and this uncertainty is difficult to estimate. It is assumed that the uncertainties in the recharge elevations derived from this curve are at least ± 300 m.

Based on the noble gas thermometry data, all the wells and Courthouse Wash Boundary Spring appear to recharge above 2900 m (fig. 7). As higher recharge elevations generally mean longer flow paths and, therefore, longer travel times, the age data support the noble gas thermometry data for Courthouse Wash Boundary Spring, and all the wells except Arches Headquarters well. The ages of water sampled at these four sites are older than the other sites sampled. Most likely, Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring have a more local recharge area, given the younger groundwater ages of these springs. Although the noble gas data suggest that the Arches Headquarters Well recharges at a high altitude, the age of the water at this site suggests that the well may also be capturing some younger water following a shorter, more local flow path, which most likely recharges at a lower elevation than as indicated by the noble gas data.

The stable isotope data shown in table 2 are insufficient to independently corroborate the noble gas thermometry. Waters recharged at higher elevations should have more negative δD and $\delta^{18}O$ values than waters recharged at lower elevations. The isotopic data for the springs supports this, with Courthouse Wash Boundary Spring having more negative δD and $\delta^{18}O$ values than the other springs sampled. The isotope data do not corroborate the noble gas data, as the δD and $\delta^{18}O$ values for the wells are similar to or more positive than the δD and $\delta^{18}O$ of the springs. This would suggest that the waters in the wells recharge at approximately the same or lower altitudes than the

springs. However, the differences between the data are within the error of the measurements, and therefore these apparent trends may be superficial at best.

A plot of the isotope data is shown in figure 8 along with the global meteoric water line (GMWL). The isotope data for wells sampled in this study lie parallel to the GMWL, indicating that the waters are of meteoric origin. Figure 8 also shows the isotopic ranges of waters that recharge in the La Sal (east of Moab) (Gardner, 2004) and central Wasatch (east of Utah Valley in northern Utah) (Mayo and Loucks, 1995) Mountains. Both these areas have elevations similar to that of the recharge elevations that were determined using the noble gas data, but have δD and $\delta^{18}O$ values that are much more negative than the samples collected in this study. This suggests that if the recharge for the wells and Courthouse Wash Boundary Spring is occurring at high elevations as indicated by the noble gas data, the samples collected in this study should have δD and $\delta^{18}O$ that are more negative than measured. The isotope data for this study might differ from these other two regions for two reasons. First, due to the high variability in storm histories, temperature, and other fractionation processes (e.g. evaporation of rain), the isotopic composition of precipitation can vary between different precipitation events, and even vary within the same precipitation event. If the recharge area for waters sampled in this study receives storms following a different storm track than the La Sal or central Wasatch Mountains, then the isotope data could be different and the recharge elevation indicated by the noble gas data could be correct. Second, the recharge lapse curve used to determine recharge elevation from the noble gas data is possibly incorrect. If the waters were recharged under cooler conditions such as prevailed during the Pleistocene, the recharge lapse curve would be shifted to the left in figure 7 and the noble gas sample

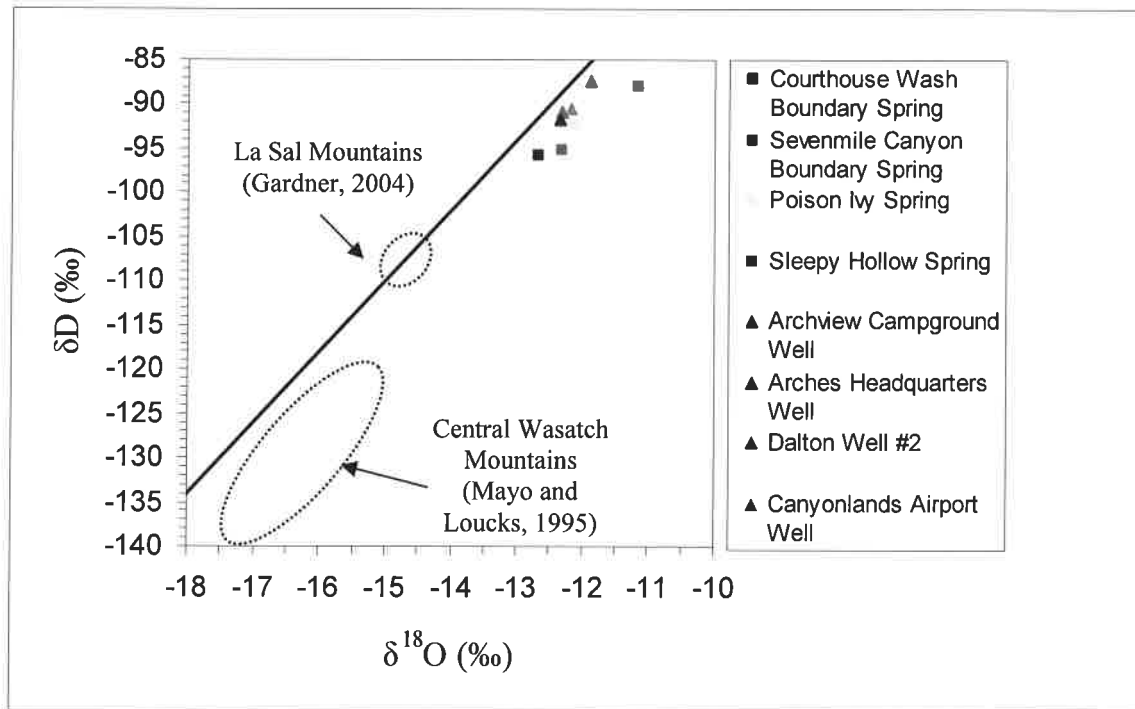


Figure 8. Plot of isotope data from sites sampled. Also shown are the global meteoric water line (solid line), the and isotopic ranges for groundwater samples from the La Sal and central Wasatch Mountains.

curves would intersect it at a lower altitude. However, cooler temperatures would also produce more negative values of δD and $\delta^{18}O$. Therefore, the isotope data indicate a lower recharge elevation than what is indicated by the noble gas data. In fact, Gardner (2004), who studied groundwater in the Matheson Wetland preserve just south of the Colorado River near Moab, suggests that samples with $\delta^{18}O$ values of -13 to -12 ‰ recharge relatively locally (at lower elevations not far above the river). Further detailed sampling would be needed, however, to resolve the discrepancy of recharge elevation based on the noble gas data and the stable isotope data.

Comparison to Samples Collected in March 2006

The sites sampled in this study were previously sampled in March 2006 for the NPS by Stefan Kirby (Utah Geological Survey). In 2006, samples were collected for the stable isotopes of hydrogen and oxygen, tritium, carbon-14, and general water chemistry, and the field parameters of temperature, dissolved oxygen, specific conductivity, and pH were measured (James Harte, NPS, personal communication, unpublished data). A general comparison of the stable isotope data, tritium data, and general analysis of the carbon-14 data are presented below.

Stable Isotope Data

Figure 9 shows a comparison of the stable isotope data. Generally, the isotope data collected in March 2006 is substantially more negative with respect to δD and slightly more negative with respect to $\delta^{18}O$ than the samples collected for this study. This suggests a possible seasonal shift in the stable isotopes of the samples, although they could also differ as they were analyzed in two different labs. The shift may indicate that in March 2006 all sites, especially Sevenmile Canyon Boundary, Poison Ivy, and Sleepy Hollow Springs, were receiving recent recharge from cooler snowmelt water that typically occurs in the spring. The most negative sample from March 2006 is from the Canyonlands Airport Well. It is highly unlikely, however, that this site would be receiving recent recharge, as it is a very deep well overlain by the Mancos Shale Formation, which is thought to be a confining unit.

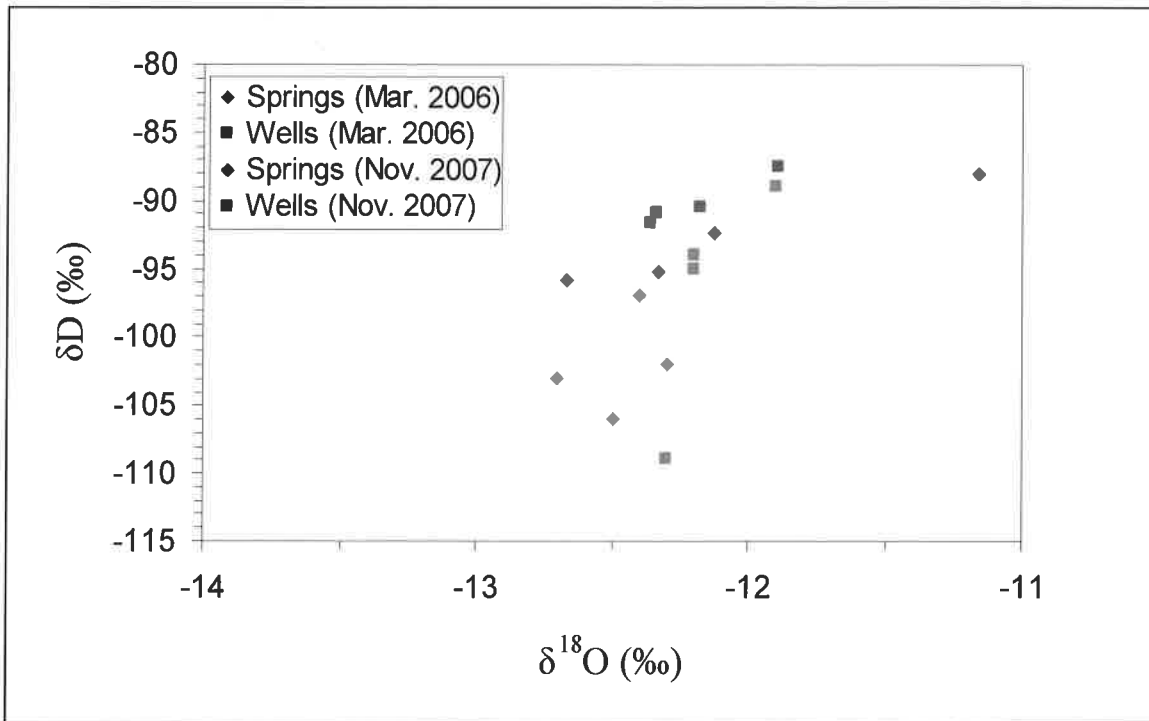


Figure 9. Plot showing comparison of stable isotope data collected in March 2006 and November 2007. Also shown is the global meteoric water line (solid line).

Tritium Data

Figure 10 shows a comparison of the tritium data. Except for two sites (Sevenmile Canyon Boundary Spring and Sleepy Hollow Spring) the tritium in the March 2006 samples are equal or higher than the samples collected in November 2007. Once again, this points to a possible seasonal shift in the tritium of the samples, although they could also differ as they were analyzed in two different labs. If the sites were receiving more recent recharge in the spring as possibly suggested by the stable isotope data, it would be expected that the water samples would contain higher amounts of tritium. However, the stable isotope data from Sevenmile Canyon Boundary and Sleepy Hollow Springs suggest that these two sites were receiving recharge from recent snowmelt but the tritium data collected in March 2006 do not support this, as the tritium concentration in the March 2006 samples is lower than the tritium in the samples collected in

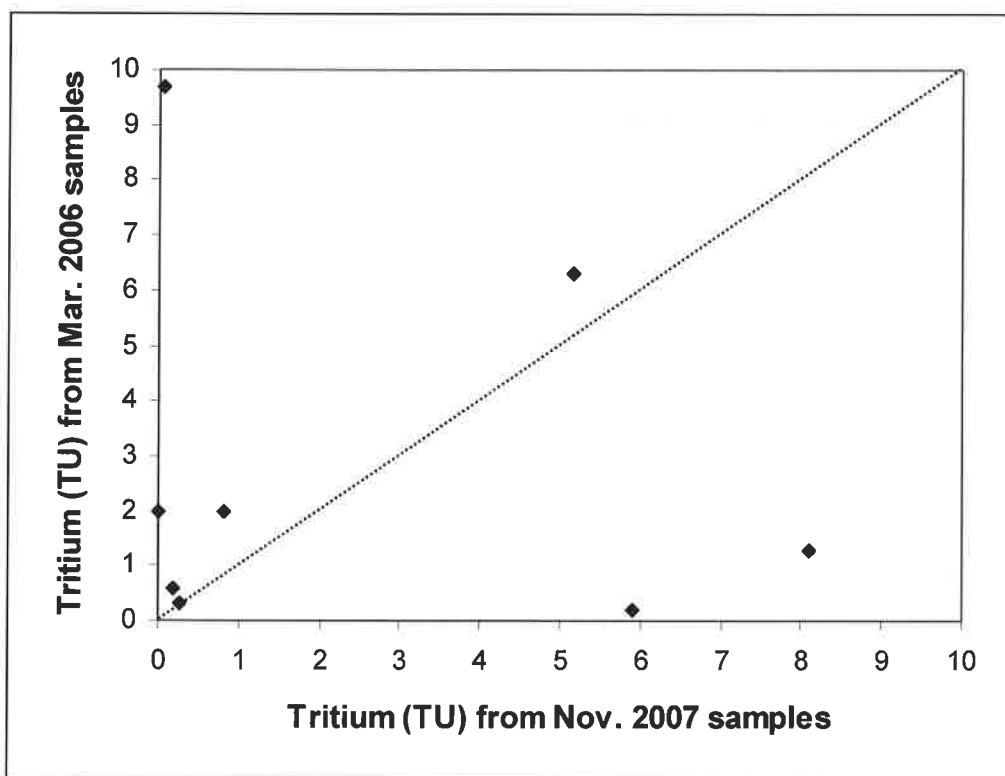


Figure 10. Plot showing comparison of tritium data collected in March 2006 and November 2007.

November 2007.

The Canyonlands Airport Well sample from March 2006 showed anomalously high tritium amounts as compared to the November 2007 sample. The stable isotope data also suggest that this well was possibly receiving recent recharge from the spring snowmelt. As stated above, however, it is highly unlikely that this site would be receiving recent recharge, as it is a very deep well overlain by the Mancos Shale Formation, which is thought to be a confining unit. Also, samples collected in the current study from November 2007 showed very low concentrations of tritium (0.1 ± 0.1 TU) and very old recharge ages from the CFC data (1954 or earlier) at this site. Therefore, the samples collected for stable isotopes and tritium in March 2006 for this site may possibly be in error.

Carbon-14 Data

Samples for carbon-14 (^{14}C) were collected during March 2006 to be used for age dating. ^{14}C radioactively decays to carbon-13 (^{13}C) with a half-life of 5,730 years. Given the long half-life, it is ideal for dating waters that may be a few thousand years old up to 40,000 years (Domenico and Schwartz, 1998). ^{14}C measured in groundwater is reported as a percent modern carbon (pmc) that is calculated as the ratio of the activity of ^{14}C in the sample to that of the international standard.

^{14}C that occurs in groundwater comes from the solution of carbon dioxide gas in the soil zone, which is typically defined as 100 pmc. Once the carbonate species moves below the water table, there are no additional sources of ^{14}C and it begins to decay. However, a major limitation to using this method is the reaction of the groundwater with minerals that contain carbon, such that carbon may transfer in and out of the groundwater. These interactions, therefore, need to be accounted for in estimating the age of the groundwater. It should be noted that due to these reactions modern recharge will not always be equal to 100 pmc.

It is beyond the scope of this study to determine absolute ages based on the ^{14}C results from samples collected in March 2006. However, the results can be used generally to quantify the ages of the groundwaters at the sites. Younger waters will generally have higher pmc values than older waters, and using the percentages we can provide a rough estimate of the “apparent” ^{14}C age. For example, if modern waters had a pmc value of 80, and a sample had a pmc of 40, the apparent ^{14}C age for the sample would be 5,730 years, or one half-life.

Samples collected from the wells in March 2006 have pmc values that range between 18 and 61 percent, with the largest value being reported for Arches Headquarters Well. This compares well with the tritium and CFC data collected for wells in this study, in that Arches Headquarters Well had the highest amounts of tritium for the well samples, and generally also showed the youngest recharge years based on the CFC data. In contrast, the springs had pmc values that ranged between 28 and 91, with the lowest value being reported for Courthouse Wash Boundary Spring. This compares well with the tritium and CFC data collected in this study which indicated that the ages of the water in wells was generally older than the springs, except Courthouse Wash Boundary Spring.

Sevenmile Canyon Boundary, Poison Ivy, and Sleepy Hollow Springs had the highest amounts of pmc, ranging between 89 and 91 percent. As these springs all contained high amounts of tritium which generally indicates young water, it can be assumed that recent recharge to this system should have pmc values of ~90 percent. Using this as the modern pmc value, apparent ^{14}C ages for the rest of the samples were estimated and ranged between approximately 3,000 and 13,000 years. The Arches Headquarters Well showed the youngest apparent ^{14}C age, while the other wells showed the oldest. Courthouse Wash Boundary Spring showed an intermediate apparent ^{14}C age of ~9,600 years. The ^{14}C data in conjunction with the tritium and CFC data for the Arches Headquarters Well and the Courthouse Wash Boundary Spring suggest that these two sites are receiving recharge from a mixture of young and old (>1,000 years) water.

Conclusions/Interpretations

The following conclusions/interpretations can be drawn from this work.

1. The apparent $^3\text{H}/^3\text{He}$, CFC, and ^{14}C ages indicate that the oldest waters are from Archview Campground Well, Dalton Well #2, and Canyonlands Airport Well. $^3\text{H}/^3\text{He}$ ages for these wells range between >67 to >103 years. All of these wells have very low amounts of tritium, nearing the detection limit of the device used to measure the tritium. Apparent CFC ages for these wells are slightly younger and range between 24 and 56 years. Apparent CFC ages of 40 years and older represent very small concentrations of CFCs and may result from a small amount of contamination during sampling, with the actual age being older than 40 years. It is likely that the 24 year CFC age is also due to some contamination during sampling. Using a general “back of the envelope” calculation, the apparent ^{14}C age of water from these wells was estimated to be as old as 12,000-13,000 years.
2. The apparent $^3\text{H}/^3\text{He}$, CFC, and ^{14}C ages indicate that the youngest waters are from Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring. The apparent $^3\text{H}/^3\text{He}$ ages for these springs appear to be very recent (approximately 0 years). Apparent CFC ages for these springs are slightly older and range between 16 and 31 years. The discrepancy in ages between these two methods may be due to: 1) a mixing of relatively older water and relatively younger water at these springs; and/or 2) there may have been some exchange of atmospheric helium with these samples during collection as the water at these sites was exposed to the atmosphere while dripping from the seeps before entering into the sample container. Helium has a very high diffusion coefficient and can exchange with the atmosphere (thereby resetting the “clock”) significantly faster

than CFCs. These springs had the highest pmc values from the ^{14}C data, ranging between 89 and 91 percent, which was considered to represent the “modern” pmc value for the sites sampled in this study.

3. The apparent $^3\text{H}/^3\text{He}$, CFC, and ^{14}C ages indicate that Courthouse Wash Boundary Spring and Arches Headquarters Well might be receiving waters of mixed ages. The apparent $^3\text{H}/^3\text{He}$ age for Courthouse Wash Boundary Spring is >19 years. However, like all of the wells except Arches Headquarters Well, it has very low amounts of tritium, nearing the detection limit of the device used to measure the tritium. The apparent CFC age for Courthouse Wash Boundary Spring ranges between 35 and 42 years, indicating that there may be mixing of slightly older and younger water at this site. Additionally, this spring only had a pmc value of 28 percent, and an estimated apparent ^{14}C age of up to 9,000 years, strongly indicating that there is a mix of waters of varying ages at this spring. The apparent $^3\text{H}/^3\text{He}$ age of water in the Arches Headquarters Well is >11 years. The apparent CFC age for this well is slightly older and ranges between 28 and 31 years. This well also had an intermediate pmc value of 61 percent, yielding an estimated apparent ^{14}C age of up to 3,000 years. This strongly indicates that this well is capturing waters of varying ages.
4. Based on the noble gas thermometry data, all the well sites and Courthouse Wash Boundary Spring appear to recharge above 2900 m. As higher recharge elevations generally mean longer flow paths and, therefore, longer travel times,

the age data support the noble gas thermometry data except for Arches Headquarters Well. Although the noble gas data suggest that the Arches Headquarters Well also recharges at a high altitude, the ages of the water at this site suggest that the well may also be capturing some younger water following a shorter, more local flow path, which most likely recharges at a lower elevation than as indicated by the noble gas data.

5. The stable isotope data do not support the very high recharge elevation indicated by the noble gas data. Waters recharged at higher elevations should have more negative δD and $\delta^{18}O$ values than waters recharging at lower elevations. When comparing the stable isotope data collected for this study to stable isotope data collected in two regions in Utah that have recharge elevations of 2900 m and above (La Sal and central Wasatch Mountains), the stable isotope data from these two regions is much more negative than that collected in this study. Two possible explanations for the discrepancy between the stable isotope data and the noble gas data are: 1) if the recharge area for waters sampled in this study receives storms following a different storm track than the La Sal or central Wasatch Mountains, then the stable isotope data could be different and the recharge elevation indicated by the noble gas data could be correct; or 2) the recharge lapse curve used to determine recharge elevation from the noble gas data is possibly incorrect. If the waters were recharged under cooler conditions such as prevailed during the Pleistocene, the recharge lapse curve would be shifted to cooler temperatures and the noble gas sample curves would intersect it at a lower altitude. However,

cooler temperatures would also produce more negative values of δD and $\delta^{18}O$.

Therefore, the stable isotope data indicate a lower recharge elevation than what is indicated by the noble gas data.

6. The stable isotope data for the springs support the assumption that Courthouse Wash Boundary Spring is recharged at a slightly higher elevation, as the stable isotopes collected at Courthouse Wash Boundary Spring have more negative δD and $\delta^{18}O$ values than the other springs sampled. The stable isotope data do not corroborate the noble gas data, as the δD and $\delta^{18}O$ values for the wells are similar to, or more positive than, the δD and $\delta^{18}O$ of the springs. This would suggest that the waters in the wells recharge at approximately the same or lower altitudes than the springs. However, the differences between the data are within the error of the measurements, and therefore these apparent trends may be superficial at best.
7. Comparison of stable isotope and tritium data collected in this study to data collected at the same sites from March 2006 indicate possible seasonal trends in both sets of data. Generally, the stable isotope data collected in March 2006 is substantially more negative with respect to δD and slightly more negative with respect to $\delta^{18}O$. Except for two sites (Sevenmile Canyon Boundary Spring and Sleepy Hollow Spring) the tritium in the March 2006 samples is equal or higher than in the samples collected in November 2007. If the sites were receiving more recent recharge in the spring (most likely from snowmelt or from cooler winter precipitation) as possibly suggested by the stable isotope data, it would be

expected that the water samples would contain higher amounts of tritium.

However, the stable isotope data from Sevenmile Canyon Boundary and Sleepy Hollow Springs suggest that these two sites were receiving recharge from cooler sources, but the tritium data collected in March 2006 do not support this. The difference in the stable isotope data and tritium data may be simply due to the difference in the analysis of these samples, as the data collected in March 2006 were analyzed in a different lab than the data collected in November 2007.

The age data suggest that the oldest waters are from Archview Campground Well, Dalton Well #2, and Canyonlands Airport Well, located to the north and west of Arches National Park. The noble gas data for these sites indicate that these sites are recharged at predominantly higher altitudes than other sites in the study, which would corroborate longer groundwater flow paths suggested by the older waters at these sites. The noble gas data also indicate that Courthouse Wash Boundary Spring, located north of the other three springs, and Arches Headquarters Well, located at the southern end of the park, also may receive a portion of water that recharges at high altitudes. However, there is an indication of some younger water at both these sites, suggesting that they are receiving a mix of younger and older waters. The apparent ^{14}C ages for these two sites indicates that Courthouse Wash Boundary Spring water is closer in age to the Archview Campground, Dalton #2, and Canyonlands Airport Wells. Although the noble gas data suggest that the Arches Headquarters Well recharges at a high altitude, the age of the water at this site suggests that the well may be capturing a significant portion of younger water following a shorter, more local flow path, which likely recharges at a lower elevation than as

indicated by the noble gas data. Most likely, the source waters for Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring are from more local recharge areas, given the younger groundwater ages of these springs.

The stable isotope data do not support the very high recharge elevations indicated by the noble gas data. Waters recharged at higher elevations should have more negative δD and $\delta^{18}O$ values than measured in the current study. Therefore, the stable isotope data indicate lower recharge elevations than the noble gas data. Further sampling is needed, however, to resolve this discrepancy.

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Appendix

Table A-1. CFC concentrations and recharge year results for all samples collected.

SAMPLE ID	CFC-11 (pmoles/kg)	CFC-12 (pmoles/kg)	CFC-113 (pmoles/kg)	CFC-11 Rech. year	CFC-12 Rech. year	CFC- 113 Rech. year
Courthouse Wash Boundary Spring-1	0.296899	0.903403	0.026456	1961.5	1972	1966.5
Courthouse Wash Boundary Spring-2	0.932447	0.508093	0.103148	1967.5	1967	1976.5
Courthouse Wash Boundary Spring-3	0.669021	0.559534	22.8706	1965.5	1968	#N/A
Courthouse Wash Boundary Spring-4	0.866498	1.207419	0	1967	1974.5	1943
Sevenmile Canyon Boundary Spring-1	14.10697	1.638243	0.251336	#N/A	1984.5	1986
Sevenmile Canyon Boundary Spring-2	4.242743	2.290947	0.378985	1988.5	1998	1989.5
Sevenmile Canyon Boundary Spring-3	3.988583	2.332174	0.404863	1987.5	#N/A	1990.5
Sevenmile Canyon Boundary Spring-4	4.009789	2.405268	0.395883	1987.5	#N/A	1990.5
Poison Ivy Spring-1	3.271601	1.629354	0.313728	1987.5	1988.5	1990.5
Poison Ivy Spring-2	26.97121	1.526332	0.243861	#N/A	1987	1987.5
Poison Ivy Spring-3	38.66331	0.606734	0.233796	#N/A	1972.5	1987.5
Poison Ivy Spring-4	28.24927	0.561789	0.250885	#N/A	1972	1988
Sleepy Hollow Spring-1	3.399178	2.421315	0.332257	1987	#N/A	1990
Sleepy Hollow Spring-2	4.781264	1.508713	0.215716	#N/A	1985.5	1986
Sleepy Hollow Spring-3	2.961355	1.692586	0.213971	1984.5	1988	1986
Sleepy Hollow Spring-4	12.4646	1.589566	0.215951	#N/A	1986.5	1986
Archview CG Well-1	0.251788	0.015095	0.019959	1963.5	1948	1969
Archview CG Well-2	0.240498	0	0.031797	1963	#N/A	1972.5
Archview CG Well-3	0.276355	0.11447	0	1964	1960	1943
Archview CG Well-4	0.235143	0.022394	0.025236	1963	1949.5	1971
Arches HQ Well-1	3.385613	3.682206	0.094162	#N/A	#N/A	1982
Arches HQ Well-2	3.848228	4.250385	0.094472	#N/A	#N/A	1982
Arches HQ Well-3	3.233222	4.238412	0.085281	#N/A	#N/A	1981
Arches HQ Well-4	3.349036	4.390661	0.085082	#N/A	#N/A	1981
Dalton Well #2-1	3.882848	0.352312	0.229372	#N/A	1969	1989
Dalton Well #2-2				#N/A	#N/A	#N/A
Dalton Well #2-3	0.137056	0.125889	0	1961	1961.5	1943
Dalton Well #2-4	0.119009	0.129212	0	1960	1961.5	1943
Canyonlands Airport Well-1	0.061894	0	0	1957	#N/A	1943
Canyonlands Airport Well-2	0.09015	0	0	1959	#N/A	1943
Canyonlands Airport Well-3	0.035421	0	0	1954.5	#N/A	1943
Canyonlands Airport Well-4	0.044514	0	0	1955.5	#N/A	1943

Table A-2. Field measurements of the groundwater for all sites.

	<i>Courthouse Wash Boundary Spring</i>	<i>Sevenmile Canyon Boundary Spring</i>	<i>Poison Ivy Spring</i>	<i>Sleepy Hollow Spring</i>	<i>Archview CG Well</i>	<i>Arches HQ Well</i>	<i>Dalton Well #2</i>	<i>Canyonlands Airport Well</i>
Collection Date	11/9/07	11/10/07	11/10/07	11/10/07	11/9/07	11/12/07	11/13/07	11/13/07
In Situ Water Temp. (°C)	12.1	10.4	15.3	15.1	16.1	19.2	18.4	20.4
Total Dissolved Gas Pressure (atm)	0.83	0.85	0.85	0.87	0.87	0.88	0.86	0.90
Dissolved Oxygen (mg/L)	5.6	9.8	8.5	8.8	3.0	4.0	1.1	1.3
Collection Date	11/11/07	11/11/07	11/11/07	11/11/07	N/A	N/A	N/A	N/A
In Situ Water Temp. (°C)	8.1	10.8	14.3	11.6	N/A	N/A	N/A	N/A
Total Dissolved Gas Pressure (atm)	0.77	0.85	0.85	0.85	N/A	N/A	N/A	N/A
Dissolved Oxygen (mg/L)	5.5	9.3	8.3	9.1	N/A	N/A	N/A	N/A