

# Groundwater Residence Time and Recharge Temperature Estimates of the Denver and Arapahoe Aquifers, Denver Basin, Colorado<sup>1</sup>

MILOS M. NOVOTNY<sup>2</sup>  
WILLIAM E. SANFORD<sup>3</sup>

- 
1. Manuscript received August 2; Accepted August 12, 2004.
  2. S.S. Papadopulos & Associates, 1877 Broadway S703, Boulder, CO 80302
  3. Department of Geosciences, Colorado State University, Fort Collins, CO 80523

## ABSTRACT

Groundwater samples were collected from six groundwater production wells in the Denver and Arapahoe aquifers of the Denver Basin along a transect from near the suspected recharge area in the south to urban centers in the central basin. Residence times were estimated with <sup>14</sup>C using an empirical factor to correct for dilution. Recharge temperature was estimated with a model that relates concentrations of dissolved atmospheric noble gases (Ne, Ar, and Kr) in the groundwater samples to temperature, elevation and an excess-air component. Residence time estimates range from 8,000 years near the outcrops of the aquifers to greater than 30,000 years near the center of the basin. The recharge temperature estimate of the youngest water is similar to modern mean-annual temperature while waters from the central basin have significantly cooler recharge temperatures. The relationship of recharge temperature and residence time to general climate records suggests possible mixing of younger Holocene waters in two of the central basin samples.

---

INTRODUCTION .....	161	Model of Recharge Temperature .....	164
Background .....	162	RESULTS AND DISCUSSION .....	164
Groundwater Flow and Environmental Tracers ..	162	Residence Times .....	164
Carbon-14 Residence Time .....	162	Estimated Paleotemperatures .....	165
Recharge Temperature .....	163	SUMMARY .....	166
METHODS .....	163	ACKNOWLEDGMENTS .....	166
Sampling .....	163	REFERENCES .....	166
Carbon-14 Activity Dilution and Determination of Residence Time .....	163		

---

## INTRODUCTION

The population of Colorado's Front Range has grown tremendously over the last 30 years and growth is predicted to continue at a similar rate over the next 20 years; however, the volume of usable water will remain relatively fixed. Surface water is already fully allocated, requiring new demand to be partially satisfied by exploiting the bedrock aquifers of the Denver Basin. Overexploitation of deep groundwater in similar basins has led to many deleterious effects including lowering of the potentiometric surface, land subsidence and degradation of water quality (Custodio, 2002).

Numerical groundwater models of the Denver Basin aquifers have been and are currently being created and modified. These models can be used to predict the effects of increased withdrawals and to estimate the total amount of water available. Many basin-scale models are calibrated to present-day potentiometric surfaces, and recharge to the aquifers is merely estimated. Data collected providing insight to the residence time of water at various locations can greatly decrease uncertainties in the groundwater models.

In this paper, apparent residence times of water sampled from several locations within the Arapahoe and Denver aquifers of the Denver Basin are presented along with

estimates of the ambient temperature at the time of recharge. The apparent residence times were determined using  $^{14}\text{C}$ , and recharge temperatures were estimated using the concentrations of atmospheric noble gases (Ne, Ar, and Kr).

## Background

The Denver Basin is centered in northeast Colorado, east of the Front Range of the Rocky Mountains. It is a foreland basin containing Upper Pennsylvanian to mid-Tertiary sedimentary rocks, underlain by Precambrian igneous and metamorphic rocks. The structural basin is asymmetric with steeply dipping to overturned and faulted beds on the western margin where it crops out against the Front Range.

The names of the formations comprising the bedrock aquifers have been adapted to represent distinct aquifers within the Denver Basin (see Fig. 2 in Reynolds, 2004, this issue). The formations of the principal bedrock aquifer system of the Denver Basin are the Fox Hills Sandstone, the Laramie, Arapahoe and Denver formations, and the Dawson Arkose. These translate into the Laramie-Fox Hills aquifer, the Arapahoe aquifer, the Denver aquifer and the Dawson aquifer. The bedrock aquifers of the Denver Basin are considered to be regionally continuous and were mapped using electric log signatures and outcrop locations around the Basin (Robson, 1987). Aquifer properties and model parameters were determined from formation samples and aquifer tests. Aquifers may cut across geologic boundaries to include parts of other formations (e.g. the Laramie-Fox Hills aquifer; cf Crifasi, 1992).

The Front Range urban corridor is found in the Great Plains region of northeastern Colorado, just east of the Front Range of the Rocky Mountains. Land surface elevations range from about 1400 to 2100 m above MSL. During the last two million years, the climate of the area has varied dramatically, including periods of glaciation. The most recent glacial period peaked about 25 ka and ended about 12 ka. Since that time, the regional climate has been generally drier and/or warmer (Stute et al., 1992; Muhs et al., 1999). Today, the area has a semi-arid climate with highly variable temperatures at any given location. Modern mean annual temperature near the southern outcrop of the bedrock aquifers is 9.3°C (National Oceanic and Atmospheric Administration, 2002) and modern mean annual precipitation ranges from 30-45 cm/yr (Hansen et al., 1978).

## Groundwater Flow and Environmental Tracers

For most regional-scale groundwater models, such as those of the Denver Basin, groundwater flux through the aquifers is not measured but is calculated in a water bud-

get. Uncertainty in model parameters (e.g., hydraulic conductivity, porosity, specific yield) (Woodard et al., 2002) can greatly affect the calculated flux. However, the flux can be estimated independently of the model if groundwater residence times are known. Residence time is estimated from groundwater samples using environmental tracers, naturally-occurring substances in groundwater that vary in concentration with time or process. Residence times may be applied to constrain parameters that affect the groundwater flux, or included as an additional model parameter. Other environmental tracers are used to characterize groundwater flux in a broad, qualitative sense by defining recharge areas or indicating the approximate period of recharge.

## Carbon-14 Residence Time

Carbon-14 is the most routinely applied dating tool for pre-modern (pre-1950) groundwater and has been used in numerous studies to characterize flow in regional aquifers (e.g., Phillips et al., 1989; Clark et al., 1998). Because the subsurface residence time is a function of both the aquifer properties and recharge rates, residence times have been used variously to constrain these values. Modern groundwater systems have been strongly influenced by temporal changes in recharge (Phillips, 1995). Where the distribution of aquifer properties is well constrained, groundwater models calibrated using residence times have demonstrated significantly higher past recharge rates in some southwestern U.S. basins (e.g., Zhu et al., 1998; Sanford, 2002). If evidence suggests that a change in recharge rate does not significantly affect the distribution of residence times, these may be used to constrain aquifer properties. Phillips et al. (1989) used hydraulic heads and residence times estimated from  $^{14}\text{C}$  activity to estimate the distribution of transmissivity in the lower Tertiary aquifers of the San Juan Basin, New Mexico.

Residence times are calculated from the percent modern carbon (pmC) of groundwater samples using the standard isotopic decay equation for  $^{14}\text{C}$  and, usually, an adjustment for the dilution of  $^{14}\text{C}$  activity. The dilution occurs as a result of interaction of groundwater with  $^{14}\text{C}$ -free carbon sources, such as limestone, and causes the groundwater to appear 'old.' Several methods have been proposed to quantify the magnitude of the dilution. However, theoretical uncertainty exists because of parameter assumptions, especially in cases where parameters cannot be easily measured, such as the environmental conditions during groundwater recharge (Clark and Fritz, 1997). Because of the uncertainty in  $^{14}\text{C}$  dilution, these residence times are generally viewed as maximum, and another environmental tracer can be used in tandem to constrain the uncertainty in  $^{14}\text{C}$  residence time.

## Recharge Temperature

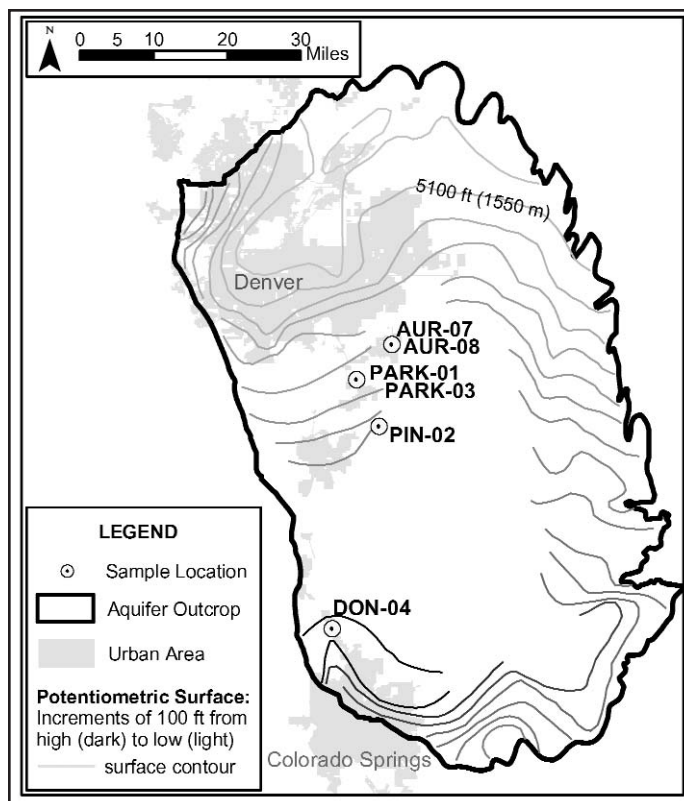
The temperature of recharging groundwater, an approximation of mean-annual air temperature, can be estimated from concentrations of atmospheric noble gases dissolved in groundwater using the general temperature-gas solubility relationship, Henry's Law (e.g., Stute et al., 1992; Aeschbach-Hertig et al., 1999). The concentrations of inert gases in groundwater result from the temperature- and pressure (elevation)- dependent equilibration of water with the atmosphere, plus the addition of excess air arising from dissolution of entrained air bubbles below the water table (Stute and Schlosser, 2000). The excess air may be fractionated due to partial dissolution or re-equilibration of the gas (Aeschbach-Hertig et al., 1999).

Variation in paleotemperatures estimated from concentrations of noble gases suggests a temperature suppression ranging from 5-9°C during the last glacial period (Aeschbach-Hertig et al., 2000). Noble gas temperatures in the south-central and southwestern U.S. during the last glacial period were approximately 5°C cooler than Holocene temperatures (Stute et al., 1992; Clark et al., 1998), consistent with other estimates of continental temperature change and local glacial-climate reconstructions (Muhs et al., 1999).

## METHODS

### Sampling

Six samples were collected from locations that lie along a transect parallel to the presumed modern groundwater flow path beginning near the southern outcrop of the aquifers (Fig. 1). The samples were collected from groundwater of the Arapahoe and Denver aquifers near Parker, Colorado during the spring of 2002 and near Aurora and Donala (near Colorado Springs), Colorado during the spring of 2003 (Table 1). One-liter water samples were analyzed for dissolved inorganic carbon (DIC) isotopes by atomic mass-spectrometry at Beta Analytical Labs. Results of DIC analysis are reported in percent modern carbon (pmC) for  $^{14}\text{C}$  and delta 13-carbon per mil VPDB ( $\delta^{13}\text{C}$  ‰) for relative  $^{13}\text{C}/^{12}\text{C}$ . Samples for dissolved gas analyses were collected following the protocol outlined by Manning et al. (2003) and were analyzed by the Noble Gas Laboratory at the University of Utah for  $^{28}\text{N}_2$ ,  $^{32}\text{O}_2$ ,  $^{20}\text{Ne}$ ,  $^{40}\text{Ar}$ ,  $^{84}\text{Kr}$ ,  $^3\text{He}$  and  $^4\text{He}$ . Results of the dissolved gas analysis are reported in molar-fraction (unit-less) and precision of measurements is a few percent. Additional field measurements of temperature (T) and total dissolved gas pressure ( $P_{\text{TDC}}$ ) of the groundwater were made. A detailed description of the sampling procedure and analysis may be found in Novotny (2004).



**Figure 1.** General locations of groundwater samples with 1978 potentiometric surface of Arapahoe aquifer (Robson, 1987) for reference.

### Carbon-14 Activity Dilution and Determination of Residence Time

Additional sources of carbon exist in most aquifers and can cause dilution of the  $^{14}\text{C}$  activity. Therefore, a correction for the interaction of these sources with groundwater was applied prior to the calculation of residence time. Correction methods involving mass-balance of  $^{13}\text{C}/^{12}\text{C}$  (e.g., Pearson and Swarzenki, 1974) were not used; ratios of these isotopes in the potential sources of carbon in the aquifers and recharge area are not known and the inference of these from other information is unreliable. Resources were unavailable for isotopic-exchange or reaction path models, and so these methods were not used. A non-site-specific, empirically-derived dilution quotient equal to 0.85 of the initial groundwater sample activity was used to correct the  $^{14}\text{C}$  activities (Vogel, 1970). While this correction does not physically represent  $^{14}\text{C}$  dilution in the aquifers, other research indicates that differences between this simple, empirical correction and more sophisticated approaches are not significant in the lower Tertiary aquifers of the San Juan Basin (Phillips et al., 1989), a hydrogeologic and hydrochemical setting similar to the Arapahoe and Denver aquifers.

**Table 1.**

Location and physical characteristics of wells sampled; data in meters above mean sea level (MSL).

Sample	Aquifer	CO-DWR Permit	PLSS Location T.R.S.Q.Q	Surface Datum [m]	Screen Interval	
					Top Depth [m]	Bottom Depth [m]
DON-04	Arapahoe	16141-F	11S.66W.31.NW.SW	2,103	243	359
PIN-02	Arapahoe	51782-F	07S.65W.18.SE.NW	1,948	538	657
PARK-01	Arapahoe	50563-F	06S.66W.15.NE.SW	1,787	396	518
AUR-08	Arapahoe	30326-F	05S.65W.21.SE.NE	1,829	378	512
PARK-03	Denver	50562-F	06S.66W.15.NE.NW	1,787	235	372
AUR-07	Denver	30323-F	05S.65W.21.SW.NE	1,829	121	351

**Table 2.**

Land surface elevation of southern recharge zones (meters above MSL) used in model of atmospheric noble gases.

Aquifer	Mean	Maximum	Minimum	Standard Deviation	Coefficient of Variation
Denver	2,084	2,250	1,861	112	0.05
Arapahoe	1,994	2,100	1,814	81	0.04

### Model of Recharge Temperature

Aeschbach-Hertig et al. (1999) have created a model that takes into account the effects of temperature, elevation, salinity, and excess-air fractionation on atmospheric noble gas concentrations. Measured values of Ne, Ar, Kr, and Xe are used in the model to minimize an objective function, essentially producing a statistical measure of the “goodness-of-fit” of the data to the model. Novotny (2004) provides a more detailed discussion of the application of this model in the Denver Basin.

Salinity of recharging water often cannot be measured and is assumed equal to zero; other researchers using similar methodology have assumed that this parameter is negligible in waters with low salinity (e.g., Clark et al., 1998). The assumption appears valid in this study area where modern recharging water is closely tied to precipitation and no significant sources of salinity exist. Concentrations of two of the measured inert gases (helium and nitrogen) were not used because it is suspected that there are significant sources or modifications of these in the subsurface. The mean elevations of the Arapahoe and Denver aquifer recharge areas were estimated from digital elevation maps to be approximately 2,000 and 2,075 m above MSL, respectively (Table 2). With three known noble gas concentrations (Ne, Ar, Kr) and two unknown parameters (recharge

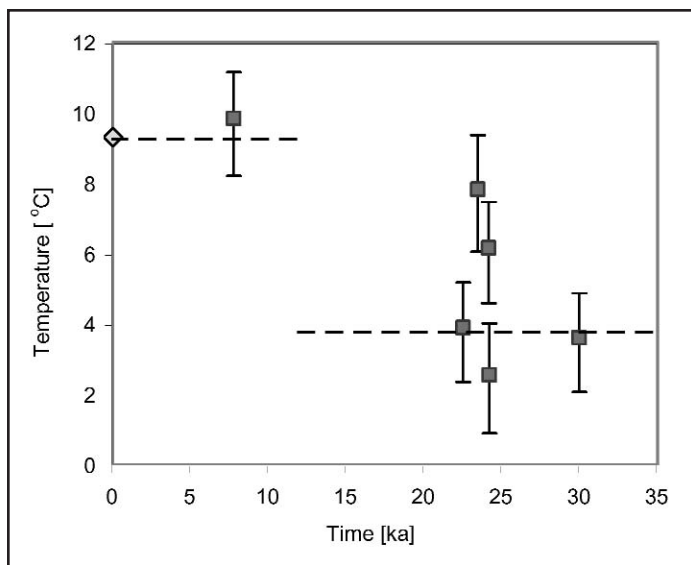
temperature and excess air), the model equations are over-determined and may be inverted. A statistical fit of the data to the model is given by the objective function,  $\chi^2$ . For the equation with one degree of freedom, and having a  $\chi^2$  value of 3.84, the probability that the unknown parameters deviate from their true values because of errors in gas concentration analysis is less than 5%.

## RESULTS AND DISCUSSION

The results of the noble gas and  $^{14}\text{C}$  analyses are presented in Table 3. As expected, the majority of the gas content is dissolved nitrogen. The  $^{14}\text{C}$  activity is highest in the well located nearest the recharge areas and is lowest in samples from the middle of the Basin.

### Residence Times

Applying the assumptions and techniques outlined above, the activity of  $^{14}\text{C}$  was used to determine the apparent residence time of the waters at each location (Table 3). The shortest residence time of 8,000 years was at Donala (DON-04) in the Arapahoe aquifer, the location nearest the outcrops and the highest potentiometric level.



**Figure 2.** Recharge temperature of groundwater samples (solid squares) and uncertainty (error bars), Denver and Arapahoe aquifers, Denver Basin, Colorado, and glacial and Holocene temperature estimates (dashed lines) reconstructed from mean annual modern temperature (solid diamond) and glacial temperature depression of 5.5°C.

Samples from wells farther toward the center of the basin, regardless of aquifer, have apparent residence times of 22,000-24,000 years. The sample from The Pinery (PIN-02) showed an estimated residence time of greater than 30,000 years, but there were some problems associated with the analysis of this sample. In a qualitative sense, the apparent residence times are what would be expected, with the younger water toward the outcrops (recharge area) and the older waters in the middle of the basin.

### Estimated Paleotemperatures

The estimated temperatures at the time of recharge are shown in Table 4. They range from 2.5 to 9.8°C. The  $\chi^2$  values of all samples were below or very near 3.84, the level of 95% probability for the model. These results suggest that the mean elevations used are reasonable, that the excess-air component of the samples is not fractionated, and the estimated recharge temperatures are reasonable. The uncertainty in derived recharge temperature resulting from the level of instrument precision was calculated as 0.9°C (Manning and Solomon, 2003). Recalculating recharge temperature with minimum and maximum elevations was used to estimate uncertainty in recharge temperature resulting from the assumption of recharge elevation (Table 2). The sum of these was used to approximate the total uncertainty in recharge temperature in this study.

Recharge temperatures and uncertainties were plotted with estimates of modern and glacial temperatures (Fig. 2). The sample from Donala (DON-04) is very close to the modern temperature in the recharge area as would be predicted by a residence time that is younger than the end of the last glacial period. The recharge temperatures of the other samples are all lower than the modern temperature. The residence times and lower recharge temperatures of these samples suggest these were recharged during the last glacial period. Samples PARK-01 and AUR-07 have recharge temperatures that are significantly greater than the estimated glacial temperature. This could reflect significant temperature fluctuations within the glacial period, mixing of Holocene groundwater and/or the dilution of  $^{14}\text{C}$  activity that makes the groundwater appear ‘old.’ The latter explanation suggests that residence times could be as young as the end of the last glacial period, approximately 12 ka in Colorado. While confined conditions are observed

**Table 3.**

Laboratory analysis results and field measurements of groundwater conditions;  $^{14}\text{C}$  reported in percent modern carbon (pmC); relative  $^{13}\text{C}/^{12}\text{C}$  reported as delta 13-carbon per mil VPDB ( $\delta^{13}\text{C}$  ‰); total dissolved gas pressure ( $P_{\text{TDC}}$ ).

Sample	Aquifer	Relative Gas Concentrations							DIC		Field Measurements	
		$^{28}\text{N}_2$ 10 <sup>0</sup>	$^{32}\text{O}_2$ 10 <sup>-4</sup>	$^{40}\text{Ar}$ 10 <sup>-2</sup>	$^{84}\text{Kr}$ 10 <sup>-7</sup>	$^{20}\text{Ne}$ 10 <sup>-5</sup>	$^3\text{He}$ 10 <sup>-11</sup>	$^4\text{He}$ 10 <sup>-4</sup>	$^{14}\text{C}$ [pmC]	$\delta^{13}\text{C}$ [‰]	T [°C]	$P_{\text{TDC}}$ [atm]
DON-04	Arapahoe	0.95	5.38	1.05	6.98	2.05	0.89	0.16	33.3	-13.6	15.5	0.908
PIN-02	Arapahoe	0.99	0.55	1.15	8.49	1.52	2.92	1.53	<2.27	-12.7	22.4	1.119
PARK-01	Arapahoe	0.97	192.01	1.08	8.00	1.72	3.19	1.11	4.59	-13.0	28.7	1.155
AUR-08	Arapahoe	1.00	3.55	1.14	8.44	0.97	5.13	2.33	5.60	-10.8	30.2	1.122
PARK-03	Denver	0.99	0.27	1.07	7.69	1.57	1.65	5.13	4.57	-13.2	29.7	1.050
AUR-07	Denver	0.86	3.46	0.95	6.67	0.86	0.83	2.71	5.00	-9.7	17.9	1.012

**Table 4.**

Carbon-14 residence times and results of recharge temperature model for groundwater samples of the Denver Basin, Colorado; objective function of noble gas model ( $\chi^2$ ); excess air component (EA) reported as  $\text{cm}^2$  gas per gram  $\text{H}_2\text{O}$  at STP.

Sample	Aquifer	Residence Time [yr]	$T_R$ [ $^{\circ}\text{C}$ ]	EA [ $\text{cm}^2\text{STP/g}$ ]	$\chi^2$
DON-04	Arapahoe	8,000	9.8	$3.9 \times 10^{-3}$	3.14
PIN-02	Arapahoe	>30,000	3.6	$8.1 \times 10^{-4}$	3.98
PARK-01	Arapahoe	24,000	6.2	$2.6 \times 10^{-3}$	0.38
AUR-08	Arapahoe	22,000	3.9	$4.2 \times 10^{-3}$	1.98
PARK-03	Denver	24,000	2.5	$1.4 \times 10^{-3}$	3.85
AUR-07	Denver	23,000	7.8	$1.9 \times 10^{-3}$	1.16

locally in the aquifers, movement of younger Holocene groundwater through the complex architecture of the alluvial sediments comprising the aquifers may occur, especially in areas with significant drawdown such as Parker and Aurora.

### SUMMARY

The use of environmental tracers, specifically  $^{14}\text{C}$  and noble gases, benefits the characterization of groundwater flow in the Denver Basin, especially as a calibration parameter for a revised groundwater model. The results can be loosely viewed as maximum residence times of those groundwater samples. Recharge temperatures are directly related to residence times, with the younger waters being recharged at warmer temperatures than the older waters, consistent with the older water being recharged during the last glaciation. The relationship of estimated recharge temperatures and residence times to climate record suggests there may be a significant component of Holocene groundwater in some samples or that dilution of  $^{14}\text{C}$  activity has caused samples to appear 'old'.

### ACKNOWLEDGMENTS

The authors acknowledge all who provided assistance in this work, especially Dr. Robert Reynolds who was able to provide research support through the Denver Museum of Nature & Science, and Dr. Andrew Manning of the United States Geological Survey who was generous in sharing knowledge regarding noble gas modeling. Gratitude is also extended to the municipalities of Parker, Aurora, The Pinery and Donala; the Colorado Water Conservation Board; Colorado Division of Water Resources; and the Cherry Creek Valley Water Authority.

### REFERENCES

- Aeschbach-Hertig, W., F. Peeters, U. Beyerle, and R. Kipfer, 1999, Interpretation of dissolved atmospheric noble gases: *Water Resources Research*, v. 35, p. 2779-2792.
- Aeschbach-Hertig, W., F. Peeters, U. Beyerle, and R. Kipfer, 2000, Palaeotemperature reconstruction from noble gases in ground water taking into account equilibration with entrapped air: *Nature*, v. 405, p. 1040-1044.
- Clark, I. D., and P. Fritz, 1997, *Environmental isotopes in hydrogeology*: Ottawa, Canada, Lewis Publishers, 328 p.
- Clark, J. F., M. L. Davisson, G. B. Hudson, and P. A. Macfarlane, 1998, Noble gases, stable isotopes and radiocarbon as tracers of flow in the Dakota aquifer, Colorado and Kansas: *Journal of Hydrology*, v. 211, p. 151-167.
- Crifasi, R. R., 1992, Alluvial architecture of Laramide orogenic sediments: Denver Basin, Colorado: *The Mountain Geologist*, v. 29, p. 19-27.
- Custodio, E., 2002, Aquifer overexploitation: what does it mean?: *Hydrogeology Journal*, v. 10, p. 254-277.
- Hansen, W. R., J. Chronic, and J. Matelock, 1978, *Climatography of the Front Range urban corridor and vicinity*, Colorado, Washington, D.C., USGS, p. 59.
- Manning, A. H., and D. K. Solomon, 2003, Using noble gases to investigate mountain-front recharge: *Journal of Hydrology*, v. 275, p. 194-207.
- Manning, A. H., D. K. Solomon, and A. L. Sheldon, 2003, Applications of a total dissolved gas pressure probe in groundwater Studies: *Groundwater*, v. 41, p. 440-448.
- Muhs, D. R., J. N. Aleinikoff, T. W. Stafford Jr., R. Kihl, J. Been, S. A. Mahan, and S. Cowherd, 1999, Late Quaternary loess in northeastern Colorado: Part I - Age and paleoclimatic significance: *GSA Bulletin*, v. 111, p. 1861-1875.
- National Oceanic and Atmospheric Administration, 2002, mean annual temperature, Colorado Springs, 1948-2001, <<http://www.noaa.gov/pub/climate/cosann.htm>> Accessed July 2002.
- Novotny, M. M., 2004, A preliminary study of dissolved noble gases and carbon-14 in groundwater of the principal bedrock aquifers, Denver Basin, Colorado, Master's thesis, Colorado State University, Fort Collins, 105 p.

- Pearson, F. J., Jr., and W. W. Swarzenki, 1974,  $^{14}\text{C}$  evidence for the origin of arid region groundwater, Northeastern Province, Kenya: Isotope techniques in ground water hydrology, p. 95-108.
- Phillips, F. M., 1995, The use of isotopes and environmental tracers in subsurface hydrology: U.S. National Report to International Union of Geodesy and Geophysics 1991-1994, p. 1029-1033.
- Phillips, F. M., M. K. Tansey, and L. A. Peters, 1989, An isotopic investigation of groundwater in the Central San Juan Basin, New Mexico: carbon 14 dating as a basis for numerical flow modeling: Water Resources Research, v. 25, p. 2259-2273.
- Raynolds, R., 2004, Stratigraphy and water levels in the Arapahoe aquifer, Douglas County area, Colorado: The Mountain Geologist, v. 41, no. 4.
- Robertson, F. N., 1992, Radiocarbon dating of groundwater in a confined aquifer in Southeast Arizona: Radiocarbon, v. 34, p. 664-676.
- Robson, S. G., 1987, Bedrock Aquifers in the Denver Basin, Colorado - A Quantitative Water-Resources Appraisal, Denver, Colorado, USGS, p. 1-73.
- Sanford, W., 2002, Recharge and ground water models: an overview: Hydrogeology Journal, v. 10, p. 110-120.
- Stute, M., and P. Schlosser, 2000, Atmospheric noble gases, in P. Cook, and A. L. Herczeg, eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic, p. 349-377.
- Stute, M., P. Schlosser, J. F. Clark, and W. S. Broecker, 1992, Paleotemperatures in the Southwestern United States derived from noble gases in groundwater: Science, v. 256, p. 1000-1003.
- Vogel, J. C., 1970, Carbon-14 dating of groundwater: Isotope Hydrology, p. 225-237.
- Woodard, L. L., W. E. Sanford, and R. G. Raynolds, 2002, Stratigraphic variability of specific yield within bedrock aquifers of the Denver Basin, Colorado: Rock Mountain Geology, v. 37, p. 229-236.
- Zhu, C., R. K. Waddell, Jr., I. Star, and M. Ostrander, 1998, Responses of ground water in Black Mesa basin, northeastern Arizona, to paleoclimatic changes during late Pleistocene and Holocene: Geology, v. 26, p. 127-130.

## THE AUTHORS

MILOS NOVOTNY



Milos M. Novotny is a Hydrogeologist at S.S. Papadopoulos and Associates, Inc. in Boulder, Colorado, where he works on groundwater model development and support, specifically characterizing aquifer conditions in the western U.S. His research interests include Environmental Tracer Hydrology and Modeling of Natural Systems. He received his B.S. in Geology from Indiana University and M.S. in Geology from Colorado State University.

WILLIAM SANFORD



William E. Sanford is a Hydrogeologist and an Associate Professor in the Department of Geosciences at Colorado State University, where he has been since 1996. His research interests include Environmental and Applied Tracer Hydrogeology and Hydrogeology of Fractured Aquifers. Prior experience includes 4 years at Oak Ridge National Laboratory in Tennessee studying radionuclide transport in fractured mudstones. He received his Ph.D. in Soil and Water Engineering and M.S. in Geophysics from Cornell University and B.S. in Geology from Beloit College.



# **S.S. Papadopoulos & Associates, Inc.**

Environmental and Water-Resource Consultants

## ***Water Resource Studies***

- Water Resource Management & Planning
- Surface Water/Groundwater Interaction
- Groundwater Recharge & Aquifer Studies
- Irrigation Efficiency Analysis
- ESA/NEPA/Riparian Hydrology
- Water Quality Analysis and Compliance

## ***Litigation Support***

- Water Rights/Interstate Issues
- Contamination/Remediation

## ***Modeling***

- Flow & Transport
- Conjunctive Use
- Groundwater Development/Impacts
- Remedial Alternatives

## ***Database Design, GIS & Mapping***

- Water Resource Applications
- Environmental & Engineering Support

## **Contact Information**

Boulder, Colorado Office

303.939.8880

Boulder@sspa.com

www.sspa.com

