2008

Hydrogeochemical characterization of springs and wells in the Cacapon Mountain Aquifer

Lacoa L. Corder
West Virginia University

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

Corder, Lacoa L., "Hydrogeochemical characterization of springs and wells in the Cacapon Mountain Aquifer" (2008). *Graduate Theses, Dissertations, and Problem Reports*. 4363.
<https://researchrepository.wvu.edu/etd/4363>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

Hydrogeochemical Characterization of Springs and Wells
in the Cacapon Mountain Aquifer

Lacoa L. Corder

Thesis submitted to the
Eberly College of Arts and Sciences at
West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Geology

Dorothy J. Vesper, Ph.D., Chair
Joseph J. Donovan, Ph.D.
Eberhard Werner, M.S.

Department of Geology and Geography

Morgantown, West Virginia
2008

Keywords: hydrogeology, carbonate, Berkeley Springs, Morgan County, geochemistry

ABSTRACT

Hydrogeochemical Characterization of Springs and Wells in the Cacapon Mountain Aquifer

Lacoa L. Corder

The Cacapon Mountain Aquifer is located near Berkeley Springs in Morgan County, West Virginia. Approximately 120 wells were selected for a synoptic survey of data including static water levels, pHs, specific conductances, and temperatures to assess regional hydrogeology and geochemistry. Six springs and four wells were sampled on a monthly basis to identify their hydrochemical types and infer the geology of their recharge areas. The potentiometric surface obtained at wells was found to be a subdued reflection of topography. The geologic structure was determined to generally control the direction of ground water flow. Ground water was transmitted in a cross-strike direction on the slopes and in an along-strike direction in Cold Run Valley, parallel to the trend of Cacapon Mountain. Springs could be categorized into two hydrochemical groups; reflecting either a carbonate or siliceous source. Although water from Ladies' Spring was much warmer than all other springs, it was chemically very similar to the carbonate-derived spring waters.

ACKNOWLEDGEMENTS

I would first like to thank the people who made this research possible, the Morgan County Rural Water Committee and the West Virginia Conservation Agency. These groups supported my research and were a pleasure to work with as they are so curious and passionate about their water resources, locally and beyond.

Much thanks to Mary Banks-Nichols, who let me stay in her beautiful home and enjoy her company. I will always miss our talks, her worldly cooking, and the care she bestows upon her friends, flowers, and family.

This project would not have been near as successful or fun if I had not had such a fantastic summer field assistant. Thank you Maxie Maggio for your energy and positive attitude. I wish you the best of luck in all your adventures and know that you will be brilliant in whatever field you choose.

Thank you to all of the well and spring owners in Morgan County who participated in this research. You often welcomed me into your homes and lives, and I am grateful to have had a home away from home in your community. I will especially miss my monthly visits as I got to know you better and we became friends.

My committee members, Dorothy Vesper (chair), Joe Donovan, and Eb Werner, have been positive and helpful throughout this long journey. It would have been impossible for me to complete this research without their insight. Thank you for always encouraging and pushing me to do better, faster. I especially appreciate all of their personal stories, which I have taken to heart, and tried to incorporate into my life and work. Thank you Dorothy for being a friend and keeping things realistic. I strive to be the teacher you are in all facets of life.

Finally, thanks to my friends and family who have always supported me and encouraged me to just get “er” done. And, thank you to all of my incredible professors at WVU who have gotten me to where I am today and have made me love this field.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
TABLES	v
FIGURES	vi
LIST OF ACRONYMS	vii
1.0 INTRODUCTION	1
1.1 <i>PURPOSE AND OBJECTIVES OF STUDY .....</i>	<i>1</i>
2.0 BACKGROUND	4
2.1 <i>REGIONAL GEOLOGY .....</i>	<i>4</i>
2.2 <i>RELEVANT LITERATURE .....</i>	<i>7</i>
2.2.1 <i>Karst settings .....</i>	<i>7</i>
2.2.2 <i>Structural controls on ground water flow .....</i>	<i>9</i>
3.0 METHODOLOGY	10
3.1 <i>SYNOPTIC WELL SURVEY .....</i>	<i>10</i>
3.1.1 <i>Site selection .....</i>	<i>10</i>
3.1.2 <i>Mapping of well locations .....</i>	<i>11</i>
3.1.3 <i>Static water level (SWL) measurement .....</i>	<i>11</i>
3.1.4 <i>Chemical screening data measurements .....</i>	<i>11</i>
3.2 <i>TEMPORAL STUDY .....</i>	<i>12</i>
3.2.1 <i>Site descriptions .....</i>	<i>12</i>
3.2.2 <i>Hydraulic measurements .....</i>	<i>15</i>
3.2.3 <i>Sample collection and chemical analyses .....</i>	<i>15</i>
3.3 <i>DATA QUALITY .....</i>	<i>19</i>
3.4 <i>STATISTICAL ANALYSIS .....</i>	<i>21</i>
4.0 RESULTS	22
4.1 <i>SYNOPTIC SURVEY CHEMICAL DATA AND WATER LEVEL DATA .....</i>	<i>22</i>
4.2 <i>TEMPORAL STUDY CHEMICAL DATA AND WATER LEVEL DATA .....</i>	<i>22</i>
4.3 <i>ANALYSIS OF RESULTS .....</i>	<i>41</i>
4.3.1 <i>Potentiometric surface .....</i>	<i>41</i>
4.3.2 <i>Derived geochemical parameters .....</i>	<i>43</i>
4.3.3 <i>Relationships between chemical parameters .....</i>	<i>50</i>
4.3.4 <i>Comparison of well and spring data .....</i>	<i>54</i>
5.0 DISCUSSION	56
6.0 CONCLUSIONS	61
7.0 REFERENCES	62
APPENDICES	65

TABLES

Table 1: Coordinates, ID, sample type, and geology at selected springs and wells.....	13
Table 2: Number and timing of water samples at selected locations.....	16
Table 3: Summary of analytical methods and sample collection and preservation.....	18
Table 4: Summary of three PCAs.....	51
Table 5: Spring groups by chemistry, location, and speculative source.....	57

APPENDIX TABLES

Table A-1: Field equipment list.....	66
Table A-2: Synoptic well survey data.....	67
Table A-3: Temporal study field measurements.....	71
Table A-4: Daily temperature measurements at Berkeley Springs 3 S weather station.....	73
Table A-5: Daily rainfall measurements at Berkeley Springs 3 S weather Station.....	74
Table A-6: Laboratory data.....	75
Table A-7: Mean and coefficient of variation for selected parameters at study sites.....	77
Table A-8: Derived chemical data.....	79

FIGURES

Figure 1:	Location of Morgan County within West Virginia.....	2
Figure 2:	Springs and wells selected for temporal survey.....	3
Figure 3:	Cross section of Cacapon Mountain anticline- Grimsley and White (1916)	5
Figure 4:	Stratigraphic column- Grimsley and White (1916).....	6
Figure 5:	Regional distribution of SC ($\mu\text{S}/\text{cm}$) in study area.....	23
Figure 6:	Regional distribution of pH at wells in study area.....	24
Figure 7:	Potentiometric surface- Donovan JJ, Werner E, Vesper DJ, Corder L (2006).....	25
Figure 8:	Chemical parameters, stage, and rainfall through time at LDY (Spring)....	27
Figure 9:	Chemical parameters, stage, and rainfall through time at NEY (Spring)....	28
Figure 10:	Chemical parameters, stage, and rainfall through time at WEB (Spring)....	29
Figure 11:	Chemical parameters, stage, and rainfall through time at CSP (Spring)....	30
Figure 12:	Chemical parameters, stage, flow, and rainfall through time at MTN (Spring).....	31
Figure 13:	Chemical parameters, flow, and rainfall through time at HGH (Spring).....	32
Figure 14:	Chemical parameters and rainfall through time at STR (Well).....	33
Figure 15:	Chemical parameters, stage, and rainfall through time at MYR (Well).....	34
Figure 16:	Chemical parameters, stage, and rainfall through time at BZK (Well).....	35
Figure 17:	Chemical parameters, stage, and rainfall through time at YST (Well).....	36
Figure 18:	Temperature differences among sites.....	37
Figure 19(a):	pH vs. SC (b): SC vs. alkalinity at all locations.....	38
Figure 20:	Box and whisker plots of silicon concentration at all sites.....	39
Figure 21:	Piper diagram of all wells and springs in temporal study.....	40
Figure 22:	Static water level through time for wells in the temporal study.....	42
Figure 23:	Box and whisker plots of the calcium to magnesium molar ratio at all sites	44
Figure 24:	Enhanced P_{CO_2} vs. pH at all locations but siliceous springs.....	46
Figure 25:	Calcium to magnesium molar ratio vs. enhanced P_{CO_2}	48
Figure 26:	Box and whisker plots of the calcite saturation index at all sites.....	49
Figure 27:	PC1 scores vs. Ca concentration for all locations.....	52
Figure 28:	PC1 scores vs. PC2 scores for all locations.....	53

LIST OF ACRONYMS

ATC	Automatic temperature compensation
BDL	Below detection limit
Ca	Calcium
Ca/Mg	Calcium to magnesium molar ratio
CBE	Charge balance error
CFC	Chlorofluorocarbon
Cl	Chloride
COV	Coefficient of variation
DI	Deionized water
DRG	Digital raster graphics
EPA	Environmental Protection Agency
Fe	Iron
GPS	Global positioning system
HCO ₃	Unit for reporting alkalinity
I	Ionic strength
IC	Ion chromatography
ICP-OES	Inductively coupled plasma-optical emission spectroscopy
IQR	Interquartile range
K	Potassium
Mg	Magnesium
Mn	Manganese
MCL	Maximum contaminant level
Na	Sodium
NAD83	North American datum of 1983
NO ₃	Nitrate
PCA	Principal component analysis
P _{CO2}	Partial pressure of carbon dioxide
P _{CO2ATM}	Partial pressure of atmospheric carbon dioxide
QA	Quality assurance
Si	Silicon
SI _C	Saturation index of calcite
SI _D	Saturation index of dolomite
SI _Q	Saturation index of quartz
SC	Specific conductance
SO ₄	Sulfate
SWL	Static water level
T	Temperature
T.U.	Tritium units
USGS	United States Geological Survey

1.0 INTRODUCTION

At the turn of the 21st century, springs supplying water to the towns of Berkeley Springs and Bath in Morgan County, West Virginia (Figure 1) declined in productivity to collectively yield a record low of $2.8 \text{ m}^3/\text{min}$ (750 gal/min) (Berkeley Springs 2006). This discharge, which was approximately half of the spring's normal output (Hobba et al. 1977), was attributed to a statewide drought that occurred roughly from 1999 to 2002. Concerns mounted over the springs' ability to sustain Morgan County's growing population and have since spurred residents to learn more about the sustainability of their water supply. A detailed hydrogeologic investigation was conducted to address this matter.

Berkeley Springs is significant from both an historical and scientific standpoint. The springs' waters were once used by Native Americans and other visitors and are now used as a public water supply for the Town of Bath (Berkeley Springs 2006).

1.1 PURPOSE AND OBJECTIVES OF STUDY

Little research has been conducted on ground water drainage and recharge patterns in Morgan County, West Virginia. Consequently, the overall purpose of this research was to characterize the regional hydrogeologic setting. The specific objectives were to:

- Identify and map springs in diverse topographical and hydrogeologic settings;
- Construct a potentiometric map and interpret ground water flow directions; and,
- Analyze spring and well water for major ion chemistry to determine hydrochemical facies and interpret sources and flow directions.

The study area extends eastward from Cacapon Mountain to the Route 522 corridor and south from the Potomac River in Morgan County to the local fish hatchery at Ridge, south of Cacapon State Park (Figure 2).

Figure 1: Location of Morgan County within West Virginia.

Figure 2: Springs and wells selected for temporal survey.

2.0 BACKGROUND

2.1 REGIONAL GEOLOGY

Morgan County, West Virginia is located within the physiographic Valley and Ridge Province, just east of the Allegheny Front (West Virginia Geologic and Economic Survey 2005). Folding and faulting is evident within the region and is prevalent throughout the Valley and Ridge Province. Former movement along these faults is apparent at Berkeley Springs, where slickensides can be found at the Gentleman's spring. Cacapon Mountain, several miles west of Berkeley Springs, marks the axis of the anticlinorium, or series of folded rocks. Rocks dip 50° eastward from the anticline along the eastern side of Warm Spring Ridge near Berkeley Springs (Grimsley and White 1916). Further south, dips decrease to 35-40° (Figure 3).

Descriptions of geologic units were taken from several older publications with detailed information pertinent to Morgan County and Cacapon State Park (Grimsley and White 1916; Price and Ludlum 1951; Minke 1964). Geologic descriptions were compared and then matched to geologic units on a digitized map of West Virginia (Cardwell et al. 1968). These descriptions were used in a general fashion to aid in determining local, surficial geology at springs and wells mapped onto the digitized geologic map of West Virginia. The descriptions were beneficial to comparisons between stratigraphy and chemical data.

Cacapon Mountain is capped by the Tuscarora (Medina) Formation (Grimsley and White 1916). Its thickness is approximately 61 m (200 ft) (Price and Ludlum 1951). This hard, white, quartzose sandstone is the oldest rock within the study area (Figure 4).

Following the eastward dip of the anticline, the next youngest rocks comprise the Silurian Clinton Group/McKenzie Formation. They are roughly 213 m (700 ft) thick and consist of shaley sandstone, sandstone, shale, and shaley limestone (Price and Ludlum

Figure 3: Cross section of Cacapon Mountain anticline- Grimsley and White (1916).

Z A R O N W A	Ct		3200	Catskill Formation.
	Ch		2115	Chemung Shales.
	Po		1765	Portage.
	Ha		1200	Hamilton Shale.
	Ma		330	Marcellus-Onondaga.
	Or		225	Oriskany sandstone.
	Hi		300	Helderberg Limestone.
	Bo.		350	Bossardville Limestone
	RwB		450	Rondout Waterlime and Bloomsburg Red Shales & S.s.
	Na		170	Niagara Formation.
SILURIA	Cl		550	Clinton Shale.
	Md		200	White Medina.

Figure 4: Stratigraphic column- Grimsley and White (1916).

1951). Colors range from red, to olive, to buff, with red signifying the presence of iron (Fe) oxides (Grimsley and White 1916).

The last sediments to be deposited in the Silurian formed the Wills Creek (Rondout Waterlime), and Tonoloway (Bossardville) formations (Price and Ludlum 1951). These limestone rocks total 244 m (800 ft) in thickness and comprise the Salina Formation (Grimsley and White 1916).

The overlying Helderberg Group consists of the Helderberg limestone and the Oriskany or Ridgeley sandstone (Price and Ludlum 1951). This group is approximately 122 m (400 ft) thick and includes shaley intervals (Grimsley and White 1916).

The Oriskany is described as a quartzose sandstone or vitreous quartz conglomerate. It may be hard, coarse-grained, or granular and is white, brownish-gray, or gray to bluish-gray in color (Grimsley and White 1916).

East of Warm Spring Ridge, the Devonian shales form a broad, shallow syncline (Grimsley and White 1916). These shales include the Marcellus Formation, the Mahantango Formation, and the Brallier and Harrell formations.

2.2 RELEVANT LITERATURE

2.2.1 Karst settings

Numerous studies have been conducted in regions with karst geology. Since Berkeley Springs has a great many springs and other features typical of karst settings, it is important to compare and contrast these features with those in other areas. In a relevant study, Shuster and White (1971) examined seasonal changes in chemical behavior to distinguish two types of karst flow mechanics, diffuse and conduit. Their work in Pennsylvania suggested that water from both diffuse and conduit springs undergo changes in geochemistry in response to season but that conduit-fed springs are more variable. Water from the diffuse-fed springs was found to be near saturation for calcite for most of the

year, while water from the conduit-fed springs did not reach saturation. The explanation given was that water discharging from conduit-fed springs was further away from chemical equilibrium than water discharging from diffuse springs. Geochemical parameters, like saturation indices for calcite and dolomite and variation in hardness, were determined to be more useful than other parameters, like hardness and magnesium (Mg) ion concentration, in distinguishing between diffuse and conduit flow mechanics.

A number of other researchers, including Shuster and White (1971), have used calcium to magnesium molar ratios (Ca/Mg) to ascertain the extent to which spring flow occurs through limestones and dolostones. When ratios were near unity, spring water was designated as having flowed through dolostone (Jacobson and Langmuir 1969). This could be a useful addition to the study since the limestones in the region are not pure.

Somewhat contrasting results were found in an analogous study on the Inner Bluegrass Region of Kentucky (Scanlon and Thrailkill 1987). There, chemical attributes showed no correspondence with physical attributes of springs. Diffuse and conduit-fed springs could not be distinguished by fluctuations in chemical parameters as they were in Pennsylvania. In Kentucky, flow path length and recharge type were shown to have a significant impact on chemical variation, rather than diffuse or conduit-fed flow styles. Investigators concluded that the lack of correlation between physical and chemical characteristics was likely due to dissimilar bedrock and structure between the two sites. The geology at Berkeley Springs is similar to that found in the Nittany Valley of Pennsylvania where clastic ridges border either side of a carbonate valley and the rocks are highly folded and faulted. Hence, it is expected that the results of this research will be more comparable to those found in Pennsylvania than Kentucky. These early studies do not fully account for all of the flow mechanisms in karst- recharge type, storage, types of permeability. However, they provide a framework for understanding variation in spring water chemistry.

2.2.2 Structural controls on ground water flow

In the Valley and Ridge Province ground water flow paths are normally short unless there is a carbonate rock aquifer, like that in Cold Run Valley (Trapp and Horn 1997). In the vadose zone, ground water flow often occurs in a down-dip direction on the slopes and in an along-strike direction in the valley (Ginsberg and Palmer 2002). Through connected conduits in soluble rock, the lengths of these flow paths can increase greatly and converge at one large spring outlet (Trapp and Horn 1997). The orientation of the conduits follows that of the joints and fractures. In unconfined carbonate aquifers located in moist climates, Worthington (1999) suggests that a network of conduits almost certainly exists. A spring may be considered an outlet for a conduit network when there is no evidence of faults or a highly permeable rock unit at the spring.

The presence of thermal springs is sometimes controlled by structure. In the Appalachians, it is not uncommon to find these springs in carbonate valleys adjacent to ridges (Dethier and Harman 1998). Secondary porosity and permeability created by jointing or faulting can provide conduits for ground water to reach the surface where it is expelled at springs (Bedinger et al. 1979).

3.0 METHODOLOGY

This section summarizes the selection of wells and springs, methods of data collection, procedures for data analysis, and assessment of data quality. Equipment accuracies and potential errors have been summarized (Appendix Table A-1). The sampling program consisted of two components: a regional, synoptic survey of well water levels, pHs, and specific conductances (SC), and a detailed, temporal study of well and spring water chemistries, discharges, and stages or static water levels (SWL).

3.1 SYNOPTIC WELL SURVEY

3.1.1 Site selection

A regional, synoptic survey of domestic wells commenced May 15, 2004 and ended the first week of August 2004. Approximately 125 wells were surveyed for SWL, pH, and SC. Homeowners were asked to provide details about their wells and water quality including well depth, casing depth, presence of filters or water softeners, odors, smells, rock type, driller name, well usage, and history of drought. Chemical measurements were not made on wells that had filters or water softeners unless requested by the owner. These data were not used in the study and were collected solely for the homeowners' benefit.

Wells were chosen based upon their geographical location and accessibility for measurement. Homeowners who were interested in the research or willing to participate granted entry to their property. Wells were selected to provide the greatest possible spatial distribution of the data and to capture topographic highs and lows that would be evident in the SWL data. The wells were located largely within Cold Run Valley, Rock Gap, or surrounding Sir Johns Run, as these homeowners did not have city water available to them. South of the city's limits, most wells were sampled just east of the Route 522 corridor.

3.1.2 Mapping of well locations

Well locations were collected using a GARMIN eTrex Vista ® Global Positioning System (GPS). Ninety-five percent of the time, this GPS unit is spatially accurate within 15 m (eTrex Vista 2001). In the field, the accuracy reported by the unit ranged from 2.44 m to 22.9 m and averaged 6.71 m (22 ft).

Well locations were overlaid onto 1:24,000-scale USGS Digital Raster Graphics (DRG). The DRGs are USGS digitized and georeferenced topographic maps that have been fitted to a Universal Transverse Mercator projection, Zone 17N (USGS 2005). The projection was based on a North American Datum of 1983 (NAD83). Land surface elevations at wells and springs were ascertained by interpolating between topographic contours.

3.1.3 Static water level (SWL) measurement

A graduated steel tape was used to measure SWLs following the method of Lapham et al. (1971). At each site, a measuring point was selected at the top of the well casing. The watermark, or length of submergence of the tape, was subtracted from the amount of tape lowered into the well and recorded as the depth-to-water level. SWL was then calculated by subtracting the depth-to-water measurement from the surface elevation of the well.

3.1.4 Chemical screening data measurements

The pH, temperature, and SC measurements were collected at each well. Error in fieldwork was estimated by repeating measurements and reduced by calibrating the instruments daily. The percent error for pH and temperature measurements collected in the field was less than 1% when repeated four times at one site. SC measurements agreed within 1.3% when repeated six times at one site. The conductivity meter was calibrated with

a standard solution of 1408 $\mu\text{S}/\text{cm}$. Commercial buffers of pH 4 and 7 were used for pH calibration. The pH meter's automatic temperature compensation (ATC) function adjusted the pH value based on the water's temperature. Distilled water was routinely used to rinse the probes between measurements.

3.2 TEMPORAL STUDY

A detailed, temporal study of four wells and six springs was performed during seven months from September 2004 to April 2005 (Figure 2). Site selection was based upon accessibility, location, spring size, and ease of measurement ascertained during the previous summer months.

3.2.1 Site descriptions

Details on sample identification (ID), location, and geology are given for each spring and well (Table 1). Geological descriptions were obtained from a digitized version of a 1968,- 1: 250,000 geologic map of West Virginia (Cardwell et al. 1968). The geologic units depict surface geology. A description of the wells follows.

- STR Well is the northernmost of the four wells. It is approximately 3.2 km (2 mi) south of Berkeley Springs and is within 6 m of Cold Run Valley road.
- MYR Well is located in a flat-lying area, near to Cold Run Valley road. It was chosen due to its proximity to WEB spring.
- BZK Well is found in the foothills of Cacapon Mountain on its eastern flank. Because this well is newer, its depth and casing length are known from markings on the well cap.
- YST Well is located high on the slope of Cacapon Mountain and was selected for its distinct topographical location, accessibility, and newness. The well depth and casing length are known.

Table 1: Coordinates, ID, sample type, and geology at selected springs and wells.

Location	UTM Coordinates	Latitude Longitude	Sample ID (Historic Names)	Sample Type	Geology at Spring Mouth
Berkeley Springs State Park	737804 4389947	39.63 -78.28	LDY "Ladies" (Berkeley Springs-McColloch 1986)	Spring	Oriskany (SS)
Cold Run Valley	736301 4387510	39.60 -78.28	STR	Well	Tonoloway, Wills Creek, Williamsport formations (LS, SS, Sh)
Cold Run Valley	733954 4384379	39.58 -78.28	MTN "Mountainside" (Coolfont Spring-McColloch 1986)	Spring	Clinton Group/McKenzie Formation (SS, Sh)
Cold Run Valley	734186 4383370	39.57 -78.27	NEY "Neely"	Spring	Tonoloway, Wills Creek, Williamsport formations (LS, SS, Sh)
Cold Run Valley	734029 4382692	39.56 -78.28	WEB	Spring	Tonoloway, Wills Creek, Williamsport formations (LS, SS, Sh)
Cold Run Valley	733956 4382626	39.56 -78.28	MYR	Well	Tonoloway, Wills Creek, Williamsport formations (LS, SS, Sh)
Rock Gap	733354 4381244	39.55 -78.28	BZK	Well	Tonoloway, Wills Creek, Williamsport formations (LS, SS, Sh)
Cacapon State Park- Rock Gap	731199 4378357	39.52 -78.30	HGH (High)	Spring	Tuscarora Formation (Quartzite)
Rock Gap	731901 4378197	39.52 -78.31	YST	Well	Clinton Group/McKenzie Formation (SS, Sh)
Cacapon State Park	731979 4375902	39.50 -78.30	CSP "Cacapon State Park" (Cacapon State Park Spring- McColloch 1986)	Spring	Tonoloway, Wills Creek, Williamsport formations (LS, SS, Sh)

LS- limestone; SS- sandstone; Sh- shale.

Springs are scattered throughout the study region and exist in heterogeneous topographic settings. Knowledge of their whereabouts was acquired from the West Virginia state inventory, community members that participated in the summer well survey, and from collaborating researchers to the research project. Springs were chosen if they were large enough to be measured for discharge with a bucket and stopwatch or could be monitored for stage. A description of the springs follows.

- LDY (Ladies' Spring) is one of several warm springs discharging from the Oriskany Formation at the eastern base of Warm Spring Ridge. These warm springs are located in Berkeley Springs State Park in the town of Bath. LDY was preferred for sampling over the other warm springs due to its large size, locked entry, and ability to accommodate a data logger and staff gage.
- MTN (Mountainside) Spring, near Coolfont resort, is located on the eastern slope of Cacapon Mountain. Although the spring is no longer used, it once provided drinking water for the housing development. The soft sediment from which it issues is protected by a metal cap and concrete seal.
- NEY (Neely) Spring discharges into Sir Johns Run. It is used for domestic purposes and is protected by a springhouse. The spring is located at the base of a steep hill sloping down from Cold Run Valley road.
- WEB Spring also discharges into Sir Johns Run and is protected by a springhouse. It is found in a low, saturated, flat-lying area at a slightly lower elevation than Cold Run Valley road.
- HGH Spring, unlike all of the other springs, is situated near a topographic high on the eastern side of Cacapon Mountain in Cacapon State Park. It is less than 1 km from the summit and is the only spring that is unprotected by a cap or springhouse.
- CSP Spring is located in the gently rolling valley area of Cacapon State Park, east of Cacapon Mountain. It is protected by a cap and springhouse and was once used for

drinking water. Visitors now receive water from a number of wells situated throughout the park.

3.2.2 Hydraulic measurements

Spring stage and discharge were measured according to each site's physical constraints. Stage was measured as the distance from a permanent reference to the water's surface. Spring discharge was obtained with a large bucket and stopwatch. To quantify error in making this estimate, the discharge measurement was repeated five times at one sampling location. The coefficient of variation (COV) was 17%.

Discharge at WEB spring was measured from a plastic pipe draining the spring. At MTN, discharge was measured about 15 m downstream of the culvert, rather than at the head of the spring. This was the only position where a bucket could be successfully placed to collect water.

At HGH, discharge was measured along the spring run as the water was ponded at the spring. The channel narrowed downstream at a small waterfall, making the measurement easier to take. This measurement was an estimate of about 80% of the spring's discharge. Discharge could not be measured at the other springs as there was no acceptable location for placing a bucket. A flow meter could not be used, because the spring runs were too shallow.

3.2.3 Sample collection and chemical analyses

Water sample collection began in September 2004 and ended in April 2005. Sites were sampled five to seven times, depending on location (Table 2). As sampling progressed, different analytes were added or excluded from laboratory analyses depending on preliminary data, laboratory equipment availability, and pertinence of the analyte to research.

Table 2: Number and timing of water samples at selected locations.

Location	Total # of Times Water Sampled	4-Sep	4-Oct	4-Nov	4-Dec	5-Feb	5-Mar	5-Apr
LDY	7							
STR	5	NC				NC		
MTN	7							
NEY	7							
WEB	7							
MYR	6	NC						
BZK	6	NC						
HGH	6						NC	
YST	6						NC	
CSP	7							

Shaded cells indicate collection of chemical samples.

NC indicates that a sample was not collected that month.

All 10 sites were measured for pH, temperature, SC, and alkalinity once monthly. Temperature, pH, and SC readings were recorded concurrently with the collection of water samples. Sample bottles, filter cartridges, and syringes were rinsed with sample water at least three times before collecting any water. Samples for cation and anion analyses were then filtered with 0.45- μm disposable cartridge filters. Cation samples were preserved with nitric acid. All samples were kept on ice to minimize any chemical reactions associated with microorganisms.

Alkalinity was calculated using a two-point gran titration to pHs 4.2 and 3.9 (Rounds and Wilde 2002). It was measured in the field when possible or within 24 hours to diminish the effects of degassing and microbial activity. Total alkalinity was calculated by using the volume of titrant, normality of acid, and sample volume (APHA et al. 2005). Alkalinity measurements were repeated six times on a single sample in order to estimate precision. Values agreed within 7%. Alkalinity data are reported in mg/L as bicarbonate (HCO_3).

Chemical measurements were conducted at the spring head for all but one of the springs. At CSP, sampling was conducted about 15 m outside of the springhouse, where it discharges from the ground. Inaccessibility prevented measurements from being taken inside the springhouse.

At all well locations except YST, chemical measurements were taken in small plastic beakers filled with water from a nearby hand pump tapping the well. Chemical data were collected differently at YST because of the lack of a hand pump. There, water was taken from an outside tap and dispensed in plastic beakers after turning off the water softener and letting the water run for 10 to 15 minutes.

Anions were analyzed by Ion Chromatography (IC), while cation samples were analyzed using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) (Table 3). Chemical analyses were conducted by the National Research Center for Coal and Energy Analytical Laboratory.

Table 3: Summary of analytical methods and sample collection and preservation.

Analytes	Filtered/Unfiltered	Bottle Type	Preservative	Analytical Instrument	Method
Cations: Ca, Mg, Na, K, Fe, Mn, Si, S	Filtered	Plastic	Nitric Acid	ICP-OES	EPA 200.7 environmental samples
Anions: SO ₄ , Cl, NO ₃	Filtered	Plastic	None	IC	EPA 300.0

As laboratory equipment availability changed, methods for analyzing ions changed.

Specific methods are given here: SO₄ (375.4 or 375.1), Cl (325.2), NO₃ (353.2)

ICP-OES: Inductively Coupled Plasma-Optical Emission Spectroscopy

IC: Ion Chromatography

A chemical equilibrium model, *Visual MINTEQ* version 2.30, was used for speciation calculations. This model is a Windows based program adapted from the EPA's *MINTEQA2* version 4.0 (Gustafsson 2004).

Using the parameters pH, temperature, alkalinity, and analyte concentration as input, charge balance error (CBE), ionic strength (I), saturation indices for quartz (SI_Q), calcite (SI_C), and dolomite (SI_D), and the partial pressure of carbon dioxide (P_{CO_2}) were calculated. Enhanced P_{CO_2} values were calculated by normalizing the P_{CO_2} concentration to the atmospheric P_{CO_2} (P_{CO_2ATM}).

3.3 DATA QUALITY

In examining error, the most important consideration is how it impacts interpretation of the results. A quality assurance (QA) program was thereby created to quantify the amount of error in field and laboratory methods and to determine whether this error limited the conclusions drawn from the data. A discussion of the program and subsequent findings are presented.

Three blind duplicates made from split samples were sent to the laboratory to check for laboratory or method precision. The average percent difference for duplicate samples from original samples was approximately 13%. The percent difference was much greater for some of the analytes at small concentrations than for analytes at large concentrations. For instance, the difference for NO_3 was 133% for one duplicate. All other percent differences ranged between 0% and 32%.

- To assess the laboratory's accuracy, six standards with known concentrations of cations were submitted for analysis. Percent error ranged between 14.7% and 27.6%.
- To determine if the filter or syringe was contaminating any of the water samples, a filter blank of deionized (DI) water was sent to the lab. Most analytes were present

at concentrations less than 0.1 mg/L or below the detection limit of the analysis. It is possible that this affects the concentration of Ca at the low-concentration springs (MTN and HGH), but the impact is minimal and does not impact the interpretation between springs.

Alkalinity values posed a potential problem at sample sites having waters with low alkalinities. How this affected the saturation indices was especially important. Waters from sample sites with low alkalinities had very high COVs for alkalinity, when compared with waters from sample sites with high alkalinities. At sites where waters have little buffering capacities; however, the error in measuring alkalinity ultimately produced higher CBEs. Although the COVs for alkalinity were high for sites having waters with lower alkalinities, interpretation of the SI_C was unaffected. The two sites having waters with low alkalinities were clearly undersaturated with respect to calcite regardless of the COV. A definite distinction could be made between sites that had waters that were near to equilibrium, slightly undersaturated, undersaturated, or very undersaturated. It was concluded that varying alkalinities did not affect the interpretation of the saturation index for calcite regardless of whether alkalinity concentration was high or low. Conclusions regarding the SI_D were similar.

Interpretation regarding P_{CO_2} was somewhat impacted. The COV in P_{CO_2} values for the sites having waters with the lowest alkalinities was much greater than for other, more alkaline waters. The P_{CO_2} is calculated from the pH, so errors in pH produce errors in enhanced P_{CO_2} . An approximately 10% error in P_{CO_2} results from an error of 0.05 pH unit (Palmer 2007). If there was an error in the collection of pH, for instance an underestimation in pH caused by using two different pH meters, one of which gave lower pH readings, then this error would be consistent among sites as long as the meter was not switched during any given sampling round. While the enhanced P_{CO_2} values through time may have some error, interpretation is not impacted in comparing these sites for any given sampling period. Only

temporal interpretation of pH and enhanced P_{CO_2} would be affected. Interpretation of SI_C was affected similarly by changes in pH. While temporal analysis may have been impacted, for any given sampling round comparisons could still easily be made among locations. Comparisons between mean chemical parameters were also possible and considered not to be affected.

3.4 STATISTICAL ANALYSIS

Statistics were used to aid geochemical and hydrologic interpretation in both the synoptic and temporal studies. Correlations with probabilities (P-values) less than a significance of 5% ($\alpha = 0.05$) are considered to be statistically significant.

Principal Component Analysis (PCA) was performed using Minitab® Statistical Software (2000) and was used to analyze the temporal data while reducing redundancy among the intercorrelated variables (Kachigan 1986). The result was a combination of intercorrelated variables into a few distinct groups or principal components.

4.0 RESULTS

4.1 SYNOPTIC SURVEY CHEMICAL DATA AND WATER LEVEL DATA

The screening data collected during the synoptic survey included pH, SC, and SWL (Appendix Table A-2). The measured pHs ranged from 5.22 to 7.73; the SC from 100 to 945 $\mu\text{S}/\text{cm}$. An area of concentrated high SC and high pH was found within Cold Run Valley in the Tonoloway/Wills Creek formations which are comprised of limestone, shale, and sandstone (Figures 5 and 6). Several wells on the eastern side of Warm Spring Ridge also had waters with both high SC and pH. Surface lithology here consists of shales in the Mahantango or the Brallier/Harrell formations.

The region with a consistently low pH and SC was found on the eastern flank of Cacapon Mountain. Wells in this area are most likely completed in the Clinton Group/McKenzie Formation which is comprised of sandstone, calcareous sandstone, and shale or in the non-calcareous Keefer sandstone, which resembles the Tuscarora sandstone (Minke 1964). Wells near the base of Cacapon Mountain may be completed in the more calcareous upper units of the Clinton Group/McKenzie Formation.

A potentiometric surface map was constructed from the water level elevation data to infer regional ground water flow directions (Figure 7). Water level elevations ranged from 141 m (464 ft) to 377 m (1238 ft). The highest elevations were generally found in the two areas of greatest vertical relief, Cacapon Mountain and Warm Spring Ridge; the lowest water level elevations were found in the valleys. Water level elevations decreased to the north on the northern side of the ground water divide inferred from the potentiometric contours.

4.2 TEMPORAL STUDY CHEMICAL DATA AND WATER LEVEL DATA

The field measurements taken during the temporal study included physical and chemical parameters (Appendix Table A-3). Changes through time are depicted for

Figure 5: Regional distribution of SC ($\mu\text{S}/\text{cm}$) in study area.

Figure 6: Regional distribution of pH at wells in study area.

Figure 7: Potentiometric surface. For full details see source reference.

some parameters for each well and spring (Figures 8-17). Temperature and rainfall data were obtained from the NOAA Berkeley Springs 3 S station which is located in Berkeley Springs, West Virginia (NOAA 2005; Appendix Tables A-4 and A-5).

The water temperatures ranged from 4.1 to 22.5 °C over the sampling period. Waters from the wells varied more in temperature than did waters from the springs (Figure 18). Water temperatures in CSP, HGH, WEB, and LDY springs were the most consistent over the studied period. LDY, furthermore, had the highest and least variable water temperatures.

The pHs ranged from 3.97 to 7.33; the SCs ranged from 32 to 945 ($\mu\text{S}/\text{cm}$). Two springs (HGH and MTN) had waters with low pH and low SC values, while the remaining springs had higher pH and SC values (Figure 19a). Waters from BZK and STR wells had higher pHs and SCs than all other sites.

Manganese (Mn) and NO_3 concentrations were measured for four and two sampling rounds, respectively (Appendix Table A-6). All concentrations were below the detection limit ($<0.1 \text{ mg}/\text{L}$) for Mn, except in waters from HGH spring. Its Mn concentrations were slightly above the detection limit for two of the sampling rounds. All sites had relatively low NO_3 but MYR. Its concentration ($3.57 \text{ mg}/\text{L}$) was below the EPA's maximum contaminant level of $10 \text{ mg}/\text{L}$ NO_3 measured as N (EPA 2005). Only in waters from YST well were Cl and NO_3 concentrations below their detection limits.

Si concentrations in spring waters ranged between 1.95 and 5.81 mg/L . In well waters Si concentrations ranged between 2.32 and 4.50 mg/L (Figure 20). Water from LDY spring had the highest median Si concentration; the range overlapped with Si concentrations in waters from CSP and WEB springs. Mean concentrations have been calculated and summarized for selected parameters (Appendix Table A-7).

All sites, except for MTN and HGH, are in the calcium-bicarbonate hydrochemical facies (Figure 21) (Fetter 2001). MTN has no dominant type of chemistry based on ratios

Figure 8: Chemical parameters, stage, and rainfall through time at LDY (Spring).

Figure 9: Chemical parameters, stage, and rainfall through time at NEY (Spring).

Figure 10: Chemical parameters, stage, and rainfall through time at WEB (Spring).

Figure 11: Chemical parameters, stage, and rainfall through time at CSP (Spring).

Figure 12: Chemical parameters, stage, flow, and rainfall through time at MTN (Spring).

Figure 13: Chemical parameters, flow, and rainfall through time at HGH (Spring).

Figure 14: Chemical parameters and rainfall through time at STR (Well).

Figure 15: Chemical parameters, stage, and rainfall through time at MYR (Well).

Figure 16: Chemical parameters, stage, and rainfall through time at BZK (Well).

Figure 17: Chemical parameters, stage, and rainfall through time at YST (Well).

Figure 18: Temperature differences among sites. The above legend provides an explanation for the box and whisker plot and is the same for all plots of this type.

Figure 19: (a) pH vs. SC (b) SC vs. alkalinity at all locations.

Note: Wells have open symbols. Springs have closed symbols.

Figure 20: Box and whisker plots of silicon concentration at all sites.

Figure 21: Piper diagram of all wells and springs in temporal study.

between the cations Ca, Mg, and Na plus potassium (K). The anions are dominated by bicarbonate except for anions in waters from springs MTN and HGH. These springs are of the SO₄-type. Spring and well waters dominated by the bicarbonate anion also have high pHs and SCs.

SWLs were collected at four wells 2-6 times over a six month period following the synoptic well survey. SWLs differed by nearly six meters in some instances; however, the elevations of the water surface at these locations remained constant relative to each other (Figure 22).

4.3 ANALYSIS OF RESULTS

4.3.1 Potentiometric surface

The illustration of the potentiometric surface (Figure 7) is from Donovan et al. (2006) and has been modified to highlight a few important inferences drawn from the map. The primary conclusions are summarized herein. The potentiometric surface indicates that there are two regional directions of ground water flow in Cold Run Valley, with an inferred ground water divide between Sir Johns Run and Rock Gap Run (Figure 7). These streams capture surface flow from tributaries on the eastern side of Cacapon Mountain and ground water flow from the underlying ground water basin (Donovan et al. 2006). Two ridges, Cacapon Mountain and Warm Spring Ridge, act as topographic divides for surface water, thereby forming a drainage basin or catchment within Cold Run Valley. This interpretation is enhanced by topographic maps, particularly the location of surface water flow and water gaps in the ridge.

The potentiometric surface is a subdued reflection of topography; the highest hydraulic heads were found on the ridges and the lowest hydraulic heads were found in the valley. The northward decrease in potentiometric head that occurred on the northern side of the ground water divide illustrates the flow of ground water and surface water to the north.

Figure 22: Static water level (SWL) through time in meters above mean sea level for wells in the temporal study.

Sir Johns Run captures drainage from both Cacapon Mountain and Warm Spring Ridge and carries it northward where it is discharged into the Potomac River. Areas of recharge occur west of Sir Johns Run on Cacapon Mountain and east of Sir Johns Run on Warm Spring Ridge.

Tributaries south of the ground water divide up to the eastern boundary of Cacapon State Park flow northerly and southerly into Rock Gap Run. This stream then drains into Sleepy Creek. Within the central portion of Cacapon State Park, tributaries and streams drain into Indian Run and then into Sleepy Creek.

Regional flow occurs in a cross-strike direction toward Sleepy Creek and is clearly related to topography. Gaps in Warm Spring Ridge occurring at Rock Gap and Cacapon State Park allow the water to be transmitted in a cross-strike, easterly direction. Surface water in the study area is ultimately transmitted to the north, via Sir Johns Run, or to the east via tributaries to Sleepy Creek.

4.3.2 Derived geochemical parameters

Ca/Mg molar ratios ranged from 0.81 to 15.83 and were used to separate springs and wells into potential water sources (Appendix Table A-8). CSP and LDY springs' waters had median Ca/Mg molar ratios of approximately five and six (Figure 23). NEY spring's and BZK well's waters had ratios between three and four, and WEB spring's and MYR well's waters had ratios of approximately four. Well water from YST had a median Ca/Mg molar ratio of about 13. Although these ratios are all indicative of a carbonate source, YST appears to have a different water source than the other springs and wells.

The high Ca/Mg molar ratio in water from YST well indicates that its water comes from a relatively pure limestone. No dolomitic beds have been mapped in the Clinton

Figure 23: Box and whisker plots of calcium to magnesium molar ratio at all sites.

Group/McKenzie Formation where YST well is likely completed. The comparatively high Fe content and limestone signature of the water suggests that it was completed in this unit. Shaley sandstone, sandstone, shale, and shaley limestone comprise the formation (Price and Ludlum 1951).

Water from STR well had a low median Ca/Mg molar ratio of approximately two, high Ca concentrations, and high pH values suggesting probable contact with dolomite. This well could have been completed in a limestone unit like the Tonoloway or Wills Creek formations with dolomitic beds.

MYR well and WEB spring are about 97 m (318 ft) apart. The most likely limestone sources for the springs in the similar valley setting and BZK and MYR wells are the Wills Creek and Tonoloway formations. For LDY spring, the Helderberg Group and the Wills Creek and Tonoloway formations are possible sources. However, calcite cements the porous Oriskany Formation of the Helderberg Group; so this formation is also a potential source, even though it is mapped as sandstone, not carbonate (Diecchio et al. 1984; Heald et al. 1962). In some locations, the Oriskany Formation grades into limestone.

MTN and HGH spring waters had low Ca and Mg concentrations, low pHs, and the lowest median Ca/Mg molar ratios of approximately one, indicating siliceous sources. Here, siliceous is used to refer to source rocks that do not contain high concentrations of siliceous minerals but are comprised primarily of non-carbonate minerals. Unlike the other springs, they are located at topographic highs along Cacapon Mountain. Given the surface geology where the springs issue, MTN's source is likely the Clinton Group/McKenzie Formation, while HGH's is likely the Tuscarora sandstone.

All locations had waters with P_{CO_2} concentrations much greater than atmospheric concentration (Figure 24). Of these sites, waters from BZK and WEB wells had the lowest P_{CO_2} concentrations, and waters from STR well, LDY spring, and YST well had the highest

Figure 24: Enhanced P_{CO_2} vs. pH at all locations but siliceous springs.
 Note: Wells have open symbols. Springs have closed symbols.

concentrations, after water from MYR well. The P_{CO_2} is not reported for MTN and HGH spring waters, because their low alkalinities limited the accuracy of the CO_2 calculation.

WEB and NEY spring waters and CSP and LDY spring waters had median enhanced P_{CO_2s} of less than 50 and 50-100 times greater than atmospheric concentration, respectively. WEB and NEY are in similar settings. Both are in pasture farm land in the carbonate valley. CSP is located in a forested area with abundant plant life. LDY lies at the base of Warm Spring Ridge. Here, the ridge is covered with trees, but the area immediately surrounding the spring is not. These springs all have the potential for P_{CO_2} to be above that of the atmosphere given the overlying soil and plant life; however, other factors like the recharge area and flowpath length are also important and were not determined in this research. Therefore, the interpretation based on P_{CO_2} is mostly speculative.

Several distinctions among locations are evident when comparing the relationship of enhanced P_{CO_2} to the Ca/Mg molar ratio (Figure 25). Springs are chemically more closely related regarding these parameters than are wells. WEB spring and BZK wells have noticeable graphical overlap for these parameters and are likely from the same carbonate source. Waters from LDY spring and STR well had similar enhanced P_{CO_2s} but very different Ca/Mg molar ratios. They are probably not from the same source of rock or combination of rock sources.

Nearly identical relationships among sites are shown graphically for SI_C and SI_D (Figure 26). STR well is the only site with water whose median indicates that it is oversaturated with calcite. BZK well water is the next nearest to saturation, followed by waters from WEB and CSP springs. MTN and HGH springs' waters have larger ranges for SI_C like NEY spring. All sites are less saturated with dolomite than they are for calcite. All sites are oversaturated with quartz.

Figure 25: Calcium to magnesium molar ratio vs. enhanced P_{CO_2} .

Figure 26: Box and whisker plots of the calcite saturation index at all sites.

4.3.3 Relationships between chemical parameters

PCA was completed using multiple strategies for the first four rounds of data. The last three rounds were excluded due to problems with the pH meter. No data were excluded from these first four rounds except for concentrations below the detection limit. A PCA was performed on spring and well data together and each set separately (Table 4). In all cases, the first two components have eigenvalues greater than 1 and are the focus of the discussion. For springs and wells together, the cumulative variation given by the first two principal components is 80.8% (Table 4). The variables with the highest loadings on PC1 are pH, SC, Ca, Mg, Na, and alkalinity. The PC1 has a high eigenvalue (>5) in all analyses run, indicating that this set of variables strongly defines the overall water chemistry. This component is termed the carbonate component because it reflects the chemistry of carbonate rock dissolution. Calcium concentrations are closely related to the PC1 sample scores (Figure 27).

PC2 is more variable among the three data sets than is PC1. This component is termed the non-carbonate component. SO_4 and Si were found to be among the most important variables to PC2 for all PCAs completed. The results of the PCA for wells are nearly identical to the results of the PCA with wells and springs combined. Wells and springs differ in that K had a high loading on PC2 for the wells-only PCA, and Na had a high loading for the springs-only PCA. Waters from STR and BZK wells had very high Na concentrations, and water from MYR well had higher K concentrations relative to the other wells and springs. LDY spring's waters had the highest SO_4 concentrations among the springs, followed by non-carbonate spring waters HGH and MTN.

When the PC1 and PC2 scores are plotted against each other, two groups of springs become apparent (Figure 28). The two siliceous springs, MTN and HGH, group together graphically, and the four carbonate springs group together. LDY spring plots with the

Table 4: Summary of three PCAs

	Springs and Wells		Springs		Wells	
	PC1	PC2	PC1	PC2	PC1	PC2
pH	0.325	-0.344	0.407	-0.043	0.355	0.294
SC	0.419	0.062	0.411	-0.035	0.388	-0.182
HCO ₃	0.415	-0.079	0.408	-0.107	0.400	-0.064
Ca	0.413	-0.040	0.392	0.023	0.401	-0.059
Mg	0.392	0.188	0.376	-0.240	0.384	-0.204
Na	0.351	0.165	0.264	0.497	0.357	-0.050
SO ₄	0.224	0.564	-0.160	0.689	0.196	-0.540
K	-0.039	0.520	0.012	0.203	-0.214	-0.545
Si	0.219	-0.468	0.329	0.406	0.207	0.490
Eigenvalues	5.53	1.74	5.67	1.65	6.13	2.12
Proportion of Variance	0.615	0.194	0.630	0.184	0.681	0.235

Only eigenvalues greater than 1 are reported; Loadings greater than ± 0.3 are in bold.

Figure 27: PC1 scores vs. Ca concentration for all locations.

Figure 28: PC1 scores vs. PC2 scores for all locations.

carbonate springs due to chemical similarities. The carbonate springs load higher on PC1, the carbonate component, while the siliceous springs load higher on PC2, the non-carbonate component. This finding shows that there are two well-defined spring types in the study area.

The wells are all distinct when comparing PC1 to PC2 (Figure 28). YST well is most similar to the carbonate springs based on this analysis. All wells load higher on PC1 than do the siliceous springs.

4.3.4 Comparison of well and spring data

Springs and wells were differentiated in several ways. The springs could be separated into two groups, those with high pHs, SCs, and alkalinities and those with low pHs, SCs, and alkalinities. These groups were termed carbonate and siliceous, respectively (Figures 19a and 19b). The concentration range for the carbonate springs fell within the larger range defined by the wells.

Differences in temperature are notable between wells and springs (Figure 18). Well waters were much more variable through time regarding temperature than were spring waters and had larger temperature ranges. Spring waters also contained lower concentrations of Na, Cl, and SO_4 than did well waters, with the exception of YST well (Appendix Table A-6). These findings suggest that the wells in this study may have a more rapid interaction between surface conditions and ground water than do the wells.

Even if wells are completed in the same aquifer, they still may differ greatly as karst aquifers are typically heterogeneous. YST is the only location among the wells that may be receiving water from a different formation than the other wells, due to the water's relatively high Ca/Mg molar ratio and Fe concentration. Although the other wells appear to be completed in the same formation, they are still unique chemically as the water quality in each well is indicative of very localized lithology.

Unlike wells, the carbonate springs in this study do not receive water from one distinct point in the aquifer. Aside from strictly conduit-fed springs, springs discharge water from a larger portion of the aquifer than do wells. Springs are spatially integrative, while wells sample water from a localized point in an aquifer. This spatial averaging of water quality is evident for the springs in this research but not for the wells.

5.0 DISCUSSION

Several factors were found to influence the direction of ground water flow and the hydrochemical facies of spring and well waters. The potentiometric surface reveals the importance of topography and structure to flow direction (Figure 7). Along the slopes of Cacapon Mountain, ground water was found to be transmitted in a down-dip direction, as given by the decreasing potentiometric contours. In the valley between Cacapon Mountain and Warm Spring Ridge, regional ground water flow may occur along strike. In similar settings, flow directions have been identified both along strike and along dip. Ground water movement along dip in the vadose zone has been observed in steeply dipping rocks (Ginsberg and Palmer 2002). In the phreatic zone, ground water was predominantly conducted along strike. Trapp and Horn (1997) have noted cross-strike ground water flow under ridges and flow parallel to strike in valleys in the Valley and Ridge Province. Burton et al. (2002) modeled ground water flow in the Valley and Ridge province and found that down-dip flow was a controlling factor. In the Cacapon Mountain aquifer, the controlling flowpaths cannot be determined based on this project and are only speculative.

The springs selected for study lie in several topographic and geologic settings (Table 5): Spring group A discharges on the ridges or slopes where siliceous rocks are present at the surface; Spring group B discharges in the upper or lower valleys where carbonate rocks are present at the surface, and spring group C discharges at the base of a ridge where siliceous rocks are present at the surface.

As the PCA indicates, some of the springs have strong carbonate signatures that others lack (Table 4). The springs with carbonate signatures, whose variables load high on PC1, are located in the upper and lower valleys between Warm Spring Ridge and Cacapon Mountain (Group B) and at the eastern base of Warm Spring Ridge (Group C); these areas are underlain by the Tonoloway/Wills Creek formations and the Helderberg Group, respectively. Group C is near the contact of the Helderberg Group and the

Table 5: Spring groups by chemistry, location, and speculative source.

Group	Chemical Signature	PCA Result	Physical Location	Interpreted Water Source	Springs
A	low SC, Ca, and HCO ₃ ; pH < 5.2; T < 14°C	loads higher on PC2	ridges, slopes; elevations > 980' (299m)	siliciclastics, shallow	HGH, MTN
B	high SC, Ca, and HCO ₃ ; pH > 6.4; T < 14°C	loads higher on PC1	lower to upper valley; elevations 780-930' (238-284 m)	carbonates, shallow	NEY, WEB, CSP
C	high SC, Ca, and HCO ₃ ; pH > 6.4; T > 22°C	loads higher on PC1	ridge base; elevations = 620' (189 m)	carbonates, possible deep flow component with travel to surface through fractures	LDY

Marcellus/Needmore formations.

The siliceous springs comprising group A are located on the eastern slopes of Cacapon Mountain and likely discharge water from the Tuscarora Formation or the Clinton Group/McKenzie Formation. These springs have chemical variables which load high on PC2, the non-carbonate component.

LDY spring is the only spring whose water issues from a siliceous rock but has a carbonate signature. Although its water (Group C) is very similar chemically to the other springs with carbonate-derived waters (Group B), this spring's water is warm, while the other springs' waters are cold. This suggests that LDY spring has a deep component of flow. A deep flow component further implies that some fraction of the water reaching the spring is old. Age dating using chlorofluorocarbons (CFC-11, CFC-12, and CFC-113) and tritium of waters at Berkeley Springs has supported this assumption (Plummer pers. comm.). Based on these analyses, the springs' waters are thought to be a mixture of young and old with the young fraction being greater than 40 years old and the old fraction being greater than 270 years old, up to 2,700 years old.

LDY spring's relatively large volume of discharge is common of springs at the bases of sandstone ridges in the Valley and Ridge Province (Trapp and Horn 1997). Recharge to thermal springs often takes place on ridge tops and is transported via fractures to minimum depths of 244-1585 m (800-5200 ft). Geothermal heating occurs with deep circulation of ground water, ultimately producing spring waters that may be more mineralized, contain hydrogen sulfide, and have long residence times (Trapp and Horn 1997). Secondary porosity and permeability created by jointing or faulting provides conduits for ground water to reach the surface (Dethier and Harman 1998).

Evidence of former movement along faults is present at Berkeley Springs State Park in the form of slickensides. This feature suggests that secondary porosity created by

faulting could provide a transportation route for the geothermally heated water to reach the surface before it cools. In Hot Springs National Park, AR the hot-springs water was produced via recharge to an artesian flow system where water moved slowly to and was heated at depth and then quickly delivered to the spring outlet through pathways created by jointing and faulting (Sniegocki 1996).

The Oriskany Formation, from which water at LDY's spring issues, does not exhibit karst features; however, a conduit network in the Helderberg Group could potentially supply water to the underlying system where it would then be delivered to the surface by way of fractures. Overland flow from Warm Spring Ridge could also possibly make its way to the conduit network by way of recharge features such as sinking streams, fissures, or sink holes (Ginsberg and Palmer 2002). These features develop at the contact between insoluble rocks like the Oriskany sandstone and soluble rocks like the limestone unit of the Helderberg Group. A down-dip flow component in the carbonate unit would provide a direct pathway for the ground water to be transported to depth where it would become heated and more mineralized. It could then be carried rapidly to the surface by way of faults or joints. While these flowpaths are possible, they may only be considered speculative as there are no data in this research to confirm their occurrence.

The wells were found to be more widely ranging for chemical parameters relative to springs. Like spring groups B and C, the wells' chemical variables were found to load higher on PC1 than on PC2. In addition to having chemistries indicative of carbonates, this implies that all of the wells in this study are likely completed in carbonate rock sources.

The Ca/Mg molar ratio can be useful in determining rock type through which water has flowed (White 1988) and may allude to hydrologic conditions (Langmuir 1971). All waters from carbonate springs and wells had median Ca/Mg molar ratios of 3.35 or greater, except for water from STR well. This finding indicates that the source rocks for all of these locations except for STR well, are likely comprised of some limestone. Other studies have

found Ca/Mg molar ratios in limestone above 4 (Jacobson and Langmuir 1969, Langmuir 1971, Shuster and White 1971, White 1988). STR well is probably completed in a carbonate source rock containing a dolomitic unit.

6.0 CONCLUSIONS

Prior to the beginning of this study, little data had been collected that gave a generalized picture of the underlying hydrogeochemistry in the area surrounding Berkeley Springs. The goal of this research was to assemble a dataset that allowed for the characterization of the regional hydrogeologic setting.

The dataset indicates that structural geology, in addition to topography, is a strong control on the hydrology of the region. The potentiometric surface reflects the topography, with high heads on the ridges and low heads in the valley. Recharge on the slopes and ridges was found to flow down-dip toward the major drains in the valley, while ground water in the valley was found to flow along strike.

All wells have carbonate signatures as do all springs except for the siliceous springs MTN and HGH, located on the slopes of Cacapon Mountain . The remaining springs are determined to receive waters that have at least partially flowed through carbonate-rich rocks.

The chemical parameters measured at the springs and wells are consistent with the surface geology where the wells and springs are located at all but one location. Although LDY spring issues from a siliceous unit, its carbonate signature suggests that some portion of flow to the spring occurs through a carbonate or carbonate-cemented source rock. Furthermore, its elevated and consistent temperature is evidence for a deep component of flow to the spring.

Wells were found to have more variable water chemistry and temperature through time than were springs. Instead of collecting water from a single, localized point in the aquifer as the wells do, springs receive water that is chemically averaged as water flows through the rock strata and issues at the spring. This averaging further minimizes potential surface influences that are exhibited in wells.

7.0 REFERENCES

- APHA (2005) Standard Methods for the Examination of Water and Wastewater, 21st edn. American Public Health Association, Washington, DC, 1368 pp
- Bedinger MS, Pearson FJ, Reed JE, Sniegocki RT, Stone CG (1979) The waters of Hot Springs National Park, Arkansas- their nature and origin. US Geol Surv Pap 1044-C, 33 pp
- Berkeley Springs State Park (2004) West Virginia Division of Natural Resources. <http://www.berkeleyspringssp.com>. Accessed 5 December 2004
- Berkeley Springs- The country's first spa (2006) <http://www.berkeleysprings.com>. Accessed 4 February 2006
- Burton WC, Plummer LN, Busenberg E, Lindsey BD, Gburek WJ (2002) Influence of fracture anisotropy on ground water ages and chemistry, Valley and Ridge province, Pennsylvania. Ground Water 40(3):242-257
- Cardwell DH, Erwin RB, Woodward HP (1968) Geologic Map of West Virginia, 1:250,000. The West Virginia Geological and Economic Survey
- Dethier DP, Harman MT II (1998) Hydrology and geochemistry of the northernmost Appalachian thermal springs, Williamstown, Massachusetts. Northeastern Geology and Environmental Sciences 20(3):200-207
- Diecchio RJ, Jones SE, Dennison JM (1984) Oriskany Sandstone: regional stratigraphic relationships and production trends. The West Virginia Geological and Economic Survey Technical Report NP-5900695; MAP-WV-17, 50pp
- Donovan JJ, Werner E, Vesper DJ, Corder L (2006) Springs, source water areas, and potential for high-yield aquifers along the Cacapon Mountain anticline, Morgan County, WV. Morgantown, WV, Hydrogeology Research Center of the WV Water Research Institute, 42 pp
- Environmental Protection Agency (2005) National primary drinking water regulations: Maximum contaminant levels and maximum residual disinfectant levels. 40CFR141. Revised July 1, 2005
- Fetter CW (2001) Applied Hydrogeology, 4th Edn. Prentice-Hall, Upper Saddle River New Jersey, 691 pp
- Grimsley GP, White IC (1916) Jefferson, Morgan, and Berkeley counties. West Virginia Geological and Economic Survey: County Geologic Report-10, 644 pp
- Ginsberg M, Palmer AN (2002) Delineation of source-water protection areas in karst aquifers of the Ridge and Valley and Appalachian Plateaus Physiographic Provinces: Rules of thumb for estimating the capture zones of springs and wells. Office of Ground Water and Drinking Water, EPA 816-R-02-015, 41pp

- Gustafsson JP (2004) *Visual MINTEQ* version 2.30.
<http://www.kwr.kth.se/English/OurSoftware/vminteq/>. Accessed April 18, 2008. Updated 10/24/2007
- Heald MT, Thomson A, Wilcox FB (1962) Origin of interstitial porosity in the Oriskany sandstone of Kanawha County, West Virginia. *J Sedimentary Petrology* 32(2):291-298
- Hobba WA, Chemerys JC, Fisher DW, Pearson FJ (1977) Geochemical and hydrologic data for wells and springs in thermal-spring areas of the Appalachians. *US Geol Surv Wat-Res Invest Pap*: 77-25, 36 pp
- Jacobson RL, Langmuir D (1969) The chemical history of some spring waters in carbonate rocks. Paper presented at the 1969 NWWA Exposition under the title "The hydrochemistry of sinking and resurgent streams in carbonate rocks of central Pennsylvania," 30 September 1969
- Kachigan, SK (1986) *Statistical Analysis- An introduction to univariate & multivariate methods*. Radius Press, New York, 589 pp
- Langmuir, D (1971) The geochemistry of some carbonate ground waters in central Pennsylvania. *Geochimica et Cosmochimica Acta* 35(10):1023-1045
- Lapham WW, Wilde FD, Koterba MT (1997) Guidelines and standard procedures for studies of ground-water quality: selection and installation of wells, and supporting documentation. *US Geol Surv Wat-Res Invest Pap*: 96-4233, 110 pp
- McColloch JS (1986) Springs of West Virginia. *West Virginia Geological and Economic Survey*: V-6A, pp 265-268
- Minke JG (1964) Geology of the Hancock and Stotlers Crossroads quadrangles in West Virginia. MSc, West Virginia University, Morgantown, West Virginia, 41 pp
- Minitab Inc. (2000) Minitab® Statistical Software Release 13.3. <http://www.minitab.com>. Accessed April 18 2008
- National Oceanic and Atmospheric Administration (2005) Record of climatological observations. National Environmental, Satellite, Data, and Information Service/National Climatic Data Center, Asheville, NC
- Palmer, AN (2007) *Cave Geology*. Cave Books, Dayton, OH, 454 pp
- Price PH, Ludlum JC (1951) The geology of Cacapon State Park, West Virginia. *State Park Series Bulletin No. 2*, 33 pp
- Rounds SA, Wilde FD (2002) Alkalinity and acid neutralizing capacity, 2nd edn.: Techniques of water-resources investigations of the US Geol Surv, Book 9, Chap A6, 50 pp
- Scanlon BR, Thrailkill J (1987) Chemical similarities among physically distinct spring types in a karst terrain. *J Hydrol* 89:259-279

- Shuster ET, White WB (1971) Seasonal fluctuations in the chemistry of limestone springs: a possible means for characterizing carbonate aquifers. *J Hydrol* 14:93-128
- Sniegocki RT (1996) Waters of hot springs national park, Arkansas- their nature and origin. *Environ Geol* 27(2):79
- Trapp H, Horn, MA (1997) Ground water atlas of the United States, Segment 11-Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, and West Virginia. US Geol Surv Hydrologic Investigations Atlas 730-L, 24 pp
- West Virginia Geological and Economic Survey (2005) Physiographic provinces of West Virginia. <http://www.wvgs.wvnet.edu/www/index.html>. Accessed 12 March 2006
- White WB (1988) *Geomorphology and Hydrology of Karst Terrains*. Oxford University Press, New York, 464 pp
- Worthington, SRH (1999). A comprehensive strategy for understanding flow in carbonate aquifers. *Karst Modeling: Special Publication 5*, The Karst Waters Institute, Charles Town, West Virginia, 30-37.

APPENDICES

Table A-1: Field equipment list.

PARAMETER	UNITS	EQUIPMENT	EQUIPMENT ACCURACY	POTENTIAL ERROR
pH	pH units	Hanna HI-9025 pH/Temperature Meter	$\pm .01$ pH	Calibration
Temperature	$^{\circ}$ Celsius	Hanna HI-9025 pH/Temperature Meter	± 0.5 $^{\circ}$ C	Calibration
Conductivity	μ S/cm	Hanna HI-9033 Conductivity Meter	± 1 % Full Scale	Calibration
Alkalinity	mg/L as HCO_3^-	Digital Titrator Model 16900	± 1 %	Degassing
Total Hardness	mg/L as CaCO_3	Hach Colorimeter 8030	0.02-0.05 mg/L CaCO_3	Dilution error
Silicon	mg/L	Hach Colorimeter 8135	± 1.0 mg/L SiO_2	Incorrect amount of sample
Flow	ft/s	Swoffer Current Meter 2100		Calibration, poor site selection, obstructions in channel
Location	NAD-83 utm	Garmin Etrex Vista GPS	Varies with clouds and coverage	Limited satellite reception
Static Water Level	ft/s	Graduated Steel Tape	0.01	Splash on tape

Table A-2: Synoptic well survey data. (Page 1 of 4)

Date	Latitude	Longitude	Northing	Easting	SWL (ft)	SWL (m)	pH	T (°C)	SC (μS/cm)
5/20/2004	39.64	-78.24	4390895.79	736470.01	858	262	NM	NM	NM
5/20/2004	39.63	-78.24	4390874.11	736467.62	859	262	6.99	13.8	305
5/20/2004	39.64	-78.24	4391514.48	736481.48	788	240	9.69	26.4	300
5/20/2004	39.64	-78.24	4390973.56	736442.65	861	262	6.72	22	NM
5/25/2004	39.64	-78.24	4390932.33	736435.06	860	262	6.86	NM	100
5/25/2004	39.64	-78.25	4390968.50	736169.18	831	253	NM	NM	NM
5/26/2004	39.64	-78.25	4391008.51	736174.16	774	236	5.22	18.9	200
5/26/2004	39.63	-78.25	4390630.30	736339.75	854	260	6.60	14.8	298
5/26/2004	39.63	-78.25	4390310.57	736275.66	908	277	6.85	19.6	235
5/26/2004	39.61	-78.25	4388152.35	735772.39	644	196	7.42	17.5	397
5/26/2004	39.61	-78.25	4388427.78	735910.52	632	193	7.73	16.2	500
5/27/2004	39.62	-78.25	4388737.41	735736.98	755	230	7.50	16.7	336
5/27/2004	39.63	-78.24	4389924.93	736575.66	620	189	7.03	19.4	562
5/27/2004	39.63	-78.23	4390382.97	737400.79	768	234	6.92	22.9	515
5/27/2004	39.63	-78.23	4390804.14	737321.85	751	229	6.72	15.1	188
5/27/2004	39.63	-78.25	4390489.51	736304.45	861	262	6.13	15.1	265
5/27/2004	39.61	-78.26	4387911.84	735625.27	682	208	6.98	15.2	350
6/8/2004	39.62	-78.24	4388819.12	736649.49	737	225	7.48	15.1	475
6/8/2004	39.62	-78.24	4388753.97	736812.27	830	253	7.06	15.9	425
6/8/2004	39.55	-78.28	4381229.88	733577.51	891	272	7.36	26.5	303
6/8/2004	39.62	-78.24	4389046.35	736864.67	844	257	6.10	15.4	NM
6/9/2004	39.62	-78.24	4389639.34	737221.40	719	219	6.99	17.8	NM
6/9/2004	39.57	-78.28	4383229.41	734072.46	792	241	7.13	18.3	NM
6/9/2004	39.64	-78.23	4391987.06	737370.03	464	142	6.10	17.1	NM
6/10/2004	39.64	-78.25	4390916.36	736285.48	856	261	6.79	15.6	NM
6/10/2004	39.62	-78.24	4389154.74	736732.60	737	225	7.12	16.0	NM
6/10/2004	39.63	-78.23	4390572.86	737390.29	788	240	6.30	25.9	NM
6/10/2004	39.61	-78.25	4388506.16	736189.54	694	212	7.12	23.5	NM
6/15/2004	39.55	-78.28	4381244.29	733353.61	876	267	7.25	21.3	NM
6/15/2004	39.55	-78.29	4381373.80	733242.30	890	271	7.01	23.0	NM
6/15/2004	39.55	-78.27	4381709.71	734274.71	927	282	7.00	36.4	NM
6/15/2004	39.54	-78.28	4380770.40	733737.35	970	296	NM	NM	NM
6/15/2004	39.55	-78.28	4381017.02	733777.18	931	284	6.95	18.2	NM
6/16/2004	39.55	-78.28	4381650.25	734121.28	902	275	6.75	13.9	NM

SWL- elevation of water level above mean sea level; NM- not measured.

Table A-2: Synoptic well survey data. (Page 2 of 4)

Date	Latitude	Longitude	Northing	Easting	SWL (ft)	SWL (m)	pH	T (°C)	SC (μS/cm)
6/16/2004	39.55	-78.28	4381143.55	733620.01	918	280	NM	NM	NM
6/16/2004	39.55	-78.28	4381859.69	733395.40	854	260	7.05	19.4	NM
6/16/2004	39.57	-78.27	4383896.78	734235.76	772	235	NM	NM	NM
6/16/2004	39.56	-78.28	4382590.56	733722.32	802	244	7.31	34.8	NM
6/16/2004	39.56	-78.28	4382458.96	733620.86	841	257	7.33	16.5	NM
6/16/2004	39.64	-78.23	4390961.13	737462.12	758	231	NM	NM	NM
6/21/2004	39.63	-78.23	4390575.56	737613.02	753	229	6.57	16.1	NM
6/21/2004a	39.55	-78.28	4381440.95	733384.70	914	279	6.32	35.1	NM
6/21/2004a	39.55	-78.28	4381312.53	733762.86	883	269	7.20	17.7	NM
6/21/2004a	39.55	-78.28	4381218.00	733676.58	888	271	6.95	16.3	NM
6/22/2004a	39.55	-78.28	4381575.49	733457.01	903	275	6.88	17.8	NM
6/22/2004a	39.51	-78.27	4377239.20	734625.72	687	209	7.10	17.0	NM
6/22/2004a	39.53	-78.29	4378872.25	733002.36	803	245	NM	NM	NM
6/23/2004a	39.53	-78.29	4378912.45	733009.32	803	245	NM	NM	NM
6/23/2004a	39.53	-78.29	4378758.62	732934.22	819	250	NM	NM	NM
6/23/2004a	39.52	-78.30	4377744.87	731899.15	1220	372	NM	NM	NM
6/24/2004a	39.52	-78.30	4377565.78	731883.39	1209	368	NM	NM	NM
6/24/2004a	39.54	-78.28	4380522.84	734099.42	882	269	NM	NM	NM
6/24/2004a	39.54	-78.27	4380434.83	734346.41	832	254	NM	NM	NM
7/7/2004	39.53	-78.30	4378684.97	731809.24	1100	335	6.21	23.0	173
7/7/2004	39.53	-78.29	4378610.20	732818.45	832	254	6.86	22.1	448
7/7/2004	39.52	-78.29	4378386.33	732698.31	864	263	NM	NM	NM
7/7/2004	39.52	-78.29	4378125.51	732751.46	830	253	NM	NM	NM
7/7/2004	39.54	-78.29	4380548.04	732460.94	1138	347	NM	NM	NM
7/8/2004	39.52	-78.30	4378197.08	731901.43	1059	323	6.09	13.3	211
7/8/2004a	39.54	-78.30	4380300.94	732373.37	1120	341	NM	NM	NM
7/8/2004a	39.54	-78.30	4379883.40	732175.81	1072	327	NM	NM	NM
7/8/2004a	39.55	-78.30	4380827.64	732369.51	1238	377	6.15	21.0	138
7/8/2004a	39.55	-78.29	4381582.09	733011.58	1107	338	NM	NM	NM
7/8/2004a	39.50	-78.28	4375285.54	733661.68	914	279	7.50	19.2	322
7/9/2004a	39.56	-78.28	4382353.21	733863.38	855	261	6.95	33.2	353
7/9/2004a	39.56	-78.28	4382383.77	733876.03	852	260	NM	NM	NM
7/9/2004a	39.56	-78.28	4382332.42	733910.16	834	254	7.02	22.2	425
7/12/2004a	39.56	-78.28	4382625.65	733955.90	803	245	6.29	20.7	319

SWL- elevation of water level above mean sea level; NM- not measured; "a"- approximate date.

Table A-2: Synoptic well survey data. (Page 3 of 4)

Date	Latitude	Longitude	Northing	Easting	SWL (ft)	SWL (m)	pH	T (°C)	SC (μS/cm)
7/12/2004a	39.54	-78.27	4379828.54	734686.34	922	281	6.38	18.4	224
7/12/2004a	39.53	-78.27	4379574.36	734482.86	899	274	NM	NM	NM
7/12/2004a	39.54	-78.28	4379796.71	734172.89	785	239	NM	NM	NM
7/13/2004a	39.49	-78.28	4374915.29	734063.20	818	249	7.42	22.2	324
7/13/2004a	39.50	-78.29	4375410.11	732989.11	819	250	NM	NM	NM
7/13/2004a	39.53	-78.30	4378640.30	731984.23	1042	318	NM	NM	NM
7/13/2004a	39.55	-78.28	4381176.59	733309.38	864	264	7.08	19.1	342
7/13/2004a	39.54	-78.29	4380022.55	732847.92	915	279	NM	NM	NM
7/14/2004a	39.54	-78.29	4380121.98	733193.44	859	262	NM	NM	NM
7/14/2004a	39.56	-78.28	4382744.23	733492.46	940	287	6.45	14.6	284
7/14/2004a	39.57	-78.28	4383056.96	733876.39	769	234	7.24	18.4	266
7/14/2004a	39.57	-78.28	4383090.86	733895.45	801	244	7.14	18.9	245
7/14/2004a	39.57	-78.28	4383122.26	733802.77	848	258	6.96	26.6	404
7/15/2004a	39.54	-78.29	4379825.02	733005.42	848	259	7.10	19.3	435
7/15/2004a	39.56	-78.27	4382850.65	734290.31	724	221	NM	NM	NM
7/15/2004a	39.57	-78.27	4383877.50	734281.84	779	237	6.43	20.7	423
7/15/2004a	39.56	-78.28	4382713.48	733764.66	798	243	7.04	19.7	554
7/16/2004a	39.52	-78.27	4377838.46	734582.49	685	209	6.83	16.9	310
7/16/2004a	39.51	-78.27	4377172.14	734762.60	710	217	7.17	21.1	282
7/16/2004a	39.63	-78.23	4390740.23	737511.07	768	234	NM	NM	NM
7/16/2004a	39.62	-78.24	4389172.99	736776.11	757	231	NM	NM	NM
7/19/2004a	39.62	-78.24	4389452.74	736732.12	572	174	NM	NM	NM
7/19/2004a	39.60	-78.25	4387510.38	736301.02	762	232	6.50	16.5	945
7/19/2004a	39.58	-78.26	4385250.12	735396.69	855	261	6.52	18.5	872
7/19/2004a	39.62	-78.25	4388773.85	736167.31	750	229	NM	NM	NM
7/19/2004a	39.52	-78.31	4378460.07	731629.76	1085	331	NM	NM	NM
7/20/2004a	39.62	-78.24	4388940.18	736684.45	790	241	NM	NM	NM
7/20/2004a	39.54	-78.27	4380614.44	734967.03	924	282	NM	NM	NM
7/20/2004a	39.54	-78.27	4380309.10	734961.52	932	284	7.44	37.8	370
7/21/2004a	39.57	-78.26	4383706.87	735582.55	801	244	NM	NM	NM
7/21/2004a	39.57	-78.26	4383275.82	735193.35	837	255	NM	NM	NM
7/21/2004a	39.55	-78.27	4381365.74	734466.14	903	275	NM	NM	NM
7/21/2004a	39.57	-78.25	4383724.51	736171.16	852	260	7.10	23.7	NM
7/22/2004a	39.56	-78.26	4382556.20	735235.58	816	249	7.16	20.2	342

SWL- elevation of water level above mean sea level; NM- not measured; "a"- approximate date.

Table A-2: Synoptic well survey data. (Page 4 of 4)

Date	Latitude	Longitude	Northing	Easting	SWL (ft)	SWL (m)	pH	T (°C)	SC (μS/cm)
7/22/2004a	39.47	-78.30	4372910.96	732382.50	793	242	6.50	16.3	286
7/22/2004a	39.47	-78.29	4372590.77	732720.02	793	242	7.02	19.2	343
7/22/2004a	39.58	-78.24	4384499.94	737025.10	864	263	6.33	19.7	202
7/23/2004a	39.55	-78.27	4381742.41	734626.53	871	265	NM	NM	NM
7/23/2004a	39.55	-78.27	4381692.63	734552.37	880	268	NM	NM	NM
7/23/2004a	39.57	-78.25	4384005.28	736120.24	851	259	6.75	18.5	346
7/26/2004a	39.57	-78.25	4383697.95	736015.80	829	253	NM	NM	NM
7/26/2004a	39.57	-78.26	4383120.00	735033.41	839	256	6.87	23.9	352
7/26/2004a	39.50	-78.29	4375638.55	732921.99	825	251	6.09	19.8	419
7/27/2004a	39.50	-78.28	4375382.00	733532.73	843	257	NM	NM	NM
7/27/2004a	39.50	-78.28	4375393.44	733594.38	880	268	NM	NM	NM
7/28/2004a	39.53	-78.28	4378627.64	733737.28	756	230	NM	NM	NM
7/28/2004a	39.51	-78.30	4376380.91	731777.53	983	300	6.65	15.5	261
7/28/2004a	39.51	-78.30	4377146.94	731974.27	1132	345	NM	NM	NM
7/28/2004a	39.51	-78.31	4376781.34	731382.84	1090	332	NM	NM	NM
7/28/2004a	39.51	-78.31	4376379.71	731141.14	1130	345	NM	NM	NM
7/29/2004a	39.50	-78.28	4375376.54	733654.15	875	267	NM	NM	NM
7/29/2004a	39.50	-78.29	4375679.26	733399.97	849	259	NM	NM	NM
7/29/2004a	39.58	-78.28	4384144.61	734012.31	871	266	6.30	13.5	169
7/29/2004a	39.59	-78.27	4385703.50	734692.90	825	252	6.90	17.8	333

SWL- elevation of water level above mean sea level; NM- not measured; "a"- approximate date.

Table A-3: Temporal study field measurements. (Page 1 of 2)

Sample ID	Date	Stage (ft)	Stage (m)	Flow (m ³ /min)	Flow (gal/min)	pH	T (°C)	SC (μS/cm)	Alkalinity (mg/L HCO ₃ ⁻)
LDY-SP01	17-Sep-04	620	189	--	--	6.82	22.5	300	162
LDY-SP02	25-Oct-04	620	189	--	--	6.88	22.0	363	185
LDY-SP03	29-Nov-04	620	189	--	--	6.89	22.0	271	140
LDY-SP04	30-Dec-04	620	189	--	--	6.84	22.0	279	129
LDY-SP05	4-Feb-05	620	189	--	--	6.51	22.0	283	148
LDY-SP06	14-Mar-05	620	189	--	--	6.49	22.3	276	157
LDY-SP07	14-Apr-05	620	189	--	--	6.46	22.3	279	140
STR-MW02	25-Oct-04	NM	NM	--	--	7.14	14.0	902	450
STR-MW03	29-Nov-04	NM	NM	--	--	7.31	11.7	779	421
STR-MW04	30-Dec-04	NM	NM	--	--	7.30	11.3	812	437
STR-MW06	14-Mar-05	768	234	--	--	6.86	14.4	894	479
STR-MW07	14-Apr-05	781	238	--	--	6.86	14.4	835	457
MTN-SP01	17-Sep-04	980	299	0.51	12	5.02	13.3	51	36.6
MTN-SP02	25-Oct-04	980	299	0.48	12	5.11	12.5	55	0.000
MTN-SP03	29-Nov-04	980	299	0.38	9.2	5.08	12.4	55	0.732
MTN-SP04	30-Dec-04	980	299	NM	NM	4.99	11.8	56	4.64
MTN-SP05	4-Feb-05	980	299	0.30	7.3	4.45	11.5	46	0.122
MTN-SP06	14-Mar-05	980	299	0.33	8.1	4.56	11.1	69	0.146
MTN-SP07	14-Apr-05	980	299	0.75	18	4.37	10.9	48	3.00
NEY-SP01	17-Sep-04	780	238	--	--	7.16	12.3	365	187
NEY-SP02	25-Oct-04	780	238	--	--	7.19	12.4	343	179
NEY-SP03	29-Nov-04	780	238	--	--	6.65	12.0	154	79
NEY-SP04	30-Dec-04	780	238	--	--	6.99	11.0	211	120
NEY-SP05	5-Feb-05	780	238	--	--	6.67	10.7	240	209
NEY-SP06	14-Mar-05	780	238	--	--	6.64	10.2	232	125
NEY-SP07	14-Apr-05	780	238	--	--	6.49	10.8	221	110
WEB-SP01	17-Sep-04	819	250	0.13	3.2	7.15	13.6	317	222
WEB-SP02	25-Oct-04	819	250	0.16	4.0	7.33	12.5	452	220
WEB-SP03	29-Nov-04	819	250	0.20	4.9	7.24	12.5	338	242
WEB-SP04	30-Dec-04	819	250	0.20	4.8	7.26	10.6	363	232
WEB-SP05	5-Feb-05	819	250	0.24	5.9	6.99	12.2	354	270
WEB-SP06	14-Mar-05	819	250	0.21	5.2	6.96	12.4	347	242
WEB-SP07	14-Apr-05	819	250	0.20	4.8	6.96	12.4	353	251

NM- not measured; -- Indicates not applicable.

Table A-3: Temporal study field measurements. (Page 2 of 2)

Sample ID	Date	Stage (ft)	Stage (m)	Flow (m ³ /min)	Flow (gal/min)	pH	T (°C)	SC (μS/cm)	Alkalinity (mg/L HCO ₃ ⁻)
MYR-MW02	25-Oct-04	812	247	--	--	6.08	15.0	273	80
MYR-MW03	29-Nov-04	816	249	--	--	5.87	11.5	282	86
MYR-MW04	30-Dec-04	811	247	--	--	6.02	7.9	237	44
MYR-MW05	5-Feb-05	811	247	--	--	6.19	6.9	286	159
MYR-MW06	14-Mar-05	810	247	--	--	5.83	5.5	253	85
MYR-MW07	14-Apr-05	813	248	--	--	5.86	12.3	252	73
BZK-MW02	25-Oct-04	868	265	--	--	7.31	13.8	557	266
BZK-MW03	29-Nov-04	869	265	--	--	7.33	9.4	539	256
BZK-MW04	30-Dec-04	873	266	--	--	7.16	6.3	484	245
BZK-MW05	5-Feb-05	874	267	--	--	7.13	7.2	477	312
BZK-MW06	14-Mar-05	874	266	--	--	7.03	4.1	484	259
BZK-MW07	14-Apr-05	881	269	--	--	7.06	14.4	494	238
YST-SP01	17-Sep-04	NM	NM	3.1	75	5.00	12.1	46	12
YST-SP02	25-Oct-04	NM	NM	2.0	50	5.08	12.1	52	0.7
HGH-SP03	29-Nov-04	NM	NM	4.1	100	4.58	12.3	42	0.0
HGH-SP04	30-Dec-04	NM	NM	3.1	75	4.74	12.0	41	2.0
HGH-SP05	5-Feb-05	NM	NM	3.1	75	4.15	11.9	32	0.0
HGH-SP07	13-Apr-05	NM	NM	6.1	150	3.97	11.7	43	0.0
YST-MW01	17-Sep-04	1062	324	--	--	6.57	16.3	206	117
YST-MW02	25-Oct-04	1063	324	--	--	6.76	17.0	249	119
YST-MW03	29-Nov-04	1061	323	--	--	6.69	16.9	200	123
YST-MW04	30-Dec-04	1062	324	--	--	6.56	13.1	188	88
YST-MW05	5-Feb-05	1061	324	--	--	6.25	12.2	188	160
YST-MW07	13-Apr-05	1055	322	--	--	6.40	11.8	184	102
CSP-SP01	17-Sep-04	929	283	--	--	6.85	13.6	297	226
CSP-SP02	25-Oct-04	930	284	--	--	7.17	12.1	358	201
CSP-SP03	29-Nov-04	929	283	--	--	7.12	11.9	278	191
CSP-SP04	30-Dec-04	929	283	--	--	7.11	11.8	324	190
CSP-SP05	5-Feb-05	929	283	--	--	6.87	11.7	294	270
CSP-SP06	14-Mar-05	929	283	--	--	6.61	11.7	318	182
CSP-SP07	14-Apr-05	929	283	--	--	6.79	11.8	312	212

NM- not measured; -- Indicates not applicable.

Table A-4: Daily temperature measurements at Berkeley Springs 3 S weather station.

Day	May-04	Jun-04	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05	Mar-05	Apr-05
1	69	68	69	79	71	60	63	42	53	25	28	47
2	71	67	71	79	70	61	56	45	51	25	31	51
3	64	69	75	77	69	61	62	38	42	30	27	45
4	51	65	76	77	70	58	51	35	52	33	25	40
5	53	62	75	77	72	60	48	38	53	39	30	49
6	58	58	78	66	72	49	48	46	40	40	39	56
7	62	62	78	62	64	52	56	42	43	41	45	65
8	67	68	77	66	71	59	60	49	38	44	51	68
9	61	72	76	70	71	61	41	45	43	51	25	56
10	68	78	74	74	68	60	37	39	34	49	25	52
11	73	76	72	77	66	56	39	44	40	29	31	57
12	73	61	76	74	66	51	50	42	40	29	37	55
13	74	66	76	68	71	54	38	42	42	40	35	47
14	74	66	76	62	71	49	36	36	54	39	35	52
15	74	76	78	68	67	57	37	29	33	42	35	53
16	72	78	74	70	66	55	42	24	29	48	37	45
17	68	77	71	70	73	50	48	31	26	45	38	48
18	71	79	70	71	66	47	52	32	14	30	40	55
19	71	78	71	74	61	47	57	33	15	22	43	65
20	69	68	73	80	57	51	52	26	25	28	46	67
21	66	61	74	78	59	55	52	14	26	37	48	69
22	70	66	75	67	63	52	53	26	16	42	37	55
23	73	73	75	70	68	46	50	41	16	43	44	49
24	78	70	76	71	68	47	47	40	15	36	38	49
25	73	72	71	73	69	47	54	25	20	25	40	42
26	73	73	66	73	69	49	42	20	32	32	40	49
27	71	65	70	77	68	53	38	21	30	32	38	56
28	72	66	73	80	65	56	41	20	17	30	41	56
29	63	67	69	79	63	53	44	29	18	--	43	55
30	62	67	70	79	63	56	42	43	22	--	51	51
31	66	--	77	78	--	66	--	40	28	--	51	--
Monthly Avg (F)	68	69	74	73	67	54	48	35	32	36	38	53

-- Indicates not measured.

Table A-5: Daily rainfall measurements at Berkeley Springs 3 S weather station.

Day	May-04	Jun-04	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05	Mar-05	Apr-05
1	--	0.26	--	2.37	--	--	--	0.55	--	--	0.48	--
2	0.04	0.02	--	0.01	--	--	--	0.03	--	--	--	0.35
3	0.71	0.12	--	--	--	0.01	0.03	--	--	--	--	0.77
4	--	--	--	--	--	--	--	--	0.04	0.06	--	--
5	--	1.03	0.14	0.29	--	--	0.88	--	0.38	--	--	--
6	--	0.53	--	--	0.04	--	--	0.02	0.7	--	--	--
7	--	--	0.02	--	0.03	--	--	0.12	0.04	--	--	--
8	0.17	--	0.03	--	0.49	--	--	0.2	0.37	--	0.09	0.46
9	--	--	--	--	5.49	--	--	--	0.11	--	0.13	--
10	--	--	--	0.02	0.03	--	--	0.69	--	0.25	0.01	--
11	--	0.26	--	--	--	--	--	0.37	--	--	--	--
12	--	1.24	0.35	0.84	--	--	0.62	--	0.24	--	0.01	--
13	--	0.1	1.26	--	--	--	0.48	0.02	0.03	--	--	--
14	--	0.07	0.09	--	--	0.23	--	--	0.7	0.14	--	--
15	0.49	0.01	--	--	0.45	0.09	--	--	--	0.32	--	--
16	0.7	0.1	--	0.02	0.01	0.06	--	--	--	--	--	--
17	--	0.01	--	--	0.06	0.27	--	--	0.02	0.01	--	--
18	--	0.14	0.19	0.04	3.72	--	0.04	--	--	--	--	--
19	1.13	--	0.02	0.05	--	0.21	--	--	--	--	--	--
20	0.2	--	0.01	0.6	--	0.11	0.31	--	0.01	--	--	--
21	0.02	--	--	0.14	--	0.66	0.02	--	--	0.19	0.02	--
22	0.58	--	--	--	--	0.07	--	--	0.01	--	--	0.06
23	--	0.17	0.15	--	--	0.02	0.03	0.01	0.5	--	0.87	0.57
24	--	0.01	0.24	--	--	0.08	0.15	0.34	--	0.03	0.71	0.1
25	0.01	--	--	--	--	0.16	0.93	--	--	0.66	0.02	0.02
26	0.2	0.08	0.05	--	--	--	0.04	--	0.01	--	0.09	--
27	0.24	--	0.12	--	--	--	--	--	--	--	0.02	--
28	0.03	--	0.75	--	0.54	--	0.72	--	--	--	0.56	--
29	0.2	0.02	--	0.02	2.73	--	--	--	--	--	1.65	--
30	--	--	--	--	0.02	0.08	--	--	0.05	--	--	0.24
31	--	--	0.03	--	--	--	--	--	0.01	--	0.01	--
Monthly Total (mm)	120	106	87.6	112	346	52.1	108	59.7	81.8	42.2	119	65.3
Monthly Total (in)	4.72	4.17	3.45	4.4	13.61	2.05	4.25	2.35	3.22	1.66	4.67	2.57

-- Indicates that no rainfall occurred.

Table A-6: Laboratory data. (Page 1 of 2)

Sample ID	Date	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	Si (mg/L)	S (mg/L)	SO ₄ (mg/L)	Cl (mg/L)	NO ₃ (mg/L)
LDY-SPO1	17-Sep-04	53.4	5.22	5.25	1.12	<0.1	<0.1	4.76	--	12.5	2.5	0.24
LDY-SPO2	25-Oct-04	47.2	4.83	4.15	0.85	<0.1	<0.1	4.52	4.57	--	--	--
LDY-SPO3	29-Nov-04	54.9	5.63	4.76	1.05	<0.1	<0.1	5.08	5.13	--	--	--
LDY-SPO4	30-Dec-04	38.7	4.34	3.42	0.78	<0.1	<0.1	3.82	3.63	--	--	--
LDY-SPO5	4-Feb-05	48.7	4.21	3.92	0.80	--	--	4.51	--	14.3	3.30	0.04
LDY-SPO6	14-Mar-05	48.1	4.78	--	--	--	--	4.46	5.26	--	3.31	--
LDY-SPO7	14-Apr-05	48.1	4.67	--	--	--	--	4.29	5.44	--	2.92	--
STR-MWO2	25-Oct-04	118	37.4	16.1	0.89	0.13	<0.1	3.59	16.7	--	--	--
STR-MWO3	29-Nov-04	110	30.5	15.9	0.90	0.16	<0.1	3.52	9.85	--	--	--
STR-MWO4	30-Dec-04	111	36.3	19.9	0.92	0.13	<0.1	3.72	13.3	--	--	--
STR-DPO4	30-Dec-04	115	37.2	17.7	0.95	0.12	<0.1	3.71	13.6	--	--	--
STR-MWO6	14-Mar-05	127	37.4	--	--	--	--	3.51	16.28	--	42.1	--
STR-MWO7	14-Apr-05	112	38.8	--	--	--	--	3.37	13.5	--	36.0	--
MTN-SPO1	17-Sep-04	3.31	2.13	0.79	0.89	<0.1	<0.1	2.84	--	8.76	1.41	0.58
MTN-SPO2	25-Oct-04	2.90	1.98	2.08	0.73	<0.1	<0.1	2.38	2.47	--	--	--
MTN-SPO3	29-Nov-04	3.45	2.58	0.62	0.86	<0.1	<0.1	2.68	3.39	--	--	--
MTN-SPO4	30-Dec-04	3.71	2.72	0.75	1.01	0.16	<0.1	3.13	3.28	--	--	--
MTN-SPO5	4-Feb-05	2.96	2.16	0.68	0.78	--	--	3.05	--	9.30	1.49	0.33
MTN-SPO6	14-Mar-05	3.38	2.26	--	--	--	--	2.50	4.07	--	1.87	--
MTN-SPO7	14-Apr-05	3.31	2.22	--	--	--	--	2.55	4.02	--	1.96	--
NEY-SPO1	17-Sep-04	56.1	9.37	2.49	1.06	<0.1	<0.1	3.46	--	6.98	5.02	0.12
NEY-SPO2	25-Oct-04	40.6	7.39	1.82	0.79	<0.1	<0.1	2.68	1.39	--	--	--
NEY-SPO3	29-Nov-04	21.2	4.50	2.92	1.05	<0.1	<0.1	2.83	2.82	--	--	--
NEY-SPO4	30-Dec-04	33.3	6.30	1.66	0.88	<0.1	<0.1	2.99	2.19	--	--	--
NEY-SPO5	4-Feb-05	44.9	6.97	1.97	0.87	--	--	3.57	--	5.84	4.24	0.25
NEY-SPO6	14-Mar-05	38.5	6.51	--	--	--	--	2.89	2.47	--	5.08	--
NEY-SPO7	14-Apr-05	35.1	6.19	--	--	--	--	2.97	2.88	--	5.14	--
WEB-SPO1	17-Sep-04	62.5	9.41	2.58	0.62	<0.1	<0.1	3.40	--	6.47	6.09	0.22
WEB-SPO2	25-Oct-04	26.1	12.91	3.49	0.68	<0.1	<0.1	4.38	1.56	--	--	--
WEB-SPO3	29-Nov-04	60.3	10.14	2.23	0.55	<0.1	<0.1	3.53	0.68	--	--	--
WEB-SPO4	30-Dec-04	58.7	10.16	2.51	0.59	<0.1	<0.1	3.55	1.19	--	--	--
WEB-SPO5	4-Feb-05	71.9	10.74	2.35	0.60	--	--	4.42	--	3.54	6.34	0.20
WEB-SPO6	14-Mar-05	64.2	9.49	--	--	--	--	3.46	1.26	--	6.32	--
WEB-SPO7	14-Apr-05	63.1	8.54	--	--	--	--	3.48	1.48	--	6.14	--

-- Indicates not measured.

< Indicates below detection limit, followed by the detection limit.

Table A-6: Laboratory data. (Page 2 of 2)

Sample ID	Date	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	Si (mg/L)	S (mg/L)	SO ₄ (mg/L)	Cl (mg/L)	NO ₃ (mg/L)
WEB-MWO2	25-Oct-04	32.0	4.83	3.45	3.90	0.13	<0.1	2.81	7.71	--	--	--
MYR-MWO3	29-Nov-04	31.8	4.79	2.70	3.66	<0.1	<0.1	2.32	8.18	--	--	--
MYR-MWO4	30-Dec-04	29.6	4.42	2.20	3.58	2.65	<0.1	2.39	9.87	--	--	--
MYR-MWO5	4-Feb-05	51.7	7.51	3.13	2.33	--	--	3.41	--	16.0	8.41	3.57
MYR-MWO6	14-Mar-05	39.9	5.18	--	--	--	--	2.41	10.8	--	22.4	--
MYR-MWO7	14-Apr-05	37.0	5.05	--	--	--	--	2.33	10.8	--	5.54	--
BZK-MWO2	25-Oct-04	67.1	12.1	23.4	<0.1	0.20	<0.1	3.86	1.53	--	--	--
BZK-MWO3	29-Nov-04	70.8	13.4	17.6	0.74	0.41	<0.1	3.25	0.80	--	--	--
BZK-MWO4	30-Dec-04	73.5	14.2	19.6	0.90	0.32	<0.1	3.59	0.92	--	--	--
BZK-MWO5	4-Feb-05	85.7	13.6	15.5	0.71	--	--	4.16	--	3.30	32.7	0.54
BZK-MWO6	14-Mar-05	78.6	14.3	--	--	--	--	3.38	1.45	--	38.8	--
BZK-MWO7	14-Apr-05	76.8	13.8	--	--	--	--	3.40	1.33	--	34.7	--
YST-SPO1	17-Sep-04	2.75	1.56	0.49	0.83	<0.1	<0.1	2.23	--	9.39	1.17	0.69
YST-SPO2	25-Oct-04	2.65	1.76	0.44	0.68	<0.1	<0.1	2.17	3.30	--	--	--
HGH-SPO3	29-Nov-04	2.82	1.50	0.41	0.77	<0.1	0.13	2.53	3.60	--	--	--
HGH-SPO4	30-Dec-04	2.70	1.70	0.38	0.75	<0.1	0.10	2.43	3.42	--	--	--
HGH-SPO5	4-Feb-05	16.9	1.73	0.54	0.70	--	--	2.54	--	10.00	0.93	0.47
HGH-SPO7	14-Apr-05	2.67	1.39	--	--	--	--	1.95	4.00	--	1.27	--
YST-MWO1	17-Sep-04	40.3	1.84	0.58	0.47	0.82	<0.1	3.15	--	8.23	<1.00	<0.02
YST-MWO2	25-Oct-04	41.9	2.06	0.51	0.62	3.81	<0.1	3.45	1.89	--	--	--
YST-MWO3	29-Nov-04	40.0	2.06	1.56	0.45	2.68	<0.1	3.61	1.26	--	--	--
YST-MWO4	30-Dec-04	40.7	2.21	0.93	0.96	0.20	<0.1	4.29	2.04	--	--	--
YST-DPO4	30-Dec-04	37.6	2.04	0.84	0.88	0.18	<0.1	4.00	1.48	--	--	--
YST-MWO5	4-Feb-05	54.8	2.10	0.68	0.47	--	--	4.50	--	5.07	0.64	0.01
YST-MWO7	14-Apr-05	39.4	1.73	--	--	--	--	3.06	2.10	--	0.81	--
CSP-SPO1	17-Sep-04	48.3	5.55	1.11	0.73	<0.1	<0.1	3.83	--	8.54	1.22	0.08
CSP-SPO2	25-Oct-04	57.2	7.11	1.08	0.55	<0.1	<0.1	3.99	1.75	--	--	--
CSP-SPO3	29-Nov-04	50.8	6.31	0.99	2.55	<0.1	<0.1	3.70	1.58	--	--	--
CSP-SPO4	30-Dec-04	51.5	6.52	0.97	0.54	<0.1	<0.1	3.88	1.58	--	--	--
CSP-SPO5	4-Feb-05	78.6	8.54	1.39	0.64	--	--	5.81	--	5.17	1.30	0.05
CSP-SPO6	14-Mar-05	60.8	6.98	--	--	--	--	4.13	2.13	--	1.48	--
CSP-SPO7	14-Apr-05	60.4	7.03	--	--	--	--	4.09	2.38	--	1.37	--

-- Indicates not measured.

< Indicates below detection limit, followed by the detection limit.

Table A-7: Mean and coefficient of variation for selected parameters at study sites. (Page 1 of 2)

Site	pH	T	SC	HCO ₃	SO ₄	Na	Cl	Si	Ca	Mg	CaCO ₃	Ca/Mg	SI _c	SI _D	En P _{CO2}
LDY															
Mean	6.70	22.2	293	151	14.1	4.30	3.01	4.49	48.4	4.81	141	6.11	-0.89	-2.47	100
COV	3	1	10	11	13	--	--	8	10	9	10	7	23	17	42
STR*															
Mean	7.09	13.2	844	449	41.7	17.3	39.1	3.54	116	36.1	437	1.95	0.11	-0.11	104
COV	3	10	6	4	18	--	--	3	6	8	5	8	140	243	50
MTN															
Mean	4.80	11.9	54	6	9.95	0.98	1.68	2.73	3.29	2.29	17.6	0.87	-5.74	-11.5	267
COV	6	7	13	208	16	--	--	10	8	11	9	5	11	11	118
NEY															
Mean	6.83	11.3	252	144	6.86	2.17	4.78	3.06	38.5	6.75	124	3.42	-1.07	-2.74	61
COV	4	7	28	31	21	--	--	10	26	20	25	9	41	31	51
WEB															
Mean	7.13	12.3	361	240	4.07	2.63	6.22	3.75	65.3	10.2	205	3.91	-0.31	-1.26	50
COV	2	7	11	7	31	--	--	11	9	13	9	8	41	23	37

Asterisks denote wells; HCO₃, SO₄, Na, Cl, Si, Ca, Mg, and hardness as CaCO₃, all given in mg/L; -- Indicates that COV was not calculated;
 En PCO₂ represents enhanced PCO₂; Ca/Mg is a molar ratio; T given in °C.

Table A-7: Mean and coefficient of variation for selected parameters at study sites. (Page 2 of 2)

Site	pH	T	SC	HCO ₃	SO ₄	Na	Cl	Si	Ca	Mg	CaCO ₃	Ca/Mg	SI _C	SI _D	En P _{CO2}
MYR*															
Mean	5.98	9.9	264	88	26.3	2.87	12.1	10.1	37.0	5.30	114	4.23	-2.18	-5.17	240
COV	2	34	7	40	22	--	--	15	20	19	20	6	13	13	30
BZK*															
Mean	7.17	9.2	506	263	3.56	19.0	35.4	3.61	75.4	13.6	244	3.37	-0.24	-1.10	46
COV	2	41	6	9	23	--	--	9	8	5	7	7	57	28	24
HGH															
Mean	4.59	12.0	43	2	10.4	0.45	1.12	2.31	5.08	1.61	19.3	1.86	-5.79	-11.8	578
COV	9	2	14	2	8	--	--	9	104	8	70	98	9	8	127
YST*															
Mean	6.54	14.6	203	118	5.86	0.85	0.73	3.68	42.9	2.00	115	13.0	-1.31	-3.75	105
COV	3	15	11	19	23	--	--	15	13	8	12	12	14	11	59
CSP															
Mean	6.93	12.1	312	210	5.99	1.11	1.34	4.20	58.2	6.86	174	5.13	-0.61	-1.98	71
COV	3	5	8	13	22	--	--	16	16	12	16	5	31	19	43

Asterisks denote wells; HCO₃, SO₄, Na, Cl, Si, Ca, Mg, and hardness as CaCO₃, all given in mg/L; -- Indicates that COV was not calculated;

En PCO₂ represents enhanced PCO₂; Ca/Mg is a molar ratio; T given in °C.

Table A-8: Derived chemical data. (Page 1 of 2)

Sample ID	Sample Date	Ca/Mg (M)	SI _C	SI _{Chal}	SI _D dis	SI _D	SI _Q	P _{CO2} (atm)	log P _{CO2} (atm)	Enhanced P _{CO2}	Ionic Strength	CBE (%)
LDY-SP01	17-Sep-04	6.21	-0.70	-0.19	-2.65	-2.09	0.26	0.023	-1.63	74.0	4.70E-03	5.99
LDY-SP02	25-Oct-04	5.92	-0.64	-0.21	-2.52	-1.96	0.25	0.023	-1.63	73.5	4.50E-03	5.96
LDY-SP03	29-Nov-04	5.91	-0.68	-0.16	-2.61	-2.05	0.30	0.017	-1.77	54.3	4.60E-03	13.83
LDY-SP04	30-Dec-04	5.40	-0.90	-0.28	-3.01	-2.45	0.17	0.018	-1.75	56.5	3.60E-03	2.58
LDY-SP05	4-Feb-05	7.02	-1.09	-0.21	-3.49	-2.93	0.25	0.044	-1.36	138	4.30E-03	2.65
LDY-SP06	14-Mar-05	6.10	-1.07	-0.22	-3.40	-2.83	0.24	0.049	-1.31	154	4.10E-03	2.31
LDY-SP07	14-Apr-05	6.25	-1.15	-0.23	-3.56	-3.00	0.22	0.047	-1.33	147	3.90E-03	8.05
STR-MW02	25-Oct-04	1.92	0.17	-0.21	-0.57	0.03	0.26	0.026	-1.58	83.2	1.32E-02	7.50
STR-MW03	29-Nov-04	2.18	0.26	-0.19	-0.49	0.12	0.28	0.016	-1.79	51.4	1.18E-02	7.69
STR-MW04	30-Dec-04	1.86	0.25	-0.16	-0.44	0.17	0.31	0.017	-1.77	54.2	1.26E-02	8.54
STR-MW06	14-Mar-05	2.07	-0.04	-0.23	-1.00	-0.41	0.24	0.053	-1.27	169	1.35E-02	2.22
STR-MW07	14-Apr-05	1.75	-0.10	-0.24	-1.07	-0.47	0.23	0.051	-1.29	162	1.26E-02	1.71
MTN-SP01	17-Sep-04	0.94	-4.39	-0.30	-9.38	-8.78	0.17	0.316	-0.50	1000	9.00E-04	34.45
MTN-SP02	25-Oct-04	0.89	-6.23	-0.37	-13.06	-12.46	0.10	0.003	-2.48	10.6	5.00E-04	45.76
MTN-SP03	29-Nov-04	0.81	-5.78	-0.32	-12.13	-11.53	0.15	0.009	-2.04	29.1	6.00E-04	31.69
MTN-SP04	30-Dec-04	0.83	-5.23	-0.24	-11.04	-10.44	0.23	0.047	-1.32	150	7.00E-04	25.27
MTN-SP05	4-Feb-05	0.83	-6.22	-0.25	-13.04	-12.43	0.22	0.072	-1.14	229	6.00E-04	19.46
MTN-SP06	14-Mar-05	0.91	-6.14	-0.33	-12.93	-12.32	0.14	0.045	-1.35	142	4.00E-04	64.33
MTN-SP07	14-Apr-05	0.90	-6.20	-0.32	-13.03	-12.42	0.15	0.098	-1.01	311	4.00E-04	59.84
NEY-SP01	17-Sep-04	3.63	-0.43	-0.21	-2.08	-1.48	0.26	0.011	-1.97	34.1	5.30E-03	5.12
NEY-SP02	25-Oct-04	3.33	-0.54	-0.32	-2.27	-1.66	0.15	0.010	-2.01	30.7	4.20E-03	5.01
NEY-SP03	29-Nov-04	2.85	-1.69	-0.29	-4.49	-3.89	0.18	0.015	-1.82	47.8	2.30E-03	3.75
NEY-SP04	30-Dec-04	3.20	-1.01	-0.25	-3.20	-2.59	0.22	0.010	-1.99	32.6	3.30E-03	3.81
NEY-SP05	5-Feb-05	3.91	-0.99	-0.17	-3.26	-2.65	0.30	0.037	-1.43	116	4.70E-03	11.54
NEY-SP06	14-Mar-05	3.59	-1.29	-0.26	-3.84	-3.23	0.22	0.024	-1.63	74.7	3.50E-03	5.86
NEY-SP07	14-Apr-05	3.44	-1.52	-0.25	-4.26	-3.65	0.22	0.030	-1.53	94.3	3.20E-03	7.37
WEB-SP01	17-Sep-04	4.03	-0.31	-0.23	-1.86	-1.26	0.24	0.013	-1.88	41.8	5.80E-03	0.98
WEB-SP02	25-Oct-04	3.57	-0.08	-0.11	-1.34	-0.74	0.36	0.008	-2.07	26.7	6.60E-03	16.19
WEB-SP03	29-Nov-04	3.60	-0.22	-0.20	-1.64	-1.04	0.27	0.012	-1.94	36.5	5.80E-03	0.64
WEB-SP04	30-Dec-04	3.51	-0.26	-0.17	-1.75	-1.14	0.30	0.010	-1.99	32.7	5.70E-03	0.23
WEB-SP05	5-Feb-05	4.06	-0.36	-0.10	-1.99	-1.38	0.37	0.023	-1.64	71.9	6.70E-03	1.10
WEB-SP06	14-Mar-05	4.10	-0.47	-0.21	-2.21	-1.61	0.26	0.022	-1.66	69.6	5.90E-03	2.01
WEB-SP07	14-Apr-05	4.48	-0.46	-0.20	-2.23	-1.63	0.27	0.023	-1.64	72.3	5.90E-03	5.49

Table A-8: Derived chemical data. (Page 2 of 2)

Sample ID	Sample Date	Ca/Mg (M)	SI _C	SI _{Chal}	SI _D dis	SI _D	SI _Q	P _{CO2} (atm)	log P _{CO2} (atm)	Enhanced P _{CO2}	Ionic Strength	CBE (%)
MYR-MW02	25-Oct-04	4.02	-2.05	-0.33	-5.30	-4.71	0.14	0.059	-1.23	186	3.10E-03	11.69
MYR-MW03	29-Nov-04	4.02	-2.29	-0.37	-5.85	-5.24	0.10	0.098	-1.01	310	3.20E-03	6.79
MYR-MW04	30-Dec-04	4.06	-2.52	-0.31	-6.39	-5.76	0.17	0.034	-1.47	108	2.90E-03	23.63
MYR-MW05	5-Feb-05	4.17	-1.60	-0.14	-4.59	-3.96	0.34	0.081	-1.09	255	4.90E-03	2.47
MYR-MW06	14-Mar-05	4.67	-2.34	-0.28	-6.13	-5.50	0.21	0.099	-1.01	312	3.40E-03	8.92
MYR-MW07	14-Apr-05	4.44	-2.27	-0.38	-0.38	-5.85	0.09	0.086	-1.07	271	2.90E-03	25.46
BZK-MW02	25-Oct-04	3.37	-0.06	-0.18	-1.27	-0.67	0.29	0.011	-1.96	34.5	7.00E-03	9.90
BZK-MW03	29-Nov-04	3.20	-0.10	-0.20	-1.42	-0.81	0.28	0.009	-2.02	30.0	7.00E-03	12.48
BZK-MW04	30-Dec-04	3.13	-0.33	-0.11	-1.93	-1.30	0.37	0.013	-1.89	41.1	7.20E-03	17.04
BZK-MW05	5-Feb-05	3.83	-0.19	-0.06	-1.73	-1.10	0.42	0.018	-1.75	56.1	8.60E-03	0.23
BZK-MW06	14-Mar-05	3.33	-0.45	-0.11	-2.25	-1.61	0.38	0.018	-1.74	57.2	7.60E-03	2.36
BZK-MW07	14-Apr-05	3.38	-0.29	-0.24	-1.72	-1.12	0.23	0.017	-1.76	55.1	7.30E-03	0.91
YST-SP01	17-Sep-04	1.07	-4.96	-0.39	-10.60	-10.00	0.08	0.113	-0.95	358	6.00E-04	17.22
YST-SP02	25-Oct-04	0.91	-5.90	-0.41	-12.41	-11.81	0.07	0.009	-2.04	29.1	5.00E-04	17.73
HGH-SP03	29-Nov-04	1.14	-6.25	-0.34	-13.22	-12.61	0.13	0.038	-1.42	121	5.00E-04	14.30
HGH-SP04	30-Dec-04	0.96	-5.84	-0.36	-12.33	-11.72	0.12	0.049	-1.31	156	5.00E-04	11.73
HGH-SP05	5-Feb-05	5.92	-5.51	-0.34	-12.45	-11.85	0.14	0.271	-0.57	858	1.30E-03	56.70
HGH-SP07	13-Apr-05	1.16	-6.28	-0.45	-13.30	-12.69	0.02	0.615	-0.21	1946	4.00E-04	43.06
YST-MW01	17-Sep-04	13.28	-1.27	-0.30	-4.24	-3.66	0.17	0.028	-1.55	89.0	3.30E-03	3.29
YST-MW02	25-Oct-04	12.33	-1.05	-0.27	-3.75	-3.17	0.20	0.019	-1.73	58.7	3.40E-03	8.31
YST-MW03	29-Nov-04	11.78	-1.12	-0.24	-3.88	-3.30	0.22	0.023	-1.65	71.4	3.30E-03	5.69
YST-MW04	30-Dec-04	11.17	-1.45	-0.12	-4.58	-3.98	0.35	0.021	-1.68	65.6	3.00E-03	19.05
YST-MW05	5-Feb-05	15.83	-1.41	-0.09	-4.67	-4.06	0.38	0.076	-1.12	239	4.30E-03	3.60
YST-MW07	13-Apr-05	13.81	-1.57	-0.25	-4.95	-4.34	0.22	0.034	-1.46	109	2.90E-03	11.08
CSP-SP01	17-Sep-04	5.27	-0.70	-0.18	-2.75	-2.16	0.29	0.027	-1.57	86.0	4.80E-03	14.70
CSP-SP02	25-Oct-04	4.88	-0.39	-0.14	-2.12	-1.52	0.33	0.011	-1.95	35.7	5.10E-03	1.54
CSP-SP03	29-Nov-04	4.89	-0.51	-0.17	-2.36	-1.76	0.30	0.012	-1.92	38.1	4.70E-03	0.98
CSP-SP04	30-Dec-04	4.79	-0.51	-0.15	-2.37	-1.77	0.32	0.012	-1.91	38.8	4.70E-03	0.74
CSP-SP05	5-Feb-05	5.58	-0.45	0.03	-2.32	-1.71	0.50	0.030	-1.53	94.1	6.80E-03	1.48
CSP-SP06	14-Mar-05	5.28	-0.96	-0.12	-3.32	-2.71	0.35	0.037	-1.43	117	5.00E-03	8.83
CSP-SP07	14-Apr-05	5.21	-0.72	-0.13	-2.83	-2.23	0.35	0.028	-1.55	89.9	5.30E-03	1.23