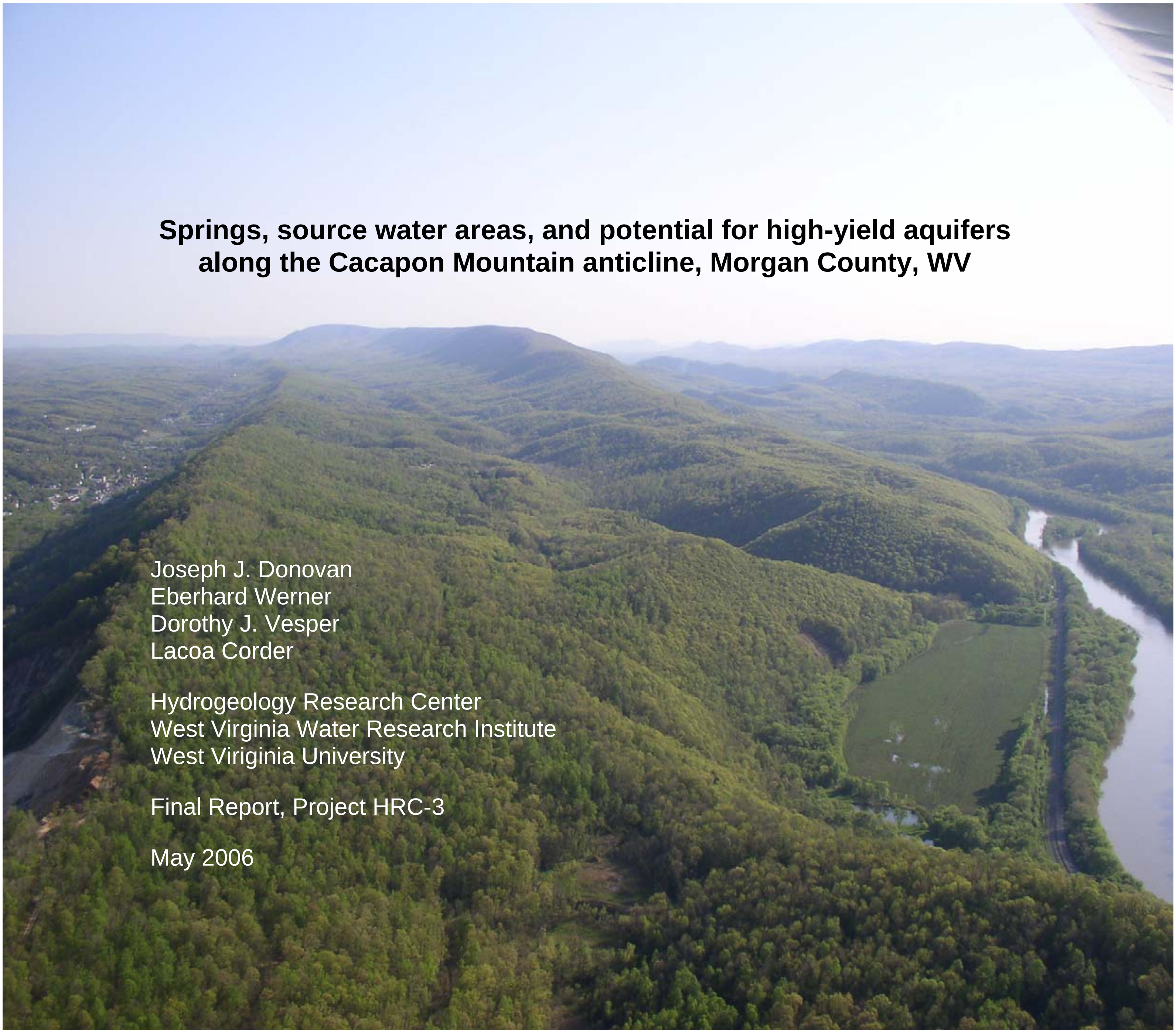

Springs, source water areas, and potential for high-yield aquifers along the Cacapon Mountain anticline, Morgan County, WV

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Abstract

An investigation was made of high-yield water resources of Morgan County, focusing specifically on the Helderberg-Tonoloway-Wills Creek limestone units. These plus the associated underlying Silurian clastic rocks are thought to constitute a groundwater flow system, here referred to as the Cacapon Mountain aquifer. It lies between sandstone aquitards of the Tuscarora and Oriskany formations and flanks both sides of the Cacapon Mountain Anticline. The purpose of the investigation is to characterize the eastern side of this potential high-yield aquifer and identify its hydrogeological elements that may be critical to its development. Objectives include physical and chemical inventory/characterization of springs >10 gpm; identification of aquifer boundaries; hydrogeological mapping; chemical sampling of selected springs; and flow/chemical monitoring of 3 groundwater discharges in different portions of the aquifer.

Results include location of wells in and springs discharging from the aquifer in Cold Run Valley. The aquifer may be subdivided into four compartments of groundwater movement based on inferred directions of groundwater flow. The largest of these is the Sir Johns Run catchment, which collects groundwater discharge at a nearly linear rate and discharges to the Potomac. The other three compartments discharge to tributaries of Sleepy Creek via water gaps in Warm Springs Ridge.

During measurements in fall 2004, discharge via Sir Johns Run near its mouth was 6.75 cfs, suggesting that aquifer-wide, in excess of 10 cfs may be available throughout the study area for additional development. However, the period of 2005-2006 saw moderate drought impact the region, underscoring the risk that this, as all shallow groundwater supplies, could be vulnerable during extended periods of low precipitation.

The high flow rate of springs at the Town of Bath suggest they must be derived from a recharge area of considerable extent. Also, the thermal elevation of these springs suggest that they must have descended to a minimum depth of 1500 feet, and probably deeper, along a fracture- or fault-induced flow path. This raises the possibility that the Cacapon Mountian aquifer could contribute some or all of the source groundwater supplying these springs. Observations at Ladies Spring during this study found that (a) flow declined at Ladies Spring in similar proportion and timing to declines observed in 2 locations of Cold Run Valley, and (b) Ladies Spring inorganic chemistry is highly similar to two springs in Cold Run Valley and reflects a carbonate aquifer source. This evidence, however, is still inconclusive to specifically ascertain the source recharge area of the springs. Further monitoring and groundwater age dating will be needed to resolve this uncertainty.

ACKNOWLEDGMENTS

This work was supported by a work agreement with the Eastern Panhandle Conservation Districyt, Martinsburg, WV. Valuable collaboration on the research was offered by the Morgan County Rural Water Committee, and in particular Jack Soronen and Alma Gorse, its chairman and secretary, respectively. Field assistants included Maxie Maggio, Dave Light, Brenden Duffy, and Geoff Richards. Brenden Duffy also assisted in the GIS work. Aviation services to support the oblique aerial photography was provided by Jack Soronen.

cover photo: aerial view of Cacapon Mountain, looking south from over the Cacapon River, April 2004.

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INTRODUCTION

Morgan County, West Virginia, (Figure 1) is the one of the-fastest growing counties in the state and has current and growing water needs. The "crown jewel" of its water supply is Berkeley Springs, not only the focus of the tourist industry but also the water supply for the Town of Bath, the State Park at Bath, and water users as distant as US Silica to the north. While the spring has demonstrated capacity and is of excellent water quality, potential future growth in Morgan County may depend on finding other sources of community water supply to supplement the Berkeley Springs resource.

In addition to the question of future supplies, the recharge source of water for Berkeley Springs has been speculated upon, but never clearly identified. The springs – second highest in flow of all Morgan County, after Ziler Spring – have a pronounced thermal anomaly, being on the order of 10º C (18º F) higher than shallow groundwater discharge in this area. Assuming zero convective cooling upon ascent, this represents a minimum depth of circulation of 400 m (1310 feet) below surface under normal geothermal gradient. The large flow of the springs (from 2-3.2 ft^3/sec, according to state Bureau of Public Health records) also suggests a sizeable recharge area. It is not certain, on the other hand, where this recharge area might be located, or what hydraulic pathway it might take on its pathway to the discharge points.

This investigation examines the potential for new groundwater resources development in Morgan County associated with the Cacapon Mountain aquifer, an informal name used here to designate the bedrock aquifer extending from the Tuscarora Formation, at the core of Cacapon Mountain, stratigraphically upward to the top of the Helderberg Formation. This study also performs a preliminary examination of the regions of groundwater recharge contributing to major elements of groundwater discharge from this aquifer, and its implications for future water supply and contamination issues.

Purpose and Objectives

This purpose of this work is to identify hydrogeological elements of the Cacapon Mountain aquifer, defined for the purpose of this study as the carbonate-dominated part of the Paleozoic section extending from the Helderberg limestone (Devonian-Silurian) down-section through the Tonoloway limestone and Wills Creek shale into the Silurian clastic beds that form the core of the Cacapon Mountain anticline.. The aquifer occurs both along the east and west flanks of Cacapon Mountain, where the geologic sequence is repeated on either side of the anticline. However, the report focuses almost completely on the eastern side of the anticline. The aquifer was examined from the southern limit of the county along Route 522 near Ridge, north to near the community of Sir Johns Run along the Potomac. It is bounded roughly by Route 522 on the east and by the crest of Cacapon Mountain to the west. The aquifer does continue a limited distance south of the state line into Virginia, a portion of its extent that was not examined.

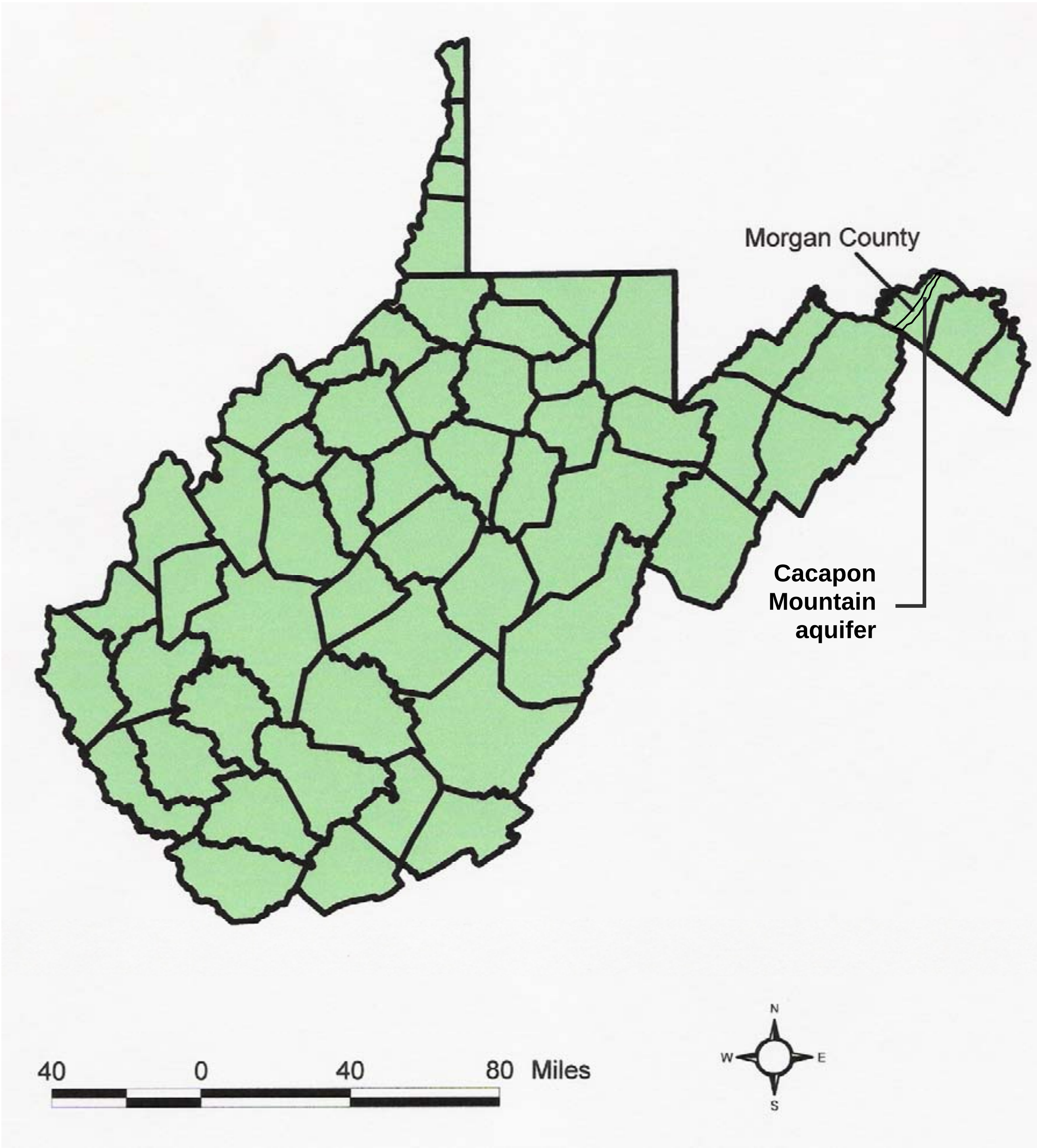


Figure 1. Location of the Cacapon Mountain study area in Morgan County, WV.

Hydrogeological elements of the Cacapon Mountain aquifer include its

- boundaries
- geology
- spring occurrence
- well distribution
- water chemistry
- springflow behavior

The objectives of the investigation include:

- comprehensive well and spring surveys for the aquifer within Cold Run Valley
- sampling of selected springs for water chemistry on a repeated basis
- measurement of flow behavior at 3 selected sites of spring discharge
- analysis of the groundwater flow system characteristics within the aquifer

The informal designation "Cacapon Mountain aquifer" is applied here to the groundwater flow system extending from the crest of Cacapon Mountain (underlain by Tuscarora quartzite) to the crest of Warm Springs Ridge (on the east) and Little Mountain (on the west), both underlain by Oriskany sandstone. The Tuscarora and Oriskany behave, in general, like aquitards in West Virginia (Kozar and Mathies, 2002), and in comparison the bedrock strata that lie stratigraphically between them behave like aquifers. Applying the term "aquifer" to a series of rock strata in a region, rather than to individual formations, can be appropriate if flow crosses formation boundaries, as is likely the case along Cacapon Mountain. The crest of Cacapon Mountain is also the axis of the Cacapon Anticline, and the geology on either side of this axis is very similar, effectively a mirror image of the other. However, in this investigation, we will focus almost exclusively on the east side of the aquifer, where population and water demand is more focused.

METHODOLOGY

Water well inventory

Water wells in Cold Run Valley – the local term used to describe the valleys of Sir Johns Run, Rock Gap Run, Indian Run, and Breakneck Run between the outcrops of the Oriskany and Tuscarora – were located and inventoried in summer 2004. A few wells were also inventoried along Route 522, outside of the valley. Information collected at each water well included wellowner name and contact information and WAAS-enabled GPS location. These field GPS locations were generally accurate to the nearest 15 meters horizontal. Also recorded were the well depth, driller, and reported total depth. If the wellhead was accessible and could be opened, static water level depth was also measured. Using this measured static water level depth and wellhead elevation, interpolated (±10 feet) directly from the 1:24,000 quadrangle maps, hydraulic head for each well was estimated. Uncertainty in the depth measurement is estimated at ± 0.1 feet, but was subject to uncertainty related to well pumping and seasonality. Error in the head measurement is estimated at ± 10 feet, mainly in wellhead elevation estimation. In addition to systematic error, the possibility of errors in hydraulic head due to well use or water level recovery also exists. Each well was numbered sequentially for reference with a 3-digit number.

The well completion report files of the West Virginia Bureau for Public Bealth were consulted for information on these wells, especially drillers logs. Since this database only includes wells drilled since 1997, almost no wells that were inventoried were found in these files.

<u>Seepage run and spring inventory</u>

In October 2004, a seepage run was performed along Sir Johns Run from its head to its mouth. The purpose was to gage stream gains in a downstream direction and to identify locations of springs contributing flow to the stream. Flow measurements were taken at approximate 100-meter intervals along the stream using a standard pygmy-type current meter and a 4-foot standard top-set wading rod. Average-velocity profiling (at depth 0.6 times water depth) was employed, with flow interpolated using a Aquacalc® system based on a minimum of 12 readings across the channel. In addition, at confluences with tributaries – many of which represented nearby springs – the flow of both the tributary and of the upstream portion of the mainstem were measured. A number of these springs were subsequently located by GPS or by examination of the 2003 high resolution SAMB digital aerial photographs.

Using the seepage run information, all springs of >5 gallons per minute (gpm) were field located by WAAS-enabled GPS. These field GPS locations, generally accurate to the nearest 15 meters horizontal, were later refined using 2003 SAMB high-resolution photography. Many, but not all, had flow measurements performed; for others, flows were visually estimated. Springs were located either by discussion with local residents, from seepage run information, or from air photo information. Flows were measured either at the source or at the stream confluence, using bucket-and-stopwatch or open-channel velocity flowmeter methods. Most of these springs represent discharge from shallow groundwater and vary considerably in rate both seasonally and from year to year; thus any reported flows are temporally-variable estimates and not necessarily precise estimates of long-term spring yield.

All springs located were within the eastern Capacon Mountain aquifer, except Ziler Spring (on the west side of the mountain) and Berkeley Springs (east of Warm Springs Ridge).

<u>Flow and chemical monitoring of springs</u>

A combined pressure-temperature-specific conductance datalogger was installed at 2 locations: the Ladies Spring in the town of Bath and Tonoloway Spring (also called Suburban Bottling

Spring) near the headwaters of Sir Johns Run. A coupled pressure-temperature logger was installed along Breakneck Run, at the water gap near Ridge, where the WV Department of Natural Resources fish hatchery has its water intake. The Ladies Spring is the largest flow at Berkeley Springs. The pressure variations at all three sites were rated to measured flows collected with a pygmy-type velocity flowmeter and wading rod by channel profiling at about 10 periods during 2005-2006.

For Ladies Spring (referred to with the abbreviation "LAD"), the combined spring channel overflow was gaged just upstream from the city water intake, on the east of the Roman Baths near Gentlemens Spring. This measured flow includes all known discharges from the springs within the State Park except (a) the Gentlemens Spring; (b) the subsurface underflow that flows via a pipe into Warm Springs Run not far from the main bathhouse, estmated at 50-100 gpm, and (c) any water diverted intermittently from the Ladies Spring impoundment to the bath house or swimming pool. This flow represents an estimated 70-80% of the total flow from all springs at Berkeley Springs. Thus, variations in stage within the containment box for Ladies Spring were rated based on flow measurements that also include other components of flow besides Ladies Spring itself, under the assumption that flow variations covary between discharges. In addition, because water is intermittently drawn from this containment structure to serve the main bathhouse and swimming pool areas, there are frequent brief declines in this pool elevation that are unrelated to variations of total flow from the spring itself. These conditions influence the quality of results of flow observations at this relatively intensively-used water source. In general, the results calculated from the data collected by the Ladies Spring datalogger will underestimate the total water resource available from all of Berkeley Springs.

Tonoloway Spring (referred to with the abbreviation "TON") is one of the larger discharges in Cold Run Valley (estimated at 99 gpm in October 2004 by bucket and stopwatch). The pressure here was measured with a 5-foot range water-level sensor installed at the bottom of a 6-foot deep storage tank into which flow from both main spring outlets is diverted and held for pumping to the spring bottling facility. During 2005-2006, the facility was generally not pumped except for intervals of direct removal by pumping. This "noise" from pumping withdrawal was most frequent in 2006, but is very temporary, as the containment pool recovers its head in less than 2 hours after pump cessation. Overflow from the holding tank flows via a pipe to a ditch nearby, and at the outfall into this ditch, flow was measured by bucket and stopwatch using a 15 gallon vessel. This overflow represents >95% of the total discharge from the spring and was used for rating the head fluctuations in the tank. Concurrent with flow measurements, stage level in the tank was measured with a steel tape with respect to the top of the concrete structure.

The Breakneck Run monitoring location (referred to with the abbreviation "RID") is along the main stem of that drainage where it flows through Breakneck Gap, near Ridge, West Virginia. This is the surface water outlet, through which nearly all of the water in this drainage leaves Cold Run Valley. The only flow not captured at this location is (a) a small side channel of the run which flows into it approximately 100 meters downstream, containing discharge from Ridge Cave and two other sources; (b) part of the discharge from a small spring (Hoverdale Spring) about 100 meters north, which is piped to the fish hatchery – generally <100 gpm and (c) subsurface underflow beneath Breakneck Run through coarse colluvial fill. The sensor is installed in a small stilling well in the impoundment behind a weir from which water is diverted to the fish hatchery. Pressure variations in this pool are correlated with flow measurements just upstream of the impoundment. The impoundment has two points of diversion: the rectangular weir itself, over which flow is directed down the channel to the hatchery, and an intake structure behind the dam through which water is piped down a valved 6-inch line that also leads to the hatchery ponds. The measured flow captures >95% of the groundwater discharge to springs upstream from this location, and except for periods when the southern side channel carries flows immediately after recharge events. Because this location is within one mile of the crest of Cacapon Mountain, runoff duration is relatively brief (<2 days), and thus for much of the year, the discharge in this channel is composed exclusively of groundwater discharge fed from nearby springs.

While the flows estimated for these stations are based on credible measurements, all three of these water sources are currently developed for water use, to different frequencies and extents. As a result, periods of water abstraction may be observed to cause short-term noise in flow measurement, especially for Ladies Spring, in which use is most intense.

Spring geochemistry

Serial sampling of spring geochemistry was performed at six springs and four wells both along Cacapon Mountain and in the Town of Bath (Figure 2). Sampling locations are listed in Table 1. Six complete and two partial rounds of water samples have been collected to date. The complete rounds include springs from Cold Run Valley sandstone – High Spring (HGH) and Mountainside Spring (MTN) – and limestone springs – Neely Spring (NEY) and Webber Spring (WEB) springs, at Cacapon State Park (CSP), and at Berkeley Springs State Park (LAD). One round of samples has also been collected from several peripheral springs (Ziler, Tonoloway and Ridge Springs) for comparison to the other locations. Additional water samples were also collected from four residential water wells during each complete round. All samples were analyzed for major cations and anions. Field screening readings were obtained for pH, temperature and specific conductance.

Water level depth was measured in all sampled wells, and stage (water elevation) and/or discharge was measured in the springs when possible. However, the geometry and physical layout of some springs limited the feasibility of measuring flows, and estimated flows were used.

Field screening parameters were measured at each location using hand-held meters for temperature, pH, and specific conductance (SC). Alkalinity was measured via an acid titration either in the field or within 24 hours of sample collection. Alkalinity values are reported as mg/L bicarbonate (HCO_3^-), which at the pH values observed was the dominant alkalinity species.

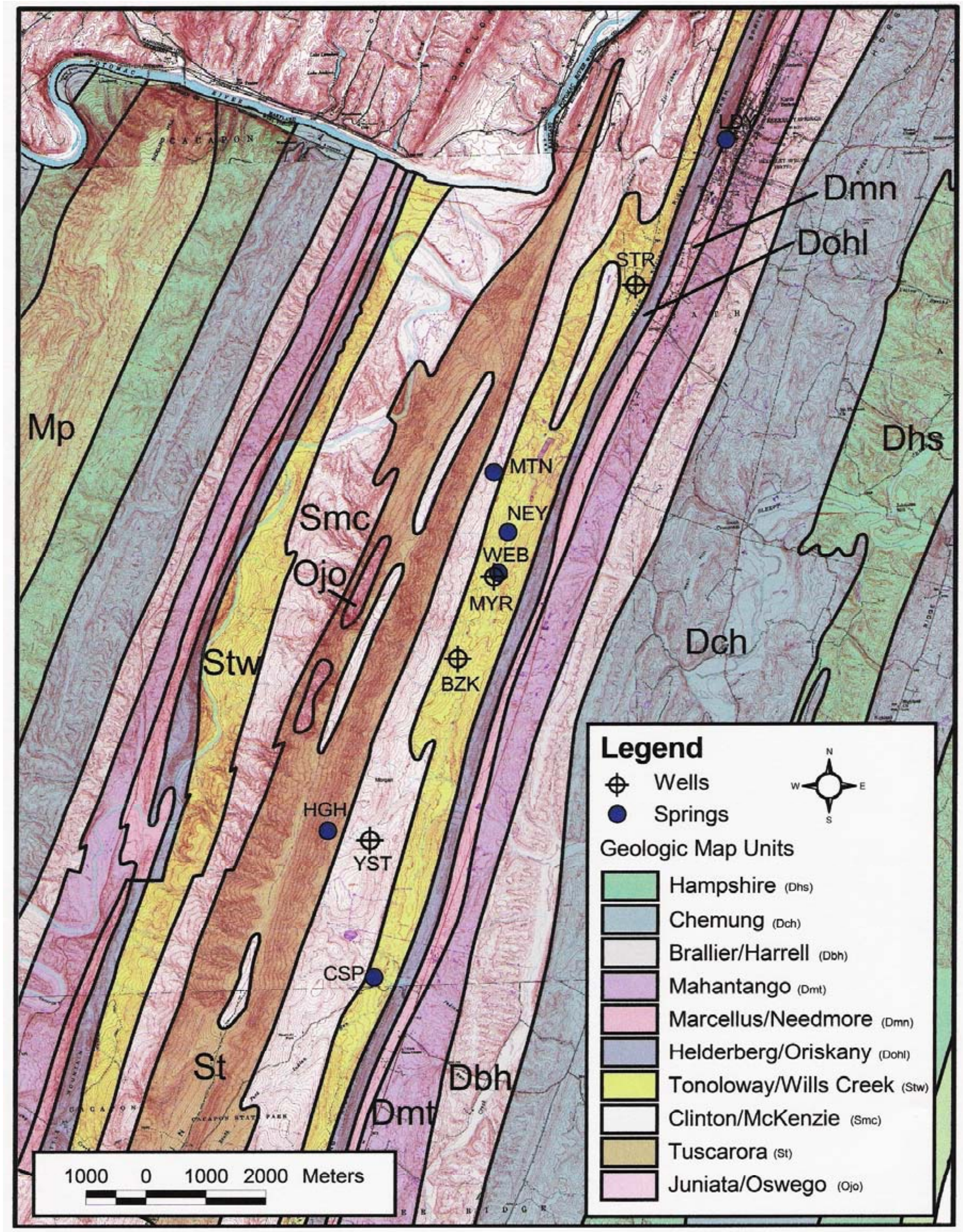


Figure 2. Location of wells and springs used for chemical sampling of groundwater.

Local name	owner	abbreviation	site type	UTM northing	UTM easting	surface geology
Ladies *	Town of Bath	LDY	spring	737804	4389947	Oriskany
--	Stotler	STR	well	736301	4387510	Tonoloway/Wills Creek
Mountainside (Coolfont *)	Mountainside Assn.	MTN	spring	733954	4384379	Clinton/MacKenzie
Neely	Neely	NEY	spring	734186	4383370	Tonoloway/Wills Creek
Webber	Webber	WEB	spring	734029	4382692	Tonoloway/Wills Creek
--	Myers	MYR	well	733956	4382626	Tonoloway/Wills Creek
--	Bilezikian	BZK	well	733354	4381244	Tonoloway/Wills Creek
High	High	HGH	spring	731199	4378357	Tuscarora
--	Yost	YST	well	731901	4378197	Clinton/MacKenzie
Cacapon State Park *	Capapon State Park	CSP	spring	731979	4375902	Tonoloway/Wills Creek

* indicates name from McCulluogh, 1986

Clastic source springs		Carbonate source springs	
MTN	Clinton/MacKenzie	NEY	Tonoloway/Wills Creek
HGH	Tuscarora	WEB	Tonoloway/Wills Creek
LDY	Oriskany???	CSP	Tonoloway/Wills Creek
		LDY	Helderberg??

Clastic source wells		Carbonate source wells	
YST	Clinton/MacKenzie	MYR	Tonoloway/Wills Creek
		BZK	Tonoloway/Wills Creek
		STR	Tonoloway/Wills Creek

Table 1. Names and locations of sampled springs and wells.

The samples for laboratory analysis were field-filtered using 0.45 µ filters and kept on ice until submitted to the chemical laboratory at WVU's National Research Center for Coal and Energy (NRCCE). Samples for cations were preserved using 1% by volume concentrated nitric acid. Elemental analysis was completed for Ca, Mg, Na, K, Fe, Mn and Si using inductively-coupled plasma-optical emission spectroscopy (ICP-OES) according to EPA method 200.7. Anion analysis for SO_4, Cl, and NO_3 was completed using colorimetric methods according to, respectively, EPA methods 375.1, 325.2, and 353.2.Analyses were obtained for major elements for all samples; however, minor element analyses were not obtained for samples expected to be below detection limits.

Several derived parameters were calculated from water chemistry data, including the molar Ca/Mg ratio, saturation indices with respect to calcite (SI_C) and quartz (SI_Q), and partial pressure of carbon dioxide (P_{CO2}). Saturation indices indicate how close the water chemistry is to equilibrium with respect to specific minerals. Water with SI_x equal to zero is at equilibrium with mineral "x", positive SI_X values indicate oversaturation (water can precipitate "x") and negative SI_X values indicate undersaturation (water can dissolve "x"). The P_{CO2} data are presented as "enhanced P_{CO2}", the ratio of calculated to atmospheric concentrations. Values near 1.0 suggest the water is under near-atmospheric pressure; high values indicate the water is pressurized with CO_2 from soil zone interaction. The value of atmospheric partial CO_2 pressure is 0.00033 ($10^{-3.48}$) atmospheres, but groundwater samples commonly are 1 to 2.5 orders of magnitude higher.

GEOLOGIC BACKGROUND

Stratigraphy

Table 2 shows a comparative historical compilation of stratigraphic nomenclature for the Morgan County area, with reference to the original county studies of Grimsley (1916) and Stose et al. (1912). The most recent geologic maps are a WVU Masters thesis (Minke, 1964) and four open-file 1:24,000 quadrangle maps for Hancock, Great Cacapon, Bellegrove, and Stotlers Crossroads quadrangles (Dean et al., 1995; Kulander et al., 1995; Lessing et al., 1997). In addition, the 1:250,000 state geologic map (Cardwell et al., 1986), shown reproduced on Plate 1, is the only mapping for which map units have been digitized. In this study, we employ the state map, although the 1995-97 open-file maps provide better detail and are thought to be somewhat more accurate.

All beds in this sequence are well exposed along the CSX access road along the Potomac River from south of Hancock to Great Cacapon. This section was not measured during this investigation, but all exposed units were examined and confirmed to agree with the state geologic map.

Figure 3 shows a cross section of regional geology, perpendicular to strike from the vicinity of Flintstone, MD (left) to Jones Springs, WV along Back Creek (right). The Cacapon Mountain Anticline is prominent at the left of this figure, with Warm Springs Ridge clearly evident underlain by dipping Oriskany Formation (blue) to its east. The rocks of the Cacapon Mountain aquifer are less resistant units that lie in the saddle between the ridges of Cacapon Mountain and Warm Springs Ridge.

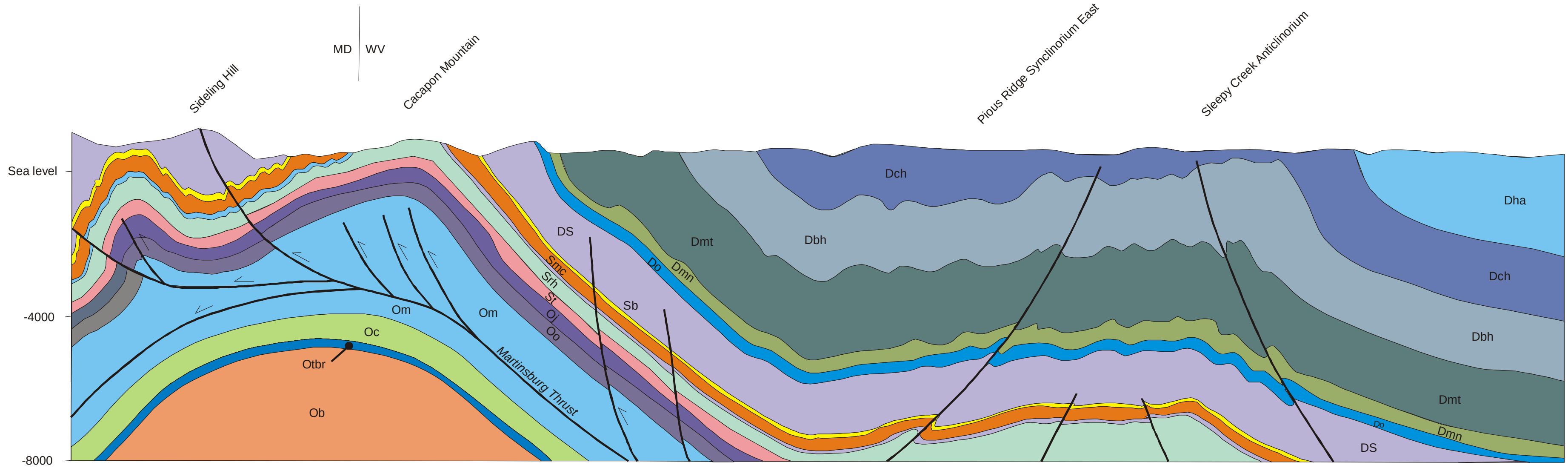
An aerial view of the Cacapon Mountain

The stratigraphy of the Cacapon Mountain area extends from Devonian shales (Brallier, Harrell, Mahantango, Marcellus, and Needmore formations) down-section through the lower Devonian and the Silurian rocks of the region (Table 2). The morphology of the mountain clearly expresses the stratigraphy of these units, as shown in the aerial view of Figure 4. The anticline's margins are marked by the prominent Oriskany sandstone (Devonian), which forms Warm Springs Ridge and Tonoloway Ridge. Younger Devonian rocks lie outside the Oriskany with respect to the anticlinal axis, and youger Silurian rocks lie within the Oriskany outcrops. At the base of the Oriskany lies the Helderberg limestone, which occurs on the back (west) side of Warm Springs Ridge from near its crest to the base of the ridge slope on the interior of the anticline. The Helderberg is not included as a map unit on the state geologic map of Cardwell et al. (1986), but is lumped with the Oriskany, due to limited outcrop of the Helderberg and to the prominence of the sandstone ridge. In the mapping of Kulander et al. (1995), the Helderberg is lumped along with the underlying Silurian Tonoloway limestone and Wills Creek shale as "Devonian-Silurian carbonates", likely because the units weather similarly to form lowland settings of limited exposure. It is these three map units that constitute the most transmissive portion of the Cacapon Mountain aquifer.

Table 2. Comparison of stratigraphic nomenclature in published maps of Morgan County geology.

Table 1. Comparative historical stratigraphic nomenclature for Morgan County, WV.

Period	Series	Stoss and Swartz (1912)	Grimsley (1916)	Minke (1964)	Kulander, Lessing, et al. (1995a, 1995b, 1995c)	approx. thick-ness.(ft.)
Mississippian	Osagean	Pinkerton ss.	Pinkerton ss.	Pinkerton ss.	Pinkerton ss.	1150
Mississippian	Osagean	Myers sh.	Myers red sh.	Myers sh.	Myers sh. Little Mountain ss.	1200 100
Mississippian	Kinderhookian	Hedges sh.	Hedges sh./coal	Hedges sh.	Hedges sh.	190
Mississippian	Kinderhookian	Purslane ss.	Purslane ss.	Purslane ss.	Purslane ss.	450-550
Mississippian	Kinderhookian	Rockwell Fm.	Rockwell Fm.	Rockwell Fm.	Rockwell Fm.	600-700
Devonian	Bradfordian	Catskill Fm.	Catskill Fm.	Catskill Fm.	Hampshire Fm.	3600-4000
Devonian	Chataquan	Jennings Fm.: transition mbr.	Chemung Fm.	Chemung Fm.: transition mbr.	Chemung Fm.	1700-2100
Devonian	Chataquan	Jennings Fm.	Parkhead ss.	Chemung Fm.: Parkhead mbr.		
Devonian	Chataquan	Jennings Fm.: Parkhead mbr.	Portage Fm.	Brallier Fm.	Brallier-Harrell Fms.	1600-1900
Devonian	Senecan	Jennings Fm.: Genesee Mbr.	Genesee Fm.	Harrell sh.		
Devonian	Senecan	Romney sh.: Hamilton mbr.	Hamilton Fm.	Hamilton Fm.	Mahantango Fm.	1800-2400
Devonian	Senecan	Romney sh.: Marcellus mbr.	Marcellus Fm.	Marcellus sh.	Marcellus-Needmore sh.	300-400
Devonian	Ulsterian	Romney sh.: Onondaga mbr.	Onondaga Fm.	Needmore sh.		
Devonian	Ulsterian	Oriskany Ss.	Oriskany Fm.	Oriskany Ss.	Oriskany ss.	200-300
Devonian	Ulsterian	Helderberg ls.	Helderberg Fm.: Becraft mbr. New Scotland mbr. Coeymans mbr. Keyser mbr.	Helderberg Fm.: Port Jervis mbr. Port Ewen sh. Becraft mbr. New Scotland mbr. Coeymans mbr. Keyser mbr.	Helderberg gp.	400-650
Silurian	Cayugan	Cayuga Gp.: Tonoloway ls.	Bossardville ls.	Tonoloway ls.	Tonoloway ls.	300-400
Silurian	Cayugan	Cayuga Gp.: Wills Creek sh.	Roundout-Waterlime Fm.	Wills Creek sh.	Wills Creek Fm.	350-450
Silurian	Cayugan	Cayuga Gp.: Bloomsburg red ss.	Bloomsburg red ss.	Bloomsburg redbeds	Bloomsburg Fm.	25-40
Silurian	Niagaran	Cayuga Gp.: McKenzie Fm.	Niagara Fm. (McKenzie Fm.)	McKenzie Fm.	McKenzie Fm.	175-225
Silurian	Niagaran	Cayuga Gp.: Keefer ss.		Clinton Gp.: Rochester sh.	Keefer ss.	20-30
Silurian	Niagaran	Clinton sh.		Clinton Gp.: Kiefer ss. Rose Hill Fm.	Rose Hill Fm.	400-450
Silurian	Albion	Tuscarora ss.	White Medina ss.	Tuscarora ss.	Tuscarora ss.	150-250



Dha Hamphire Fm.
Dch Chemung Fm.
Dbh Brallier Fm.
Dmt Mahantango Fm.
Dmn Marcellus-Needham Fms.
Do Oriskany Group
DS Devonian-Silurian carbonates (includes Helderberg, Tonoloway, Wills Creek)
Sb Bloomsburg Fm.
Smc Mackenzie Group
Sk Keefer Fm.
Srh Rose Hill Fm.
St Tuscarora Fm.
Oj Juniata Fm,
Oo Oswego Fm.
Om Martinsburg Fm.
Oc Conococheague Fm.
Ob Beekmantown Fm.

Figure 3. Northwest-to-southeast Structure cross section of Morgan County across strike, from near Flintstone, MD to Jones Creek, WV. From Dean et al. (1995). No vertical exaggeration.

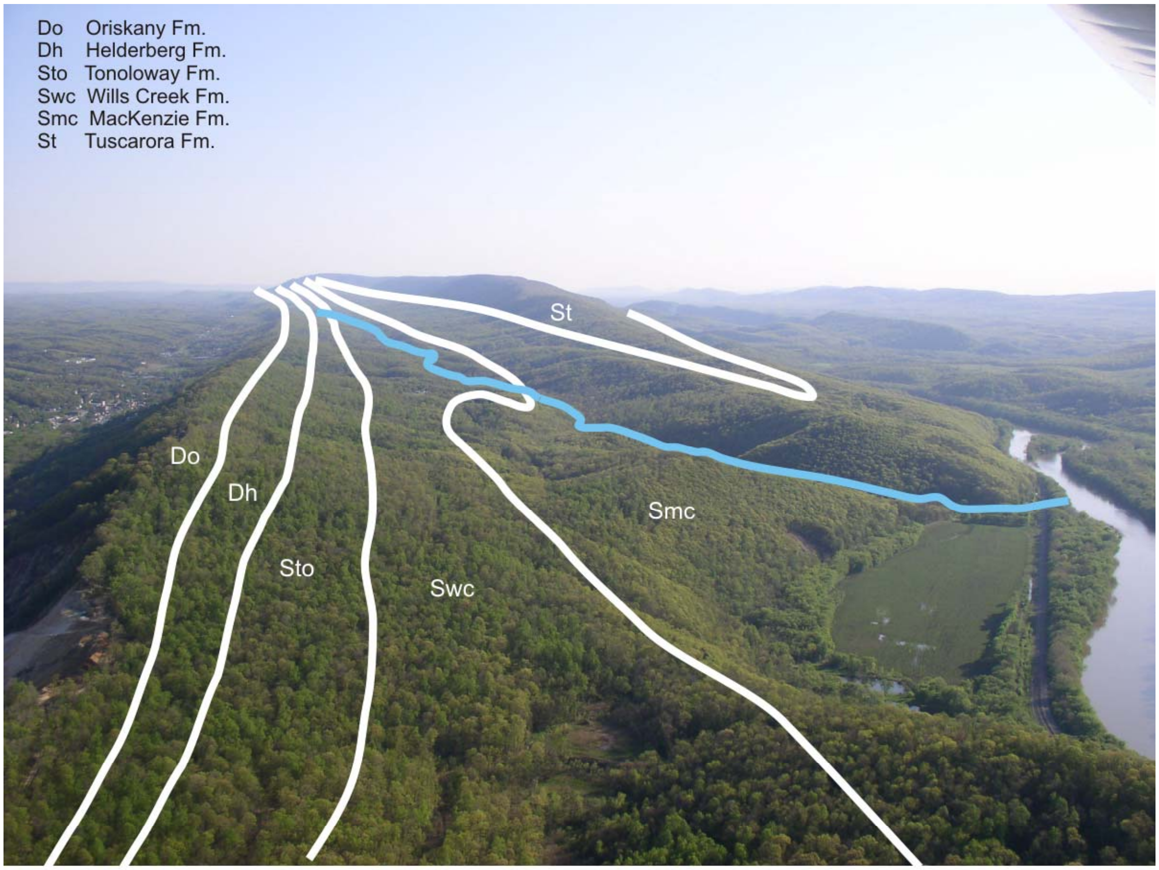


Figure 4. Aerial view from 3 miles SW of Hancock, MD overlooking the Cacapon Mountain Anticline. The US Silica mine pit is just shown at lower left. Berkeley Springs at upper left.

Below the Wills Creek, the Bloomsburg redbeds form a thin but distinctive marker horizon, exposed in outcrops on the south side of Sir Johns Run near the community of the same name. Underlying this is the McKenzie Formation and Clinton Group sediments, a nearly 700-foot sequence composed primarily of grey and black shales and siltstone. The Keefer sandstone, while thin, is the most resistant layer in the sequence and is a minor ridge former. At the base of the Clinton lies the Tuscarora sandstone, a distinctive white quartzite formerly known as the White Medina sandstone. The Tuscarora is the most resistant sedimentary unit in the lower Paleozoic sequence and one of the common ridge-formers of the folded Appalachians, and here forms the core of Cacapon Mountain, continuously exposed along its crest.

The aggregate thickness of rocks from the top of the Oriskany (near Berkeley Springs) to the top of the Tuscarora is estimated to be 1900-2700 feet (Dean et al., 1995). The thickness of the carbonate sequence of the Cacapon Mountain aquifer, where the highest potential for groundwater development lies, is about 1000-1500 feet, over half the thickness of the sediments occurring within the anticline above the Tuscarora. The Tuscarora is a dense unit of low porosity, and is likely to be the base of most fresh groundwater flow within the aquifer.

Structure and deformation

The rocks of Morgan County are part of the eastern portion of the folded Ridge and Valley Physiographic Province. The cross section of Figure 3 shows inferred structure to a depth of nearly 9000 feet below land surface and may be thought of as somewhat speculative, although it is based on review of deep seismic profiles. The area has been subjected to moderate compressive force associated with the Alleghenian orogeny (Pennsylvanian-Permian), with less crustal shortening than observed farther east in Berkeley and Jefferson Counties but more than occurs to the west on the Allegheny Plateau. The area is marked by a single major structure forming a prominent mountain (Cacapon Mountain anticline) flanked by less pronounced folds of, to the east, the Sleepy Creek Anticlinorium and, to the west, the Sideling Hill Syncline. A series of thrust faults are interpreted to occur within the Ordovician Martinsburg shale at great depth, similar to what is found exposed within the Martinsburg in Berkeley and Jefferson counties but here at 1-2 miles depth. Rising from this low-angle décollement zone are a series of steeply-dipping reverse faults, showing the same sense of movement as the Martinsburg Thrust but at a steeper angle. These are depicted as being of generally minor displacement but thought to extend to the surface in several locations. The map shows a number of such reverse faults as blind (without surface exposure) but they may well – and probably do – crop out at the surface. One such reverse fault outcrop is exposed in the Fairfax Spring pool (Figure 5), marked by slickensides (rock grooves created by opposing movement across a fault plane). It is a reasonable speculation that fracturing associated with this reverse fault is directly associated with the enhanced rate of fluid flow from springs at Berkeley Springs, and is also responsible for providing the hydraulic pathway for deep circulation and ascent. The attitude of these reverse faults near the surface is steep to near vertical.

Figure 5. Exposure of slickensides (arrow indicates lineation direction) in Oriskany sandstone, Fairfax Spring, Berkeley Springs.

Plate 1 shows a geologic map of the Cacapon Mountain area, showing geologic units as well as major structures. The beds on the east side of Cacapon Mountain form a monoclinal ramp dipping a nearly uniform 45º. The continuity of beds along strike is not interrupted by cross-strike faults or other discontinuities, although restricted exposure within the anticline may have limited the number of faults that have been identified. However, there are a number of minor folds or "wrinkles" within the anticline, and some of these are doubly-plunging, suggested by the "canoe-shaped" appearance of the outcrop pattern. For example, there are "keels" (doubly-plunging synclines) of Clinton Group shale along the crest of Cacapon Mountain that represent such folds warped in a second direction.

Plate 2 shows a map employed a shaded digital elevation model (DEM) of the Cacapon Mountain area. The physiography clearly expresses the geology of the valley, with the resistant Oriskany (Warm Springs Ridge, Tonoloway Ridge) and Tuscarora (Cacapon Mountain) sandstones bracketing the less resistant interior of the anticline. This interior is composed of relatively non-resistant carbonate lithologies in the (from top to bottom) Helderberg, Tonoloway, and Wills Creek units, as well as the older McKenzie and Clinton clastics. This forms a one-mile wide valley on the east flank, known colloquially as Sir Johns Run valley or Cold Run Valley. The eastern half of the valley is floored by carbonates and the western half by clastics. The aquifer term is applied to both clastic and carbonate portions, as groundwater is produced from all these formations, and groundwater may well cross from one formation to another in some locations. The dip of the beds is about 45º to the east, and so the organization of these aquifers is distinctly three-dimensional.

The Cacapon Mountain aquifer

Groundwater flow is commonly driven by topography, and the Cacapon Mountain anticline has two distinct topographic elements; 1) the slope of Cacapon Mountain itself, which is perpendicular to strike, and 2) a much more gradual northeastward slope of the surface of the anticline, plunging to the north towards the Potomac. The relief between Cacapon Mountain and the land beyond the Oriskany is about 1500 feet; between the north and south ends of Cold Run Valley, relief is about 200 feet.

Surface water drainage can help determine to groundwater flow directions. Cold Run Valley drains in its northern half directly into the Potomac River via Sir Johns Run, a small perennial strike-parallel stream of low to moderate discharge. In its southern half, it drains via three small tributaries of Sleepy Creek's West Fork: Breakneck Run, Indian Creek, and Rock Gap Run. Each of these three is strike-normal and exits Cold Run Valley through one of a series of spectacular water gaps in the Oriskany. In this way, surface (and ground) water can be thought to be partly confined within Cold Run Valley by the Oriskany, particularly within its northern half, and "spilling" from the valley through its points of exit at the three water gaps and at the intersection of the anticline with the Potomac.

Both the Tuscarora and the Oriskany are thought to serve primarily as aquitards, due to their low primary porosity and well-cemented competent nature. The aquifers with the highest porosity, and presumably with the highest aquifer potential, are the three carbonate units: the Helderberg, Tonoloway, and Wills Creek.

The Helderberg limestone (Devonian-Silurian) is one of the state's notorious cave-forming formations (Davies, 1965). It is present all along Warm Springs Ridge on its western flank, yet tends to be poorly exposed, to the point of not being field mappable. Figure 6 shows a small exposure of Helderberg from near Ridge that is cavernous and ephemerally discharges at least as much as 9 ft^3/sec (1 ft^3/sec = 448 gpm) of groundwater; however, after periods of dry weather, this flow will completely cease. The tendency of the limestone to form caverns is in part due to its relative purity. It is a biohermal (reef) limestone and fossiliferous, but also contains chert nodules (very hard silica). The expected nature of conduit development in the Helderberg is parallel to bedding, forming a type of dissolution feature known as stratigraphic karst (Figure 7).

The Tonoloway and Wills Creek formations (Figure 8) are both calcareous, but of very different origin and stratigraphic nature in comparison to the Helderberg. Both were formed in periods of shallower water compared to the Helderberg. The Tonoloway is of intertidal origin and forms parallel-laminated, generally thin-bedded sequences with occasional mudcracks, shale partings, fecal pellets, and gypsum and/or halite casts. Its fabric is commonly fenestral as is typical of intertidal limestones. The Wills Creek is in fact a limey shale, and may represent portions of the intertidal zone in proximity to a sediment source. Both formations have the capability to become porous on dissolution, but neither are cavernous or have the potential for conduit development, as does the Helderberg.

Figure 6. Exposure of cavernous Helderberg limestone, August 2004. At this time, the cave was dry; in October 2004, its flow ranged from 3 to 7 cfs.

Figure 7. Helderberg cave in the Cacapon Mountain Anticline near Hancock MD, showing conduit formed parallel to strike

Figure 8. Exposure of Wills Creek (lower shaly part of slope) and Tonoloway limestones near Rocky Gap State Park off the I-68 southbound exit ramp.

RESULTS

Spring Occurrence and Baseflow to Streams

Plate 2 shows the distribution of springs (yellow triangles) and stations of baseflow discharge to Sir Johns Run observed during the seepage run of October 2004 (blue circles, graduated in size according to flow). The springs were either located directly or, in some cases, inferred from flow measurements made on tributaries to Sir Johns Run during the seepage run. Of 39 mapped springs to date on the eastern side of the anticline, 17 occur in the Tonoloway or Wills Creek formations, 8 in the Helderberg, 7 in the McKenzie-Clinton, and 1 in the Tuscarora, as will as the 4 discharges in the Oriskany at Berkeley Springs.

These springs are listed in Table 3, identified by name or an arbitrary sequential 3-digit number that corresponds to locations shown on Plate 2. It is a temptation to sum up the discharges for these springs into an estimate of total yield from the aquifer. For several reasons, this would be invalid. First, these flows represent only a portion of the groundwater discharge from the aquifer; additional components are represented by (a) evapotranspiration; (b) diffuse seepage into streams; (c) deep underflow beneath Warm Springs Ridge; and (d) unreplenished well withdrawals (that is, water pumped from wells not allowed to infiltrate back into the aquifer). Second, the flows from these springs are extremely variable from time to time, and flows measured at one point of time could bear little relationship to either average flow or flow at other times for the same spring. The range of values at any spring may vary considerably and unpredictably. Most of these flow measurements were taken in October 2004, in the low-flow season of a fairly humid year. It is practically impossible to convert these flows into estimates of long-term yield.

Figure 9 shows the results of the seepage run profile, performed for Sir Johns Run in October 2004. The measurements were taken on 2 dates separated by 6 days, over which there had been negligible recession based on replicate measurements at 3 stations. Figure 9 is a plot of increase in stream baseflow (blue squares connected by lines) in a downstream direction (left to right). In addition, variations in pH (yellow X's) and specific conductance (black X's) are shown. The blue triangles Flow increases in an almost linear rate with respect to distance downstream, allowing for some “porpoising” of water into and from the hyporrheic zone beneath the stream channel. The symbols at the bottom represent location of tributary inflows (springs). There is a somewhat greater-than-average rate of gain in the area upstream of Coolfont, and a somewhat lower rate of stream gain between Coolfont and Route 9. From Route 9 down to the mouth of the run, there is an approximately linear rate of gain, punctuated by two large spring discharges from the Helderberg/Tonoloway limestone to the east. The flow at Sir Johns Run town was 6.75 cfs in mid-fall, typically a low flow period. This rate would be highly subject to flow variations caused by weather, and cannot in itself be employed as a recharge rate estimater for the aquifer. Such an estimate would require monitoring of flow over a period of one or more years.

Groundwater flow patterns

ident. no.	Date of visit	by	local name	latitude degrees	longitude degrees	altitude (ft)	surface geology	flow (gpm)	flow method	pH	SC µsiemens/ cm	temp °C
Mor-303	10/08/04	JD	Rte 9 pond	39.62544	-78.23599	695	Dohl	160	F	8.01	585	15.3
Mor-309	10/09/04	JD	Clearcut	39.63941	-78.23303	640	Smc	130	F	8.04	429	14.2
Mor-413	10/13/04	JD		39.58483	-78.26532	740	Stw	90	F	7.90	257	11.9
Mor-416	10/13/04	JD		39.58909	-78.26516	768	Smc	13	F	8.00	214	12.4
Mor-423	10/13/04	JD		39.59926	-78.25434	692	Stw	22	F	7.96	245	13.7
Mor-424	10/13/04	JD		39.60019	-78.26331	793	Smc	49	F	7.38	172	12.5
Mor-424	10/13/04	JD		39.59945	-78.25345	720	Stw	50	F			
Mor-427	10/13/04	LC		39.61218	-78.25108	690	Stw	9	F	7.47	229	12.6
Mor-428	10/13/04	LC		39.61380	-78.25054	670	Stw	76	F	8.07	570	13.0
Mor-429	10/13/04	LC		39.61748	-78.24885	665	Stw	9	F	7.26	210	13.7
Mor-430	10/13/04	LC		39.62217	-78.24597	740	Stw	7	F	7.80	274	12.4
Mor-431	10/13/04	LC		39.62305	-78.24555	705	Stw	4	F	7.76	254	12.3
Mor-432	10/13/04	LC		39.62376	-78.24379	673	Stw	11	F	7.99	445	12.5
Mor-506	10/24/05	JD	Fleece Spring	39.55329	-78.27674	878	Dohl	100	E	8.22	520	13.6
Mor-508	10/25/04	JD	Tonoloway A	39.55536	-78.27526	876	Dohl	50	B	7.05	69	16.3
Mor-508	10/25/04	JD	Tonoloway B	39.55533	-78.27543	876	Dohl	50	B	7.05	69	16.3
Mor-510	09/17/04	LC	Webber Spring	39.56202	-78.27584	819	Stw	3	B	8.22	150	17.2
Mor-515	09/17/04	LC	Neeley Spring	39.56808	-78.27378	780	Stw	66	F	7.30		19.4
Mor-516	10/13/04	JD		39.57238	-78.27630	895	Smc	61	F	7.15	71	15.3
Mor-520	10/13/04	JD		39.57459	-78.27479	882	Smc	99	F	7.23	60	15.5
Mor-713	09/17/04	LC	Cacapon SP Spring	39.50146	-78.30204	930	Stw	40	E	6.85	297	13.6
Mor-726	09/17/04	LC	High Spring	39.52377	-78.31025	1400	St	75	B	5.00	46	12.1
Mor-749	09/17/04	LC	Mountainside Spring	39.57997	-78.27274	890	Smc	10	B	5.02	51	13.3
	10/01/04	JD	Ridge Cave	39.46275	-78.31540	930	Dohl	1187	F			
	10/01/04	JD	Hoverdale Spring	39.46433	-78.31527	925	Dohl	250	E			
		JD	Gap Spring	39.47131	-78.31260	1005	Dohl					
		EW	Ladies Spring	39.61764	-78.21794	620	Dohl			6.82	300	22.5
		EW	Gentlemens Spring	39.61772	-78.21790	620	Dohl					
		EW	Lord Fairfax Spring	39.61769	-78.21791	620	Dohl					
		EW	Bathhouse Drain	39.61762	-78.21785	620	Dohl					
		EW	Ziler Spring	39.51742	-78.33399	535	Dohl					
		JD	Ridge Pond	39.46520	-78.31969	1030	Smc					
		JD	Ridge #2	39.46342	-78.31507	913	Stw					
		JD		39.58845	-78.26025	757	Stw					
		JD		39.59495	-78.25545	782	Stw					
		JD	Thunderbird Hills Pond	39.52120	-78.29179	835	Stw					
		JD		39.58175	-78.26112	822	Stw					
		JD		39.60423	-78.25071	822						
		JD		39.61055	-78.24991	718						

Table 3. Inventoried springs in Cacapon Mountain aquifer.

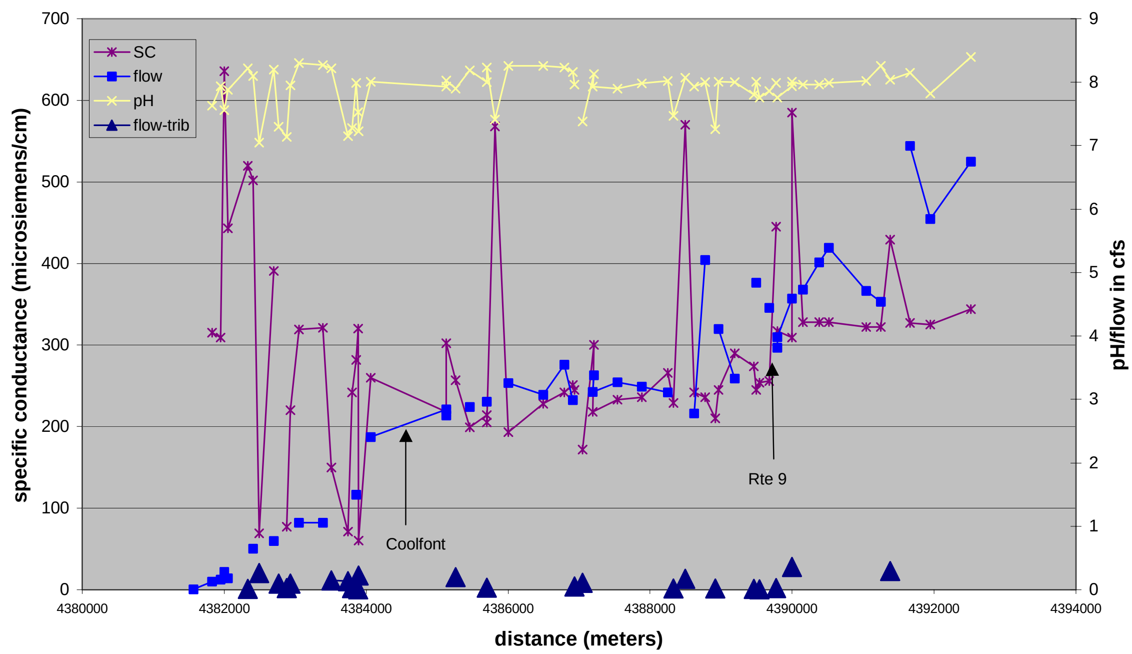


Figure 9. Seepage run results collected from Sir Johns Run, October 2004. Symbology: channel flow (blue squares); tributary inflows (blue triangles); specific conductance (blue x's); pH (yellow x's). Distance is UTM northing in meters, approximately parallel to the stream orientation.

Plate 3 shows location of water wells in Cold Run valley, with a 3-digit well location code plotted adjacent to it. The contour lines represent generalized potentiometric head based on the measurements taken in summer 2004, representing “combined” heads from one or more aquifer zone, depending on the well construction at each location of measurement. In fractured bedrock aquifers, it is not unusual to see abrupt contrasts in such generalized heads over short distances, due to dominance of aquifer zones from different depths in different wells in close proximity. Nonetheless, such generalized heads can give an indication of shallow groundwater movement if sufficient data are available. These data are contoured in fifty-foot potentiometric intervals in two areas of the aquifer (Sir Johns Run and Rock Gap Run). In other portions of the aquifer (Indian Run and Breakneck Run), there are insufficient well data to merit contouring. Even in the areas for which contours are shown, there are locally-anomalous well heads.

In Rock Gap Run, contouring of heads suggests that flow converges in a southeastward direction on the mouth of the Gap itself, discharging into either fork of the run. This is consistent with the pattern of discharges observed at local springs. In Sir Johns Run, on the other hand, the contour pattern suggests convergent flow of shallow groundwater on the run itself, resulting in a northeastward flow direction and close coupling with surface flow in the stream. These results are consistent with the pattern of stream gain (Figure 9) as well as the low-lying locations of springs in the valley.

The well survey indicates that hydraulic heads are highest in the aquifer within the Helderberg outcrop area, and that shallow groundwater divides exist breaking the Cold Run Valley aquifer into a series of flow "compartments". One such compartment – of Sir Johns Run – is dominantly northeast-flowing, parallel to strike. The other three are dominantly southeast-flowing, perpendicular to strike. These are drained by Rock Gap Run, Indian Run, and Breakneck Run, respectively. The control on these groundwater flow directions are the three water gaps through which the latter streams emerge from Cold Run Valley. There also appears to be a divide between groundwater flowing to the east (beneath or through the Oriskany sandstone) and that flowing within Cold Run Valley. Hydraulic heads in a small number of wells beneath Warm Springs Ridge range from about 700 to 900 feet – substantially higher than the town of Bath. It is observed that few springs occur on the east side of Warm Springs Ridge, excepting the springs at Bath. Therefore, the well data suggest that hydraulic heads are sufficiently high to drive flow eastward, yet in few locations is groundwater discharge seen to the east.

<u>Spring geochemistry</u>

Results of chemical analyses are included in Table 4. Temporally-averaged chemistries for each spring or well are presented in Table 5.

The screening parameters provide a comparison between different categories of springs occurring in the dataset (Figure 10). Temperature of most springs ranged between 10º and 15ºC and pH between 6.3 and 7.4). Springs that discharge from clastic rocks (sandstone and shale), such as HGH and MTN, showed considerably lower pH (3.8 to 5.2). Ladies Spring (LDY) has a near-neutral pH, similar to the other springs, but considerably higher temperature (22-23ºC, or 71-

Location	Sample ID	Date	Temp. °C	SC µS/cm	pH	Alk. mg/L as HCO_3^-	Ca mg/L	Mg mg/L	Fe mg/L	Na mg/L	K mg/L	Mn mg/L	Si mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
Ladies'	LDY-SP01	09/17/2004	22.5	300	6.82	161.53	53.4	5.22	<0.1	5.25	1.12	<0.1	4.76	12.50	2.5	0.24
	LDY-SP02	10/25/2004	22.0	363	6.88	184.95	47.2	4.83	<0.1	4.15	0.85	<0.1	4.52	13.69		
	LDY-SP03	11/29/2004	22.0	271	6.89	140.30	54.9	5.63	<0.1	4.76	1.05	<0.1	5.08	15.37		
	LDY-SP04	12/30/2004	22.0	279	6.84	128.59	38.7	4.34	<0.1	3.42	0.78	<0.1	3.82	10.87		
	LDY-SP05	02/04/2005	22.0	283	6.51	148.11	48.7	4.21		3.92	0.8		4.51	14.30	3.3	0.04
	LDY-SP06	03/14/2005	22.3	276	6.49	157.14	48.1	4.78					4.46	15.76	3.31	
	LDY-SP07	04/14/2005	22.3	279	6.46	139.81	48.1	4.67					4.29	16.30	2.92	
Stotler	STR-MW1/2		16.5	945		n/a										
	STR-MW02	10/25/2004	14.0	902	7.14	450.42	118.3	37.44	0.13	16.12	0.89	<0.1	3.59	49.88		
	STR-MW03	11/29/2004	11.7	779	7.31	420.90	109.8	30.53	0.16	15.89	0.90	<0.1	3.52	29.51		
	STR-MW04	12/30/2004	11.3	812	7.30	437.25	111.1	36.29	0.13	19.85	0.92	<0.1	3.72	39.87		
	STR-MW06	03/14/2005	14.4	894	6.86	478.73	127.4	37.40					3.51	48.77	42.10	
	STR-MW07	04/14/2005	14.4	835	6.86	456.77	112.2	38.80					3.37	40.44	36.00	
Mountainside	MTN-SP01	09/17/2004	13.3	51	5.02	36.60	3.31	2.13	<0.1	0.79	0.89	<0.1	2.84	8.76	1.41	0.58
	MTN-SP02	10/25/2004	12.5	55	5.11	0.00	2.90	1.98	<0.1	2.08	0.73	<0.1	2.38	7.40		
	MTN-SP03	11/29/2004	12.4	55	5.08	0.73	3.45	2.58	<0.1	0.62	0.86	<0.1	2.68	10.16		
	MTN-SP04	12/30/2004	11.8	56	4.99	4.64	3.71	2.72	0.16	0.75	1.01	<0.1	3.13	9.83		
	MTN-SP05	02/04/2005	11.5	46	4.45	0.12	2.96	2.16		0.68	0.78		3.05	9.30	1.49	0.33
	MTN-SP06	03/14/2005	11.1	69	4.56	0.15	3.38	2.26					2.50	12.19	1.87	
	MTN-SP07	04/14/2005	10.9	48	4.37	3.00	3.31	2.22					2.55	12.04	1.96	
Neely	NEY-SP01	09/17/2004	12.3	365	7.16	186.90	56.1	9.37	<0.1	2.49	1.06	<0.1	3.46	6.98	5.02	0.12
	NEY-SP02	10/25/2004	12.4	343	7.19	178.61	40.6	7.39	<0.1	1.82	0.79	<0.1	2.68	4.16		
	NEY-SP03	11/29/2004	12.0	154	6.65	78.81	21.2	4.50	<0.1	2.92	1.05	<0.1	2.83	8.45		
	NEY-SP04	12/30/2004	11.0	211	6.99	120.29	33.3	6.30	<0.1	1.66	0.88	<0.1	2.99	6.56		
	NEY-SP05	02/05/2005	10.7	240	6.67	209.11	44.9	6.97		1.97	0.87		3.57	5.84	4.24	0.25
	NEY-SP06	03/14/2005	10.2	232	6.64	124.68	38.5	6.51					2.89	7.40	5.08	
	NEY-SP07	04/14/2005	10.8	221	6.49	110.29	35.1	6.19					2.97	8.63	5.14	
Webber	WEB-SP01	09/17/2004	13.6	317	7.15	221.80	62.5	9.41	<0.1	2.58	0.62	<0.1	3.4	6.47	6.09	0.22
	WEB-SP02	10/25/2004	12.5	452	7.33	219.84	76.1	12.91	<0.1	3.49	0.68	<0.1	4.38	4.67		
	WEB-SP03	11/29/2004	12.5	338	7.24	241.56	60.3	10.14	<0.1	2.23	0.55	<0.1	3.53	2.04		
	WEB-SP04	12/30/2004	10.6	363	7.26	231.80	58.7	10.16	<0.1	2.51	0.59	<0.1	3.55	3.57		
	WEB-SP05	02/05/2005	12.2	354	6.99	270.35	71.9	10.74		2.35	0.6		4.42	3.54	6.34	0.2
	WEB-SP06	03/14/2005	12.4	347	6.96	242.05	64.2	9.49					3.46	3.77	6.32	
	WEB-SP07	04/14/2005	12.4	353	6.96	251.32	63.1	8.54					3.48	4.43	6.14	
Myers	MYR-MW1/2	07/09/2004	20.7	319		n/a										
	MYR-MW02	10/25/2004	15.0	273	6.08	80.03	32.0	4.83	0.13	3.45	3.90	<0.1	2.81	23.10		
	MYR-MW03	11/29/2004	11.5	282	5.87	86.01	31.8	4.79	<0.1	2.70	3.66	<0.1	2.32	24.51		
	MYR-MW04	12/30/2004	7.9	237	6.02	43.92	29.6	4.42	2.65	2.20	3.58	<0.1	2.39	29.57		
	MYR-MW05	02/05/2005	6.9	286	6.19	158.84	51.7	7.51		3.13	2.33		3.41	16.00	8.41	3.57
	MYR-MW06	03/14/2005	5.5	253	5.83	84.91	39.9	5.18					2.41	32.35	22.40	
	MYR-MW07	04/14/2005	12.3	252	5.86	72.71	37.0	5.05					2.33	32.35	5.54	
Bilezikian	BZK-MW1/2	06/15/2004	23.0	264		n/a										
	BZK-MW02	10/25/2004	13.8	557	7.31	266.45	67.1	12.06	0.20	23.4	<0.1	<0.1	3.86	4.58		
	BZK-MW03	11/29/2004	9.4	539	7.33	255.96	70.8	13.41	0.41	17.61	0.74	<0.1	3.25	2.40		
	BZK-MW04	12/30/2004	6.3	484	7.16	245.46	73.5	14.23	0.32	19.58	0.90	<0.1	3.59	2.76		
	BZK-MW05	02/05/2005	7.2	477	7.13	311.83	85.7	13.57		15.5	0.71		4.16	3.30	32.7	0.54
	BZK-MW06	03/14/2005	4.1	484	7.03	259.13	78.6	14.30					3.38	4.34	38.80	
	BZK-MW07	04/14/2005	14.4	494	7.06	237.90	76.8	13.78					3.40	3.98	34.70	
High	HGH-SP01	09/17/2004	12.1	46	5.00	12.20	2.75	1.56	<0.1	0.49	0.83	<0.1	2.23	9.39	1.17	0.69
	HGH-SP02	10/25/2004	12.1	52	5.08	0.73	2.65	1.76	<0.1	0.44	0.68	<0.1	2.17	9.89		
	HGH-SP03	11/29/2004	12.3	42	4.58	0.00	2.82	1.50	<0.1	0.41	0.77	0.13	2.53	10.78		
	HGH-SP04	12/30/2004	12.0	41	4.74	1.95	2.70	1.70	<0.1	0.38	0.75	0.10	2.43	10.25		
	HGH-SP05	02/05/2005	11.9	32	4.15	10.05	16.88	1.73		0.54	0.7		2.54	10.00	0.93	0.47
	HGH-SP07	04/13/2005	11.7	43	3.97	0.00	2.67	1.39					1.95	11.98	1.27	
Yost	YST-MW1/2	07/08/2004	13.3	211		n/a										
	YST-MW01	09/17/2004	16.3	206	6.57	117.00	40.29	1.84	0.82	0.58	0.47	<0.1	3.15	8.23	<1.00	<0.02
	YST-MW02	10/25/2004	17.0	249	6.76	118.83	41.88	2.06	3.81	0.51	0.62	<0.1	3.45	5.66		
	YST-MW03	11/29/2004	16.9	200	6.69	122.85	40.00	2.06	2.68	1.56	0.45	<0.1	3.61	3.77		
	YST-MW04	12/30/2004	13.1	188	6.56	87.60	40.71	2.21	0.20	0.93	0.96	<0.1	4.29	6.11		
	YST-MW05	02/05/2005	12.2	188	6.25	160.06	54.8	2.1		0.68	0.47		4.5	5.07	0.64	0.01
	YST-MW07	04/13/2005	11.8	184	6.40	101.75	39.40	1.73					3.06	6.29	0.81	
Cacapon State	CSP-SP01	09/17/2004	13.6	297	6.85	226.19	48.27	5.55	<0.1	1.11	0.73	<0.1	3.83	8.54	1.22	0.08
	CSP-SP02	10/25/2004	12.1	358	7.17	200.57	57.21	7.11	<0.1	1.08	0.55	<0.1	3.99	5.24		
	CSP-SP03	11/29/2004	11.9	278	7.12	190.81	50.84	6.31	<0.1	0.99	2.55	<0.1	3.70	4.73		
	CSP-SP04	12/30/2004	11.8	324	7.11	189.83	51.53	6.52	<0.1	0.97	0.54	<0.1	3.88	4.73		
	CSP-SP05	02/05/2005	11.7	294	6.87	269.86	78.62	8.54		1.39	0.64		5.81	5.17	1.3	0.05
	CSP-SP06	03/14/2005	11.7	318	6.61	182.27	60.80	6.98					4.13	6.38	1.48	
	CSP-SP07	04/14/2005	11.8	312	6.79	211.55	60.40	7.03					4.09	7.13	1.37	

Table 4. Results of water chemical analyes for spring sampling locations.

Location	type	Temp. °C	SC mS/cm	pH	Alk. mg/L as HCO_3^-	Ca mg/L	Mg mg/L	Fe mg/L	Na mg/L	K mg/L	Mn mg/L	Si mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
CLASTIC SOURCE															
Mountainside	spring	11.9	54.3	4.8	6.5	3.3	2.3	<.1	1.0	0.9	<.1	2.7	10.0	1.7	0.5
High	spring	12.0	42.7	4.6	4.2	5.1	1.6	<.1	0.5	0.7	<.1	2.3	10.4	1.1	0.6
Yost	well	14.4	203.7	6.5	118.0	42.8	2.0	1.88	0.9	0.6	<.1	3.7	5.9	0.7	0.0
CARBONATE SOURCE															
Stotler	well	13.7	861.2	7.1	448.8	115.8	36.1	0.14	17.3	0.9	<.1	3.5	41.7	39.1	
Bilezikian	well	11.2	471.3	7.2	262.8	75.4	13.6	0.31	19.0	0.8	<.1	3.6	3.6	35.4	0.5
Webber	spring	12.3	360.6	7.1	239.8	65.2	10.2	<.1	2.6	0.6	<.1	3.7	4.1	6.2	0.2
Cacapon State	spring	12.1	311.6	6.9	210.2	58.2	6.9	<.1	1.1	1.0	<.1	4.2	6.0	1.3	0.1
Ladies' Spring	spring	22.2	293.0	6.7	151.5	48.4	4.8	<.1	4.3	0.9	<.1	4.5	14.1	3.0	0.1
Neely	spring	11.3	252.3	6.8	144.1	38.5	6.7	<.1	2.2	0.9	<.1	3.1	6.9	4.8	0.2
Myers	well	11.4	271.7	6.0	87.7	37.0	5.3	0.93	2.9	3.4	<.1	2.6	26.3	12.1	3.6

Table 5. Time-averaged chemistry from spring sampling locations, organized according to geological source of springs .

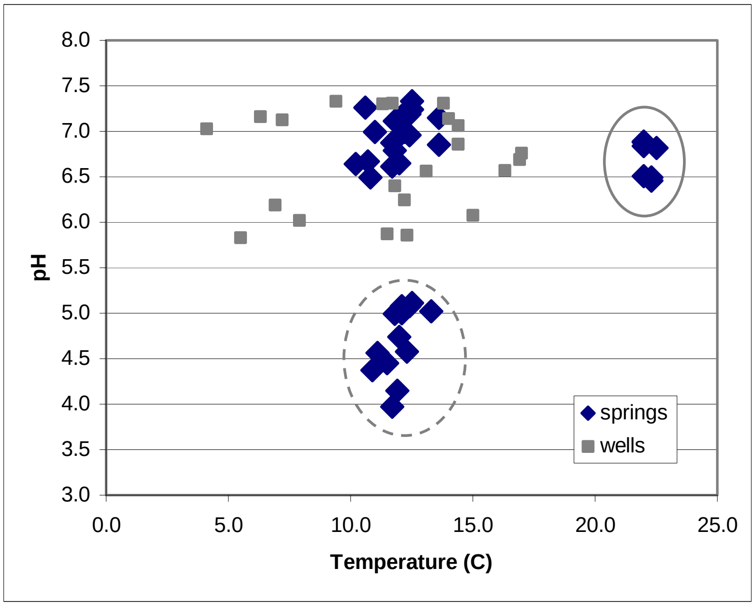


Figure 10. pH vs tempe rature for spring and well waters, including Ladies' Spring (solid circle) and HGH/MTN springs (dashed circle).

73ºF). In general, pH and temperature showed little variance within the clastic and carbonate categories, just difference between them (Figure 10).

Calcium (Ca) is a good indicator of carbonate rock or calcite cement dissolution. Springs from sandstones have low Ca concentrations and low pH (Figure 11, left-hand cluster; Figure 12). The Ca concentrations at Ladies Spring were similar to the median of the Cold Run Valley carbonate springs. Tonoloway Spring (TNW), located near Rock Gap, and the Stotler well, about halfway between Coolfont and Route 9, had the highest Ca concentrations (106-130 mg/L) of the sampled waters.

Silicon (Si) was examined as a possible geothermometer for estimating the depth of water circulation for Berkeley Springs. Quartz solubility is a direct function of temperature, but its reprecipitation is slow, and in thermal springs, dissolved silica may persist at higher concentrations than that expected from discharge temperature. However, the Si concentrations at Ladies Spring were no greater than those measured throughout the study area, suggesting that, if Si had once been elevated in this water, it had re-equilibrated at lower temperature during ascent. Thus Si is not useful for estimating depth of fluid circulation.

The Ca/Mg molar ratio indicates if the water has interacted with calcite, dolomite, or both. Water that has flowed only through dolomite [$CaMg(CO_3)_2$] generally has a Ca/Mg molar ratio of approximately 1, while water that has flowed through calcite (limestone) has much higher ratios. The Ca/Mg molar ratio for waters in this study were between 3 and 8 (Figure 13), suggesting a dominant calcite source but with minor dolomite exposure. The molar ratio for Ladies Spring is somewhat higher than measured at all other springs.

P_{CO2} (carbon dioxide partial pressure, expressed in units of atmospheric CO_2 partial pressures) and SI_C (saturation index with respect to calcite) are plotted against each other in Figure 14. Because calcite is sparingly soluble, the longer water resides in a limestone aquifer, the closer the water approaches equilibrium. Most carbonate spring waters are slightly undersaturated because the rate of calcite dissolution decreases at it nears the saturation concentration. This was observed in springs and wells of this study (Figure 14).

P_{CO2} indicates the influence of the soil zone on the ground water. All of the springs and wells in this study have P_{CO2} values far in excess of atmospheric concentrations (Figure 14).

The P_{CO2} and SI_C trend appears semi-continuous, from strongly undersaturated values (values to right and below, from both wells and springs in the clastic formations) to values approaching and even exceeding (for the Stotler well) saturation (SI_c=0.0) at the top of the plot. The cluster at left is composed of the waters from carbonate springs and wells. This trend is thought to define a continuum from strongly-undersaturated waters of the clastic rocks (little calcite available), through waters with minor to major amounts of carbonate dissolution at their prevailing CO_2 pressure. Waters with SI_c=0 are completely at equilibrium and can dissolve no additional calcite without some increase in CO_2 pressure. Thus many spring and well waters have a relatively

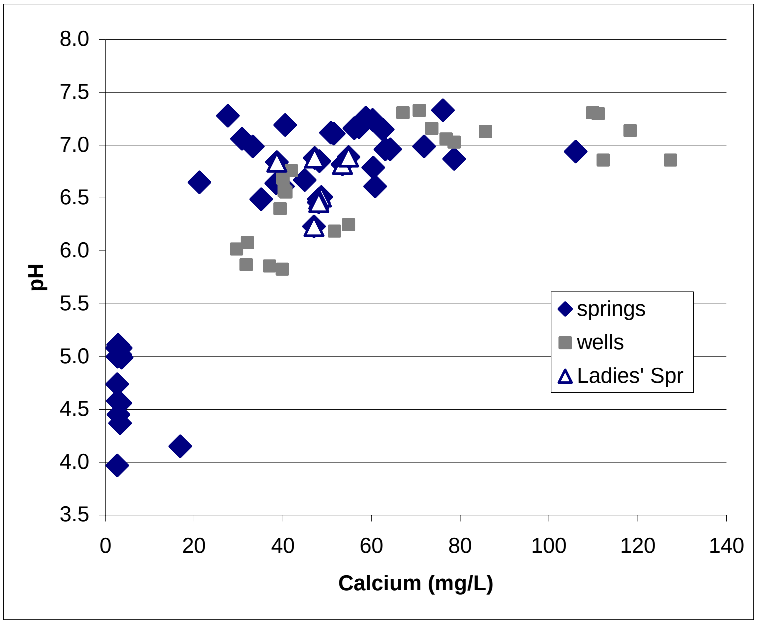


Figure 11. Calcium vs pH in spring and well waters.

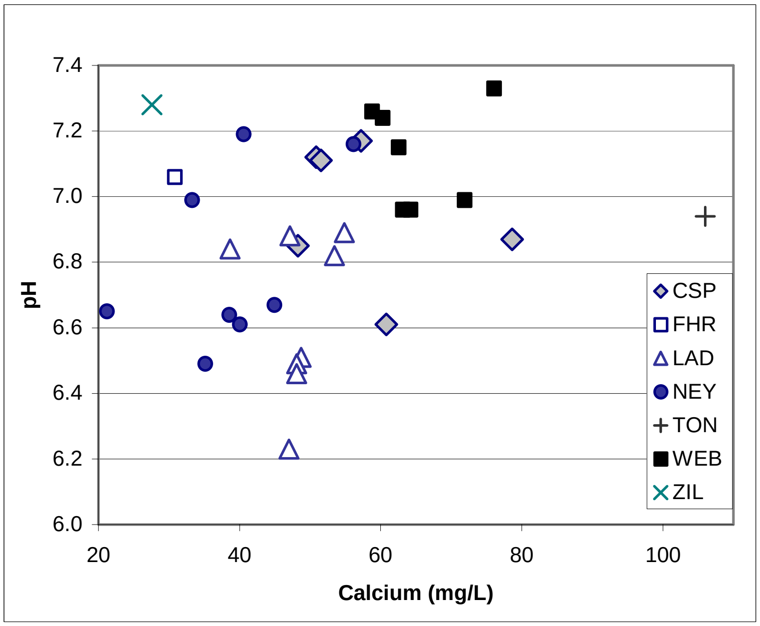


Figure 12. Calcium vs pH as for Figure 11, but at larger scale to show only carbonate springs.

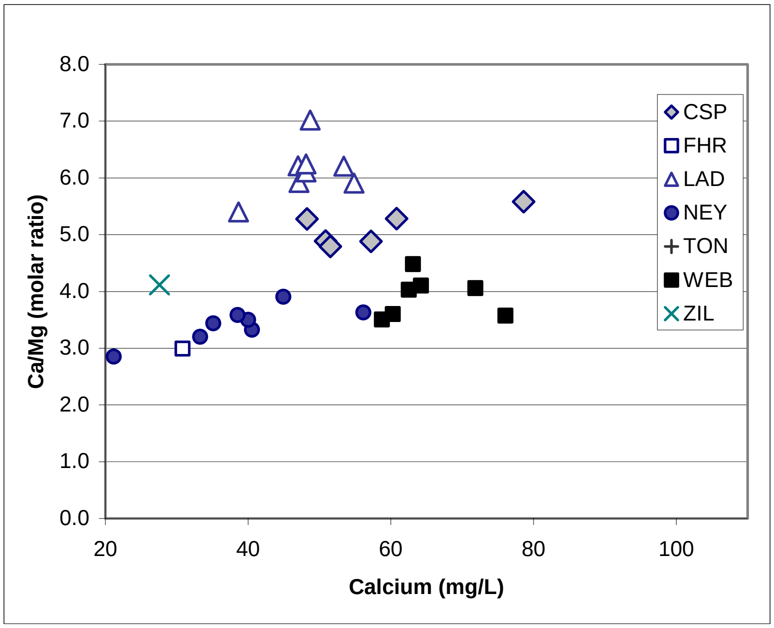


Figure 13. Calcium vs Ca/Mg molar ratio for carbonate springs in Cold Run Valley plus Ladies Spring.

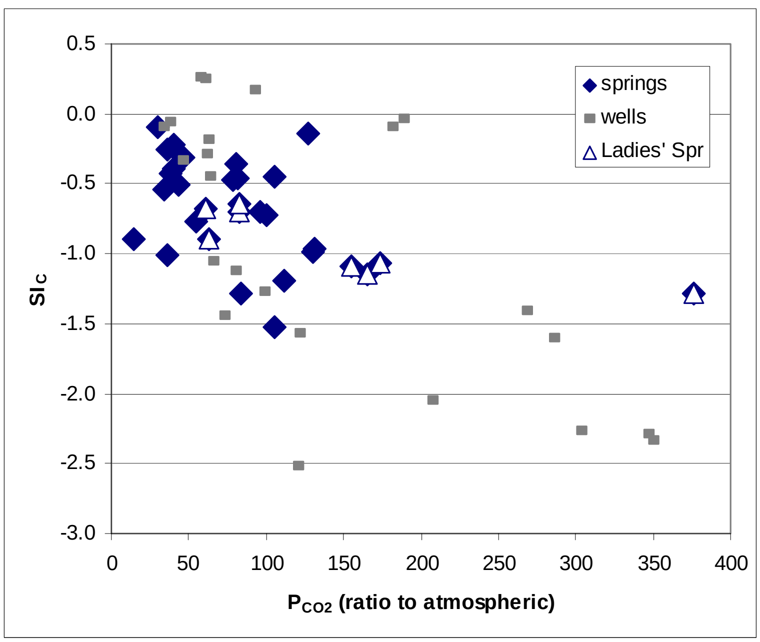


Figure 14. P_{CO2} and SI_C for waters from springs and wells.

mature water chemistry suggesting relatively long residence times within the aquifer, sufficient to attain equilibrium withn calcite.

Figure 15 shows Ca and Mg concentration time series for several springs. WEB – also the lowest in flow at about 5 gpm – generally showed the highest concentrations for both ions. The lowest concentrations were observed at NLY for Ca and at LAD for Mg. NLY and WEB appear to have the most temporally-variable water chemistry. These springs are located close to each other in Cold Run Valley and are believed to issue from the Tonoloway limestone.

The pattern of seasonal covariation in Ca (Figure 15) is rather similar between LAD, NEY, and WEB springs. It is less similar between these and CSP, which shows a more pronounced Ca "spike" in late winter 2005. CSP lies much farther south from the others and in another flow compartment of the Cacapon Mountain aquifer. The CSP "spike" is also observed for Mg. The Mg data otherwise show much weaker correlation between springs.

<u>Springflow variations over time</u>

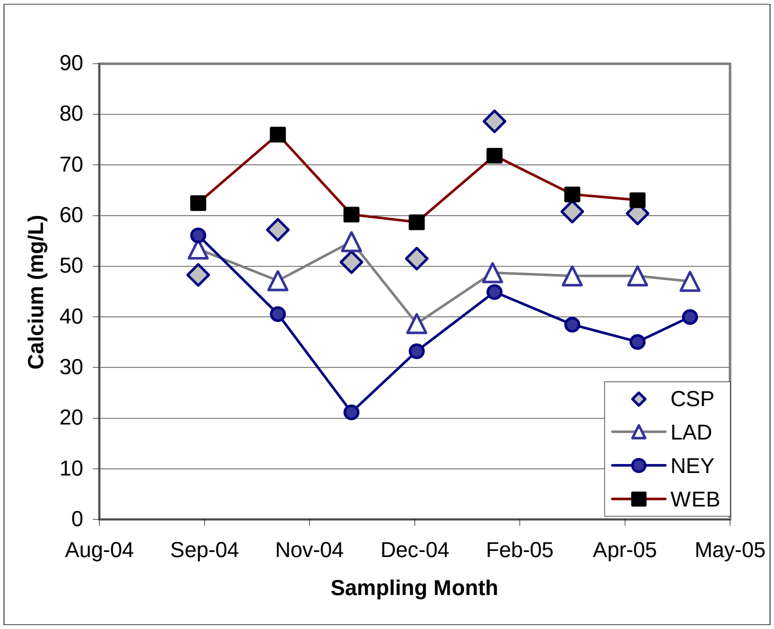
Figure 16, 17, and 18 represent the rated flow data for Ridge (RID), Tonoloway (TON), and Ladies (LAD) springs, respectively. These were created by cross-correlation between the hydraulic head variations in the pools of each monitoring location and periodic flow measurements using bucket and stopwatch (TON) or open-channel flow meter with a pygmy sensor (RID and LAD). The LAD flows were taken downstream from the LAD discharge itself and represents Ladies Spring plus Lord Fairfax Spring, plus any distributed seepage inflow that occurs along the main spring channel in the state park. It does not include Gentlemans Spring flow or that of the Bathhouse Spring pipe that discharges directly into Warm Springs Run.

The Ridge discharge (Figure 16) is composed of the combined discharge from several springs upstream at most times of the year. The narrow time span of the two storms in early July 2005 represent an estimate of time of less than one day for storm runoff from Cacapon Mountain to reach the gage. The springflow peaks in response to winter storms, on the other hand, in November 2005 to February 2006 are broader and show up to a weeks recessional limb. This is due to several factors, including the lack of evapotranspiration in winter as well as to the impact of snow on recharge and infiltration rates. In summer months, recharge appears to be much less effective, and flows continue a gradual decline, until mid-September, when all discharge was diverted by the operator into the flow bypass and the gage becomes inoperative as water ceases to flow over the weir except during storm events. Flow returned to the weir in early December, and throughout winter months recharge increased flows reaching the aquifer, until early February when precipitation nearly ceased. The declining-flow trend in February and March reflects how low flows had become in a fairly dry antecedent summer and fall. The highest flows observed in the period of monitoring were about 4.4 cfs. The lowest were about 0.6 cfs. In September 2004, a discharge of 11.2 cfs was measured at the same site. The period of monitoring record shown in Figure 16 may be a good example of a drought-year condition at this Breakneck Run site.

The Tonoloway Spring discharge (Figure 17) is shown plotted along with Martinsburg daily precipitation (top) and with Tonoloway Spring specific conductance (bottom). The downward deflections in the flow data are periods when a water truck was filled from the storage reservoir where the stage readings are made, causing a temporary (<4 hour) drop in reservoir level. The paucity of recharge "spikes" between May and September reinforces that only one intense summer rainstorm (July 8) generated detectable recharge. Starting in late fall however, a series of recharge events developed recharge and more than tripled the flow from its low-flow value of 13 gpm. As for Ridge, the entire range of monitored flows (12-80 gpm) were less than the single measurement (99 gpm) measured in March 2005 prior to initiation of monitoring; this is a low-flow season for flow at this spring.

The cross-correlation between flow and specific conductions (Figure 17, bottom) is inverse; that is, during recharge events, aquifer water is diluted instantaneously by 20-25%. This may be induced by a nearby sinkhole supplying quickflow recharge, or could represent rapid drainage of recharge via a conduit that supplies the spring. The location of this spring closely corresponds to a topographic low, oriented parallel to strike, at its intersection with another topographic depression, oriented perpendicular to flow (Figure 19). It is interpreted that the strike-parallel depression is a limestone bed – perhaps the Helderberg – in which a continuous conduit network exists. The intersection between this bed and the strike-normal depression – interpreted as a fracture zone – provides effective rationale for why this fairly large spring occurs in this location. The strike-normal fracture is one of a set of approximately 25 cross-valley fractures that may be observed on aerial photos or, as in this case, simply on topographic maps/DEMs. The spacing between adjacent fractures in this locality is from 250-350 meters.

Figure 18 shows the flows for Ladies + Lord Fairfax springs, plotted along with the Tonoloway Spring water level fluctuations. These data are quite noisy, due in part to the nature of the spring enclosure and in part to the frequent withdrawals from the spring box itself. As a result, some of the "low flows" are erroneous artifacts of water abstraction. Discharge varied from less than one cfs to slightly over 4 cfs during the early spring of 2005. As at the other two locations, the period from summer 2005 to spring 2006 was relatively dry and showed a steady decline in flow, with winter-spring of 2006 showing flows about one half those of the previous year. There is limited obvious correlation between recharge events at Tonoloway Spring and those at Ladies Spring, in part due to the high noise level at Ladies Spring. These data indicate that Ladies Spring does appear to be responding sensitively to the drought conditions in 2005-06 and on a similar timeframe to that observed in Cold Run Valley. Continued observation would be needed to determine the extent of correlation.



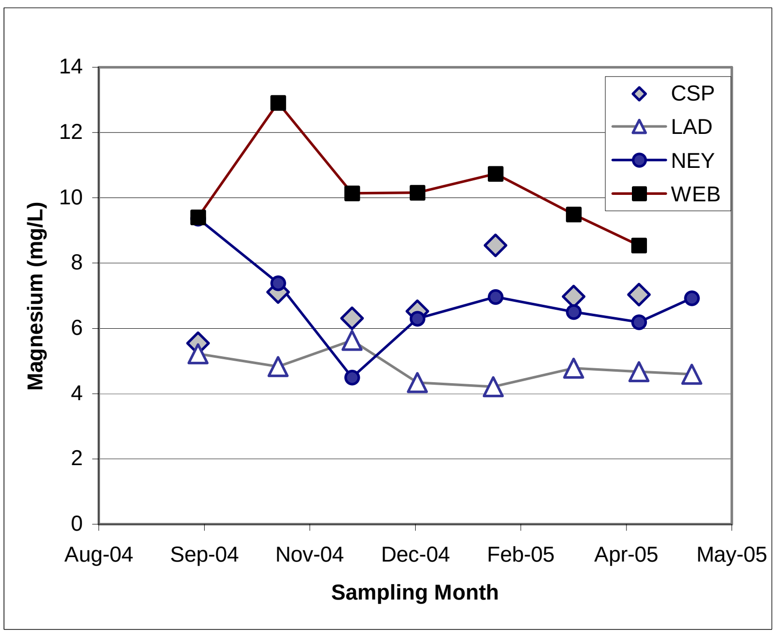


Figure 15. Calcium (a) and magnesium (b) concentration time series for selected carbonate spring waters.

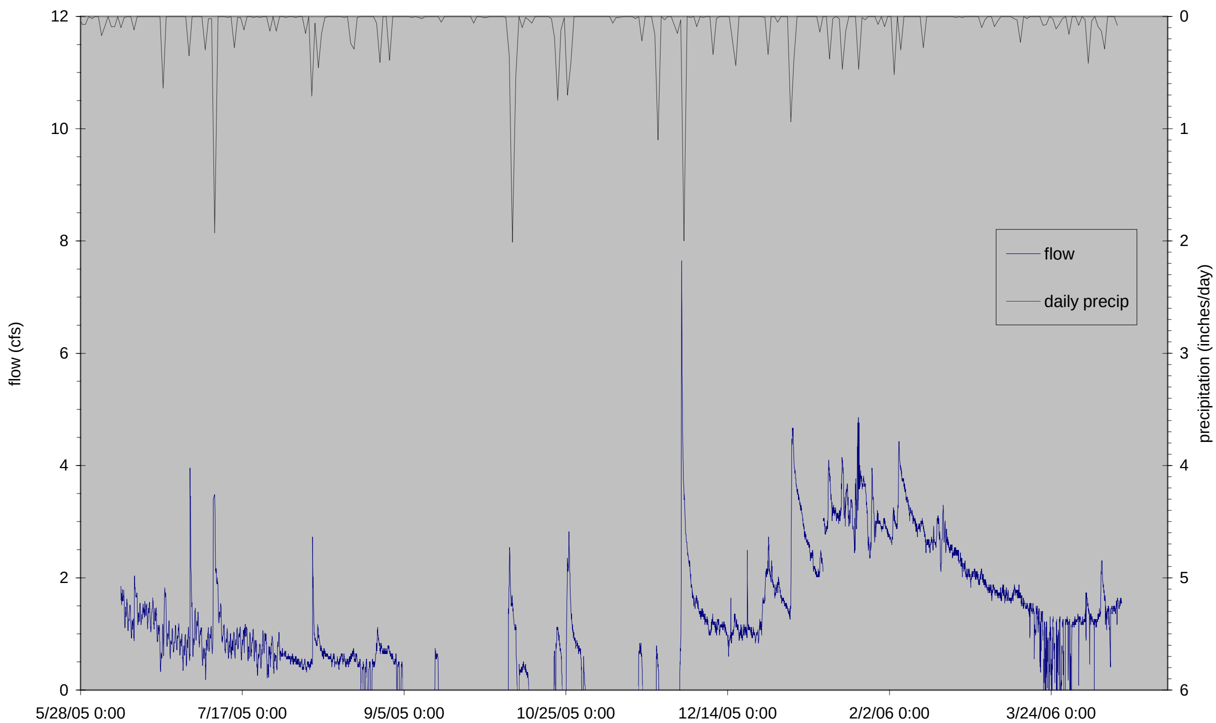


Figure 16. Springflow time series for Ridge, measured at the WVDNR impoundment at Breakneck Run. Also plotted are daily precipitation for the Martinsburg, WV NWS station.

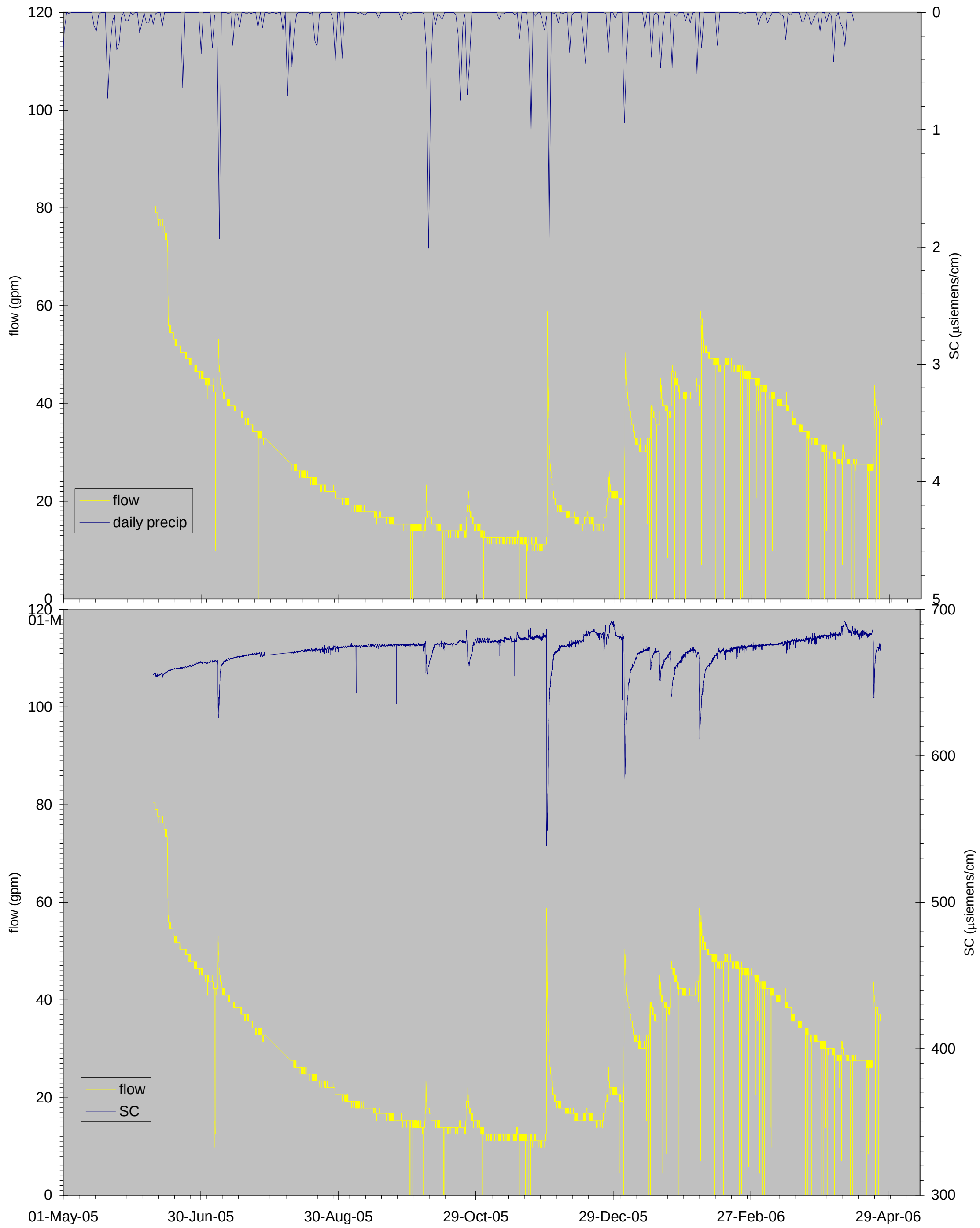


Figure 17. Springflow time series for Tonoloway Spring (top) flow and daily precipitation, (b) flow and specific conductance.

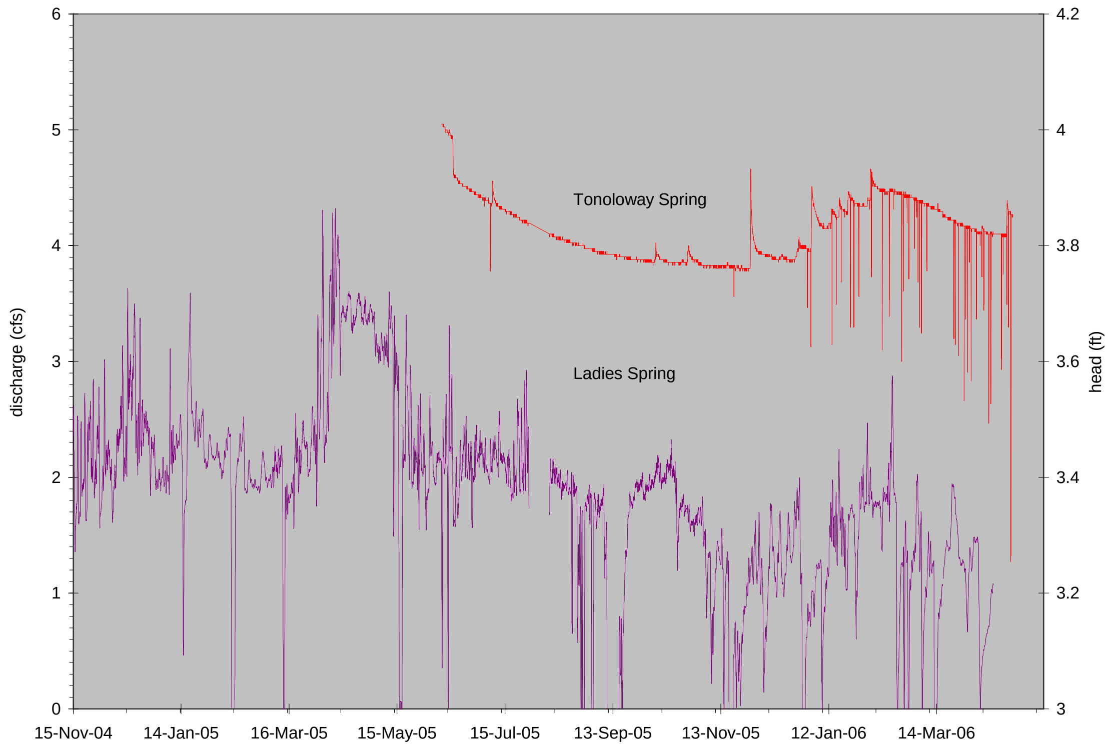


Figure 18. Springflow time series for Ladies Spring plus Lord Fairfax Spring (bottom line) plotted versus head variations at Tonoloway Spring (top line).

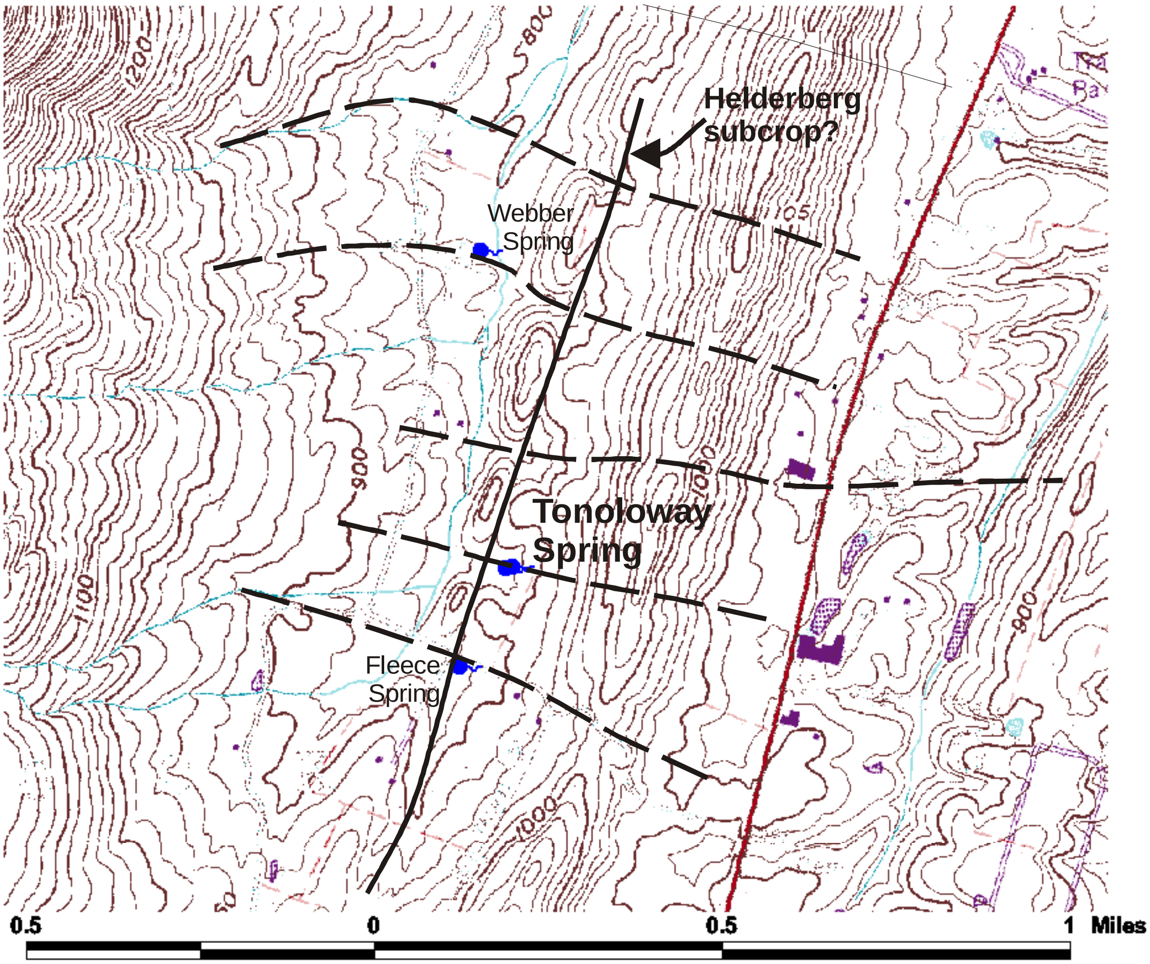


Figure 19. 1:24,000 topographic map of the landscape surrounding Tonoloway Spring, Cold Run Valley. Indicated are the suspected location of the Helderberg limestone and of cross-strike fracture zones.

SUMMARY AND CONCLUSIONS

Hydrogeology

The Cacapon Mountain aquifer appears to be a productive aquifer with an appreciable rate of recharge captured from the eastern side of Cacapon Mountain. The most transmissive portion of the aquifer, based on spring occurrence, appears to be the Devonian-Silurian carbonate sequence (Helderberg-Tonoloway-Wills Creek), which are the source of multiple springs throughout the valley. At least one spring in the Helderberg (Tonoloway Spring) appears to host conduit flow, resulting in very dramatic increases in flow and decreases in specific conductance immediately following recharge events. It also hosts sinkholes and at least one cave (Ridge Cave) that is an ephemeral, sometimes large discharge.

Based on locations of discharges and on potentiometric data from measured water levels in wells, the flow regime may be broken into four sub-basins, thought to be controlled by the location of water gaps in Warm Springs Ridge. The steeply-dipping Oriskany sandstone appears to act as a lateral confining bed, forcing groundwater flow to the north (parallel to strike) in the northern part of the valley (Sir Johns Run) where no breaks in the Oriskany occur. In the south, the Oriskany water gaps allow drainage of surface and ground water out of the valley, and the net direction of flow is to the southeast, into Sleepy Creek watershed. Thus groundwater may flow either across strike or parallel to strike, according to the local nature of Warm Springs Ridge. Competing water users include residential households, Cacapon State Park, the WVDNR fish hatchery at Ridge, a water bottling operation near Rock Gap, and Coolfont. Consumptive use for household water is relatively small as most homes have sanitary field subsurface waste disposal that returns flow to the aquifer. However, the nutrient loadings associated with this use may influence future groundwater development strategy.

Groundwater yield was not estimated in the current study. Flow rate of groundwater was monitored continuously at 2 springs and 1 surface-water location containing dominantly groundwater discharge. These observations indicated that flow was below long-term norms in most of the period of measurement in 2005-06. Flows in all locations declined in summer and fall months and increased during periods of winter recharge.

Seepage run measurements along Sir Johns Run show that it gains nearly continuously along its entire reach, due to groundwater inflow from both spring and diffuse sources. During the experiment its maximum flow at its mouth was 6.6 cfs, but its flow varies both upward and downward from this figure. Its long-term average flow is currently unknown, but is undoubtedly the largest single surface-water discharge to emerge from Cold Run Valley.

Aqueous chemistry

In general, the springs in this study can be readily divided into two groups based on water chemistry:

- sandstone springs (low pH and Ca), and

- carbonate springs (neutral pH, higher Ca, and normal ground water temperatures)

The springs in the first group include HGH and MTN and flow from the Tuscarora sandstone or nearby. The carbonate springs are located in Cold Run Valley (WEB, NLY) or near water gaps (TON, CSP). Ziler spring, located west of Cacapon Mountain, generally also has the chemistry of a carbonate spring although the concentrations of Ca nd Mg are generally lower than found at the other locations. Ladies Spring (LAD) at Berkeley Springs State Park has water chemistry quite similar to the other carbonate springs, particularly Neeley spring, but a slightly-elevated temperature indicating a deeper, and possible longer-duration, flow path. These geochemical data support that the upper valley limestones may be the source of water for this spring, although this evidence is not conclusive.

The maturity of groundwater chemistry may be expressed in terms of saturation index for calcite. Clastic-source springs have very low pH and negative saturation indices. The saturation indices for carbonate springs are high, ranging from near zero (equilibrium) to –1.5, about a factor of 30 undersaturated. This suggests there may be variations of contact time between carbonate materials and infiltrating recharge, due to either variations in flowpath length or to the hydraulic conductivity of rock units. The most mature groundwaters are at near equilibrium, saturated with the mineral calcite.

Variations in water chemistry of surface water in Sir John's Run occur only in its headwaters, where flows are low. This is ascribed to the duality in chemistry of the clastic vs. carbonate springs, and the fact that contributions come from each. Farther downstream, water chemistry is very uniform, buffered against change due to the substantial discharge of bicarbonate-rich groundwater already in the stream. The net chemistry of this water is undoubtedly the result of sume mixture of carbonate and clastic spring discharge plus diffuse seepage to the stream. Sir Johns Run is sustained largely by groundwater and its flow could potentially be impounded as a high-quality water source.

<u>Hydrogeology of springs in the Town of Bath</u>

Most of the groundwater in Cold Run Valley, excepting that associated with Sir Johns Run downstream from Route 9 to the Potomac, lies at higher hydraulic head than the springs at Bath (elevation 615 feet). This applies to the entire catchments of Rock Gap Run, Indian Creek, and Breakneck Run west of the Oriskany outcrop. Even these streams themselves are at heads of 760, 860, and 880 feet respectively within their water gaps. Therefore, the potential exists for a fairly substantial area of vertical leakage downward to great depth, then upward to Berkeley Springs. Such a circulation system would require a flow pathway to the surface via a fracture zone or fault through the Oriskany, which are known to exist near Berkeley Springs. High-angle reverse faults of the style shown Figure 2 would be capable of offering such a flow pathway.

The inorganic chemistry of water from Ladies Spring is virtually identical to several of the springs sampled in Cold Run Valley. This is not conclusive evidence that their source water is the same; carbonate groundwaters evolve to similar chemistries in different aquifers. It is, however, evidence that the discharge at Ladies Spring is consistent with the possibility of deep artesian underflow from Helderberg limestone water to the surface through fractures in overlying sandstone.

No data presented here are conclusive proof that the water source for Berkeley Springs lies in the Cacapon Mountain aquifer. However, these data do present that sufficient hydraulic head appears to be available in the Helderberg limestone to offer between 50-250 feet of driving force for such vertical flow. The chemistry observed is not inconsistent with the possibility, Additional light may be shed on this problem by spring geochemistry and age dating work in progress, as well as continued monitoring of response of springflows to large recharge events.

Whatever the recharge source is for the springs at Bath, it must draw upon a fairly substantial recharge area. At an average discharge of 1200 gpm, 84 million cubic feet of water per a year discharge from the springs. That is approximately one sixth of the total estimated groundwater recharge from the Cacapon Mountain aquifer from Route 9 to the WV-VA border, as estimated using rates of long-term aquifer recharge cited in this region by Kozar and Mathies (2001).

<u>Limitations of results</u>

The results of this preliminary analysis are not highly quantitative, and the sustainable yield of this aquifer remains to be defined. As for any aquifer, the ability to develop its water yield requires both adequate long-term recharge (including through drought periods) and locations in which the groundwater may be successfully extracted. Both of these remain to be proved, in detail, for the Cacapon Mountain aquifer.

REFERENCES

Cardwell, D.H., R.B. Erwin, and H.P. Woodward, 1986. *Geologic Map of West Virginia* [revised]: 1:250,000.

Davies, William E., 1965. *Caverns of West Virginia*. West Virginia Geological Survey Volume XIX (A), 402 pages.

Dean, S.L., P. Lessing, B.R. Kulander, and D.W. Hawley, 1995. *Geology of the Hancock Quadrangle, Morgan County, WV*. West Virginia Geologic and Economic Survey Open-File Report OF9503, 1:24,000 map and accompanying text/tables.

Grimsley, G. P. 1916. *Jefferson, Berkeley and Morgan counties*. West Virginia Geological Survey County Report, 644 pp.

Kozar, M.D., and Mathes, M.V., 2001, Aquifer-characteristics data for West Virginia. U.S. Geological Survey Water Resources Investigation Report 01-4036, 74 p.

Kulander, B.R., P. Lessing, S.L. Dean, and C.S. Kulander, 1995. *Geology of the Stotlers Crossroads Quadrangle, Berkeley and Morgan Counties, WV*. West Virginia Geologic and Economic Survey Open-File Report OF9504, 1:24,000 map and accompanying text/tables.

Lessing, P., S.L. Dean, B.R. Kulander, and E.A. Langenderfer, 1995, *Geology of the Big Pool Quadrangle, Berkeley and Morgan Counties, WV*. West Virginia Geologic and Economic Survey Open-File Report OF9502, 1:24,000 map and accompanying text/tables.

Minke, J. Garrett. 1964. *Geology of the Hancock and Stottlers Crossroads quadrangles in West Virginia*. Masters thesis, West Virginia University Department of Geology and Geography, 41 pp.

Stose, G. W. and C. K. Swartz. 1912. *Paw Paw-Hancock Folio*. U. S. Geological Survey, Geological Atlas No. 179, 25 pp.