Maryland Department of the Environment
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EVALUATION OF POTENTIAL HYDROLOGICAL IMPACTS AND DEVELOPMENT OF SINKHOLES CAUSED BY DEWATERING OF THE FREDERICK AND MEDFORD QUARRIES, WESTERN PIEDMONT PROVINCE, MARYLAND

by

Patrick A. Hammond

2022

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CONVERSION FACTORS AND SYMBOLS

Multiply	by	to obtain
Length		
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.59	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (l)
Discharge Rate		
gallon per minute (gpm)	3.785	liter per minute (l/min)
Production Rate		
gallon per day (gpd)	3.785×10^{-3}	cubic meter per day (m^3/d)
Transmissivity		
gallon per day per foot (gal/d-ft)	0.0124	square meter per day (m^2/d)

Annual average use gallons per day = gallons per day average (gpd avg)

Use during the month of maximum use =-gallons per day maximum (gpd max)

Use of notation: As close as possible, the original scientific or mathematical notations of any papers discussed have been retained, in case a reader wishes to review those studies

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Key Results

The **Fredrick Quarry** has a long history starting in 1801, when a lime burning business was started at the site. In 1889, M.J. Grove Lime Company purchased the property and by 1906, the company was producing 1,000,000 bushels of lime yearly. Dewatering of the quarry started between 1902 and 1906 after deepening of the pit to get a suitable working face. The first water appropriation permit (FR70S002) was issued for a surface water withdrawal in 1970. In 1986 the permitted source was changed to groundwater in the amounts of 4.0 Mgd avg and 5 Mgd max. The most recent permit was issued in 2018 to Bluegrass Materials Company LLC increasing the amounts to 10.42 Mgd avg and 16.3 Mgd max.

KCF Groundwater, Inc. (2016) prepared a report that included hydrogeologic projections for dewatering of the Frederick Quarry~~,~~ producing existing and ultimate projected water demands of 6.25 Mgal/d and 13.5 Mgal/d, respectively. The major components consisted of visually observed spring and diffuse groundwater recharge making up 90% to and 95% of the total water balance. The 2018 permit decision was based on adding the highest internal use to the highest discharge to the Monocacy River, plus 10% for large storm events, resulting in an estimated use of 9.26 Mgal/d avg in 2018. The KCF projected increased demand was added to produce an estimated maximum demand during the 12-yr permit period. Relative to actual reported use, there was a 24% error in the 2018 estimated demand in the permit decision and a 57% error in the KCF estimated demand for the same year.

The Carroll Creek watershed is underlain by about 56% carbonate rocks. The nearest comparable watersheds are the nearby Ballenger Creek (40% carbonate rocks), and Antietam Creek at Sharpsburg, Washington County (64% carbonate rocks). Carroll Creek, immediately upstream of the Frederick City WWTP, was observed to have only pooled water with no detectable flow on September 19, 2002. On the same date, unit flows measured at the USGS gage sites on Ballenger Creek and Antietam Creek were both 0.177 cfsm. At that unit flow rate, it is likely that 3.03 cfs or 1.96 Mgal/d was lost in the Carroll Creek watershed above the Frederick City WWTP. That flow would have been as comparable to the 2.3-2.5 Mgal/d withdrawn by the Frederick Quarry in August and September 2002. On 29 December 2004, flows were measured in Carroll Creek at three sites, College Avenue, Highland Street, and just above the WWTP (12.96 cfs). The unit flow at the Antietam Creek gage on that date was 0.98 cfsm. If that unit flow were applied to the drainage area above the WWTP (17.2 mi^2), the result is 16.86 cfs, indicating that 3.90 cfs or 2.5 Mgal/d were lost in that watershed, which again is comparable to the 2.7 Mgal/d pumped from the quarry in December 2004.

Some of the features that might reflect the capture zone for quarry dewatering are the sinkhole distribution and water levels measured in groundwater wells the area of the quarry and Carroll Creek. The highest concentration of sinkholes in Frederick County occur in the vicinity of the Frederick Quarry. A sinkhole zone was constructed on a map that extended from the quarry to the confluence of Carroll Creek with the Monocacy River. To the water level contour map of KCF Groundwater, Inc. was added water levels measured in test wells at the Frederick Airport, near the confluence of the two streams. The static water levels in two wells were significant because they were 15 ft to 38 ft below either Carroll Creek or the Monocacy River.

Changes caused by pumping of groundwater from the quarry and changes in drainage patterns by land development and road construction or a combination of both factors likely caused the formation of sinkholes in the study area. Newton (1981, 1987) identified 4000 sinkholes recorded in Alabama between 1900 and 1980, most which occurred after 1950, and only 50 were related to natural events. This indicates that nearly all the sinkholes formed between the quarry and Carroll Creek likely are anthropogenic.

Prior to about 1989, quarry withdrawals were determined by law and regulation to be reasonable, even if they caused nearby water supplies to go dry, had diminished yields or experienced water quality problems. That policy was based on the 1968 Finley vs Teeter Stone Company court case which concerned withdrawals for dewatering of the **Medford Quarry** causing a diminished or lost water supply and development of sinkholes on the adjacent Finley farm. Changes of the State regulations were made for water use in 1989, which adopted most of the elements of the Restatement (Second) of Torts, and in 1991 for surface mines (ZOI in karst terrain), so that quarries could be held liable for mitigation of impacts caused by dewatering activities.

Only three known sinkholes pre-dated Medford Quarry operations, that were within about 4000 feet of pit 2. Between 1980 and 1998, Carroll County Government mapped 119 sinkholes within the ZOI area, mostly between the quarry and Little Pipe Creek. Other factors often considered as causing sinkholes are land development and road construction; however. there has been no significant development in the study area and the last significant road construction occurred in 1966. In March 1994, a fatal accident occurred after a sinkhole opened in the westbound lane of MD Route 31 about 2000 ft from the quarry. In late October 1994 dye injected into the sinkhole was not recovered at the quarry. In July 1994 a major slug of the tracer injected in a sinkhole along Copps Branch, more than one mile northeast of the quarry, arrived in the spring discharge of the quarry pit within six days. Optical brightener sampling in November suggested there was a gradient or flow path from the Westminster WWTP discharging to Little Pipe Creek then to quarry pit 1. A map of water level contours from monitoring wells indicate that an anisotropic trough of depression extends from the quarry northeast to the confluence of Copps Branch and Little Pipe Creek. During the October 1994 dye trace, it is possible that there was no direct hydraulic connection between the sinkhole injection point and the primary fracture or conduit controlling flow to the quarry, but flow was diffuse and slow causing dispersion and/or absorption of the tracer.

Synoptic flow measurements were taken in the Turkeyfoot Creek watershed in July 1989 indicating that there were substantial reductions in flows in the North Stream, Danner Spring Branch and Stone Chapel Creek, all of which are within the capture zone of the quarry. An unaccounted flow of 23% was possibly water diverted from Little Pipe Creek. Chloride and Fluoride data from October 2002 indicate if there was a hydraulic connection from the WWTP discharge to Little Pipe Creek then to the quarry, with an estimated 12% and 20%. of the quarry discharge diverted from Little Pipe Creek.

A biological assessment was conducted in 2007. Proximity to roads appears to be the reason for degraded PHI conditions. The lack of fish in Danner Spring Branch and Stone Chapel Creek is probably related to lack of flow or barriers to passage related to quarry operations. It appears that stream segments with low BIBI indices may have been due to both proximity to roads and the effects of quarry dewatering. The slightly elevated pH levels at several sites likely were related to the calcareous nature of an aquifer partially feeding the streams. High nitrate levels at two sites were probably related to farming activity.

A water balance analysis was performed to determine the sources of water for dewatering operations at the quarry. Key points were that Danner Spring Branch and Stone Chapel Creek went dry, and the Northern Stream flows were reduced by about 50%, while dye trace studies indicated that there was a possible hydraulic connection between Little Pipe Creek/Copps Branch and the quarry. The results indicated that most of the water (53.4%) captured by quarry dewatering was from the spring-fed Danner Spring Branch and 96% of the total runoff within the capture zone and upstream tributaries is withdrawn by the quarry dewatering operation. The result of the water balance analysis indicates that 78% of the pumpage comes from captured runoff from the upstream tributaries, while it is likely that the remaining 22% is diverted from Little Pipe Creek. This is consistent with the 20% of chloride recovered in the quarry pit during the 2002 dye trace of Little Pipe Creek and the arrival at the quarry of a major slug of dye after injection into a Copps Branch sinkhole in 1994.

The available information on potential impacts to water wells due to dewatering of the Medford Quarry indicates that four wells in the Medford area had reported problems. Three wells were located outside of both the capture zone and the 1997 ZOI of the quarry. The remaining well, was within the ZOI and just outside of the capture zone. The owner reported a reduced yield in 1986 that was still sufficient to meet water demand. All the well problems occurred during the droughts of 1986, 1998 and 2002. The wells were drilled into a crystalline, non-carbonate rock aquifer known to produce low-yielding wells that are subject to decreased yields during droughts. Although there were no detailed investigations completed concerning impacts to individual wells, the available information indicates that droughts likely caused the reported well problems, not dewatering of the Medford Quarry.

Introduction

Limestone/Cement History

The World Cement Association (2021) provides the following account of the history of cement. As early as 12,000 years ago in Turkey a form of cement was in use, when a whitewashed floor was made from burned limestone and clay. About 800 BC, the Phoenicians made a mixture of burnt lime and volcanic ash ('pozzolana'), which was stronger and could also harden under water. The Romans developed a type of concrete made of lime with aggregates of sand and crushed rock, with which they erected massive buildings such as the Colosseum and Pantheon in Rome, and the Hagia Sophia in Istanbul. There are no written records from the Middle Ages, but mortars from that time were probably made of lime and sand.

The late 18th century Industrial Revolution in Europe saw many new developments in cement and concrete. John Smeaton discovered that the hydraulicity of lime was directly related to limestone clay content. In 1824 Joseph Aspdin developed portland cement by heating limestone and clay until the mixture calcined, grinding it, and then mixing it with water. In 1845, Isaac Johnson fired chalk and clay to much higher temperatures of about 1400-1500° C and produced what is essentially modern-day cement. The advent of reinforced concretes in 1840s France allowed construction of larger bridges, taller and larger buildings, and other innovations. Cement production and applications then surged globally at the turn of the century, which the introduction of rotary kilns that replaced the original vertical shaft kilns.

Limestone Quarries of Maryland

The first known mention of limestone as a resource in central Maryland was in a 1744 Daniel Dulaney report to Lord Baltimore indicating the Frederick Valley abounded with limestone, and stone fit for building, good slate, and some marble, which formed the basis for local industrial development that included limestone quarrying through the late 18th century, Porter (1975). Iron furnaces operated in Frederick County primarily from the 18th to the early 19th centuries which needed limestone from quarries for a flux. Industry in Frederick expanded during the 19th century that included the manufacture of lime and bone fertilizer. Merrill and Mathews (1898) notes that the earliest scientific reference to quarrying of Maryland stone was in 1811 about the production of stone on both sides of Jones Falls. There follows in 1834 the first accounts of quarrying of the " Potomac Marble " a few miles east of Hagerstown and the first mention of the marbles of Point of Rocks, Carroll County and Boonsborough. The blue and gray limestones of Paleozoic age have never been quarried in Maryland as building stones except for local use. Nearly all the stone taken out was burned to produce lime.

Early on, inefficient transportation networks limited the production of limestone; however, with the construction of railroads starting in the 1830s, that changed. The amount of natural cement produced in 1818-1830 was 300,000 barrels, but the rate rapidly increased to 11,000,000 barrels by 1850-60 and then to 45,000,000 barrels in 1880-1890, Clark (1909). This was also the period when the processes for the manufacture of portland cement and reinforced concrete were developed. By the mid-19th century, the nation had shifted from an agriculture-based economy toward manufacturing and factory-produced goods, with a subsequent increase in the population and wealth in Maryland and the United States. At the same time there was a remarkable growth of the portland cement industry and the accompanying decline in the production of natural cement. In 1870-1880, the production of natural cement was 22 million barrels, while that of portland cement was 82 thousand barrels; however, natural cement production declined to 1.7 million barrels by 1908, with portland cement increasing to 51 million barrels.

Mathews and Grasty (1910) made the first report of dewatering by a quarry. To get a suitable working face, the M.J. Grove Quarry (now Frederick Quarry) had to be deepened and upon encountering water, it had to be pumped out to prevent flooding of the quarry. The MDE Water Supply Program has electronic records of water use from 1979. There are a limited number of known paper records of water use in the state from the early 1960's, which may have been archived or destroyed. In addition, The Maryland Geological Survey (MGS) may have some other water use records.

Mathews and Grasty (1910) listed 38 active limestone quarries in Washington, Frederick, and Carroll Counties in 1909. Today, there are 13 operating quarries in those counties, 7 of which were in business in 1909. The decline of the smaller enterprises was because profitable quarrying required considerable capital investment in efficient machinery to handle large volumes of stone. In 1969, limestone production in Maryland was 9.8 million tons, most of which was crushed stone used in road construction, with minor amounts for building stone, cement production, metallurgical flux, and agricultural uses. In recent years (2000-2019), production was 19.7 – 35.3 million metric tons of crushed stone, 0.9 – 3.2 million metric tons of portland cement, and 0 – 17.3 thousand tons of building stone.

Laws and Regulations Governing Dewatering of Quarries

Outside of quarries, most of the water withdrawn in the carbonate areas of the Maryland is from surface water for public water supplies in the Hagerstown, Frederick, and Wakefield (Westminster) valleys. Prior to about 1989, quarry withdrawals were determined by law (in a 1969 court decision) and regulation to be reasonable, even if they caused nearby water supplies to go dry, had diminished yields or experienced water quality problems. The legislation requiring permits for surface mines was passed in 1975. Changes of state regulations were made for water use in 1989 and surface mines ("Zone of Influence" or ZOI in karst terrain) in 1991, so that quarries could be held liable for mitigation of impacts caused by dewatering activities. By that time, most quarries had been operating for decades, so any impacts that could have occurred may have already happened and there were probably few, if any, records available concerning such problems. Under the 1991 Amendment to Maryland's Surface Mining Law, the MDE Mining Program is required to develop ZOIs around all limestone quarries in Baltimore, Carroll, Frederick, and Washington counties. The zones are based upon local topography, watersheds, and geologic and hydrologic factors. When establishing ZOIs, MDE conducts field investigations and evaluates any available information, such as groundwater studies and well monitoring data. Upon completion in the 1990s of the ZOIs for existing quarries, The MDE Mining Program started tracking impacts to water supplies and the formation of sinkholes. This also corresponds with the approximate period when the MDE Water Supply Program upgraded its aquifer test and monitoring program in the fractured rock aquifers of Maryland.

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Acknowledgements

This study fulfills one of the objectives of a cooperative regional study, Fleming et al., 2012, (USGS Publication SIR 2012-5160) of the fractured rock areas of Maryland that involved the Maryland Department of the Environment (MDE), the Maryland Geological Survey (MGS), the U.S. Geological Survey (USGS) and the Monitoring and Non-Tidal Assessment (MANTA) division of the Maryland Department of Natural Resources (MDNR).

Geology and Hydrogeology of the Frederick and Wakefield Valleys

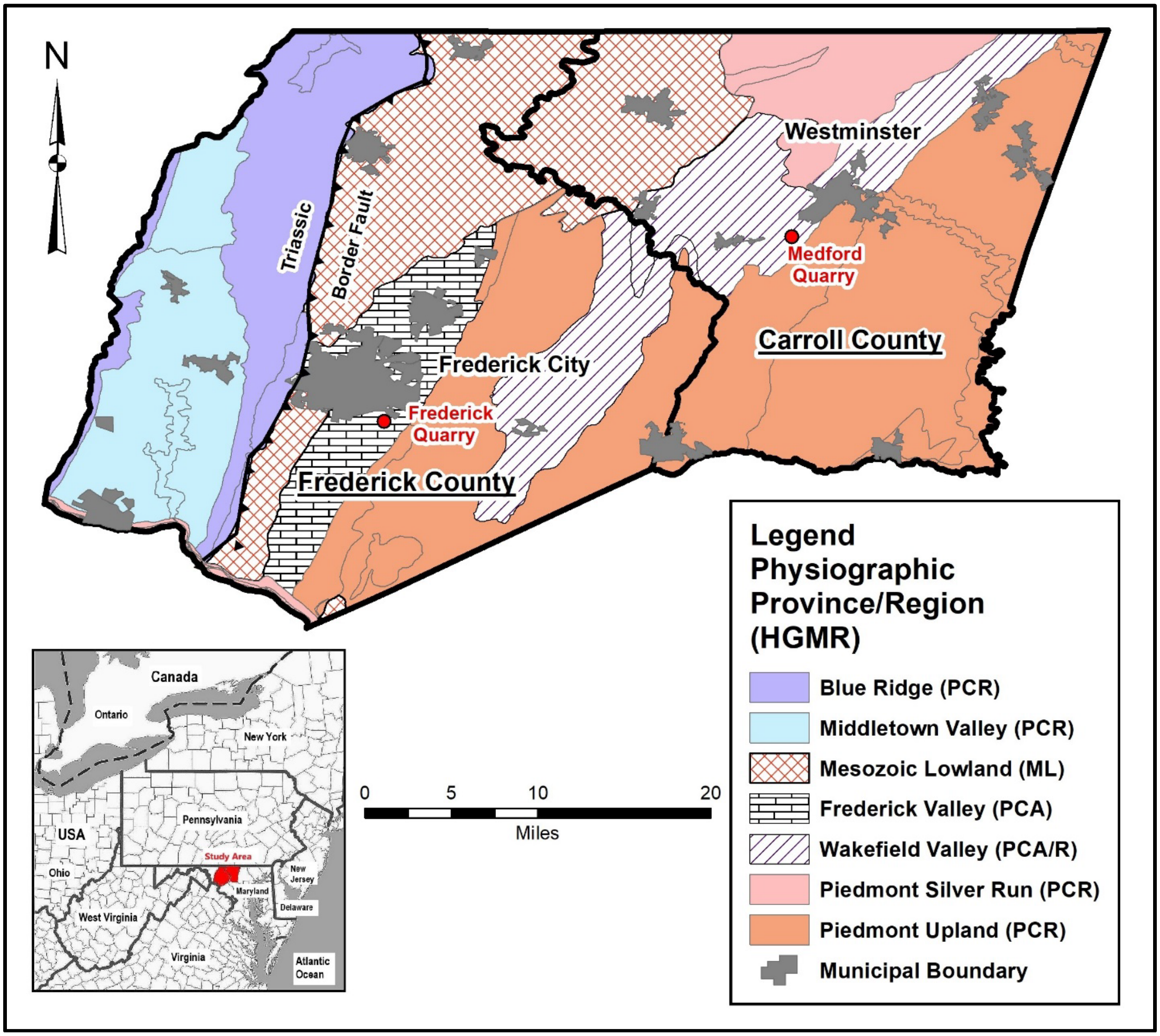

Figure 1. Physiographic and hydrogeomorphic (HGMR) regions of portions of the western Piedmont and Blue Ridge regions of Maryland. The HGMRs are the Blue Ridge (BR), Mesozoic Lowland (ML), Piedmont Carbonate (PCA) and Piedmont Crystalline (PCR) regions.

The Frederick and Medford quarries are in the Frederick and Wakefield valleys of Frederick and Carroll counties, respectively, within the western Piedmont region of Maryland. Bachman, Lindsey, Brakebill and Powers (1998) combined physiographic provinces with generalized lithology to define eleven hydrogeomorphic regions (HGMRs) for the Chesapeake Bay watershed. Figure 1 shows four HGMRs; the Piedmont Crystalline (PCR), the Piedmont Carbonate (PCA), the Mesozoic Lowland (ML), and the Blue Ridge (BR) regions. The Piedmont Carbonate HGMR (PCA) is represented by the Frederick Valley, within the Monocacy River basin, which is a folded overturned syncline that exposes soluble carbonate rocks of the Cambrian Frederick and Ordovician Grove formations. The valley is bordered on the west by the consolidated sedimentary rock Triassic New Oxford Formation (ML) and on the east by metamorphosed crystalline rocks of the Antietam Formation (PCR). The Frederick Formation is subdivided into the Monocacy, Rocky Springs Station, Adamstown, and Lime Kiln members. The Grove Formation consists of the Ceresville, Fountain Rock, and Woodsboro members. The older units were deep water deposits. As the sediments continued to accumulate, they steadily aggraded upward towards sea level until the youngest ones were deposited in shallow water. The Grove Formation was deposited in sand shoals and algal reefs that were ultimately drowned during an early Ordovician submergence. Brezinski (2004) developed a scale of karst susceptibility within the valley. The Ceresville, Woodsboro, and Fountain Rock members of the Grove Formation and the Lime Kiln Member of the Frederick Formation have very high karst susceptibility. When unlined drainage, storm-water management areas, drainage diversions, or quarries are located near these units, sinkholes are likely to occur. The Rocky Springs Station Member has a slightly lesser karst susceptibility, while the Monocacy and Adamstown members have the lowest karst susceptibility.

The Piedmont Crystalline HGMR (PCR) occurs in the eastern portion of the area, Figure 1. The two prominent formations underlying most of the area are the Marburg Schist and Ijamsville Formation. The Marburg Schist is a bluish gray to silvery green, fine-grained schist that underlies parts of Carroll, Frederick, and Montgomery counties. The Ijamsville Formation consists of blue, green, or purple phyllite and phyllitic slate and interbedded metasiltstone and metagraywacke rock. Intermingled with the Ijamsville Formation are other metavolcanic and carbonate rocks, located primarily in the Wakefield Valley, that extends from the eastern portion of Carroll County at the Pennsylvania border through Westminster into eastern Frederick County. The two primary geologic formations in the valley are the Wakefield Marble and Sams Creek Formation. The Wakefield Marble may have originated as carbonate reef rocks but was recrystallized to a white, fine-grained marble; subordinate white, green, and pink variegated marble, and blue marble, and is found southwest of Westminster. The Sams Creek Formation originated as a volcanic island built up as a pile of basaltic lava flows that was metamorphosed to massive metabasalt and chlorite schist and is located throughout the Wakefield Valley.

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Frederick Quarry Case Study

The Fredrick Quarry has a long history starting in 1801, when Jacob and Amelia Brengle started a lime burning business. Their son inherited the property in 1836, which included a quarry and lime kilns. The M.J. Grove Lime Company was founded in 1860, when M.J. Grove purchased a tract of limestone land, which became the village of Lime Kiln, and began manufacturing lime for agricultural purposes. In 1889, the company purchased the Brengle Lime Kilns property, as well as the lime kilns of Samuel Hoke, which were located at the southeast edge of the city, near present day Interstate 70 and Reich's Ford Road. The property included six lime quarries with 14 iron clad kilns for burning of the lime. In 1902, the M.J. Grove Lime Company erected a stone crushing mill at the Frederick plant to supply crushed stone for railroad ballast and hard surfaced roads. In 1905 the company entered into a road building and bridge construction business. By 1906, the company was producing 1,000,000 bushels of lime yearly. Mathews and Grasty (1909) made the first known report of dewatering by a quarry, indicating that to get a suitable working face, the M.J. Grove Quarry (now Frederick Quarry) had to be deepened and upon encountering water, it had to be pumped out to prevent flooding of the quarry. This information indicates that dewatering of the quarry likely started between 1902 and 1909.

State laws governing water use were first passed in 1933 after the extreme drought of 1930-31; however, the first known permits for dewatering of quarries were issued in the 1970s, after the severe 1962-69 drought. The first water appropriation permit (FR70S002) was issued for a surface water withdrawal from the Frederick Quarry to the M.J. Grove Company on March 20, 1970. The second permit (FR70S017) was issued to the Flintkote Stone Products Company on February 28, 1980, for 169,000 gpd avg / 338,000 gpd max. On December 1, 1986, a new permit, FR1970G035, was issued to the Genstar Stone Products Company changing the source to groundwater. The amounts were changed to 4.0 Mgd avg and 5 Mgd max, apparently to reflect the actual water withdrawn, since previous pumpage reports only included water used to process the stone product. The second, third and fourth revisions of FR1970G035 were issued between 1998 and 2014 to Genstar Stone Products Company, Lafarge Mid-Atlantic LLC, and Bluegrass Materials Company LLC, respectively, with no changes in the permitted amounts. The application for the fifth revision was withdrawn. The sixth revision of FR1970G035 was issued on November 1, 2018, to Bluegrass Materials Company LLC increasing the permitted amounts to 10.42 Mgd avg and 16.3 Mgd max.

KCF Groundwater, Inc. (2016) prepared a report that included hydrogeologic projections for dewatering of the Frederick Quarry. They consisted of applying unit flow rates for the various input factors, listed in Table 1, to the existing (103 ac) and ultimate (273 ac) mined areas, producing existing and ultimate projected water demands of 6.25 Mgal/d and 13.5 Mgal/d, respectively. Also, the effective groundwater recharge rates (Q_{SP+G}) were unusually high (54,468 and 43,717 gpd avg/ac). KCF Groundwater, Inc. (2018) revised the evaluation, producing existing and 2020 projected water demands of 7.02 and 8.18 Mgal/d, respectively, with lower, but still substantial effective groundwater recharge rates of 31,222 and 27,244 gpd avg/ac. The major components consisted of visually observed spring and diffuse groundwater recharge making up 90% (2016) and 95% (2018) of the total water balance. The final permit decision, Table 2, was based on adding the highest internal use (2014) to the highest discharge to the Monocacy River (2016), plus 10% for large storm events, producing an estimated existing use of 9.26 Mgal/d avg for 2018. The KCF projected increased demand was added to that value to produce the estimated maximum demand during the 12-yr permit period. Relative to actual reported use, there was a

24% error in the 2018 estimated demand in the permit decision and a 57% error in the KCF estimated demand for the same year.

Table 1. Dewatering projections for Frederick Quarry. Data taken from KCF Groundwater, Inc reports dated October 7, 2016 and April 27, 2018 (revised July 17, 2018).

Model Yr	Mined Area	Total Flow	Spring Recharge	Diffuse Recharge	Total Recharge	Overland Recharge	Rainfall	Stormwater Recharge	Pit Evaporation	Internal Use	Flow units
Pumpage	ac	Q_T	Q_{SP}	Q_G	Q_{SP+G}	Q_O	Q_I	Q_{KL}	$-Q_{EV}$	$-Q_{IU}$	
2015	103	4,343	2,200	1,696	3,896	150	236	120	-59		gpm
6.91		6.25	3.17	2.44	5.61	0.22	0.34	0.17	-0.08		Mgal/d
		60,718	30,757	23,711	54,468	2,097	3,299	1,678	(825)		gpd/ac
Ultimate	273	9,389	3,200	5,088	8,288	279	623	223	-24		gpm
Development		13.52	4.61	7.33	11.93	0.40	0.90	0.32	-0.03		Mgal/d
		49,524	16,879	26,838	43,717	1,472	3,286	1,176	(127)		gpd/ac
12/2015-11/2016	214	4,878	2,220	2,420	4,640	150	185.2	120	-59	-137.9	gpm
7.99		7.02	3.20	3.48	6.68	0.22	0.27	0.17	-0.08	-0.20	Mgal/d
		32,824	14,938	16,284	31,222	1,009	1,246	807	(397)	(928)	gpd/ac
2030	226	5,684	2,220	2,945	5,165	175	196	123	-59	-137.9	gpm
12-yr permit		8.18	3.20	4.24	7.44	0.25	0.28	0.18	-0.08	-0.20	Mgal/d
		29,982	11,710	15,534	27,244	923	1,034	649	(311)	(928)	gpd/ac

Table 2. Pumpage from Frederick Quarry in 2018 and estimated water demand from the final decision on Water Appropriation or Use Permit FR1970G035(06) issued November 1, 2018.

FR1970G035(06) Final Permit Decision (November 1, 2018)	
Highest Discharge to Monocacy River (2016)	6.96 Mgal/d
Highest Internal Use (2014)	1.46 Mgal/d
10% large storm events	0.84 Mgal/d
Total estimated existing use (2018)	9.26 Mgal/d
Quarry expansion	1.16 Mgal/d
Total 12-yr projection (2030)	10.42 Mgal/d
Actual Pumpage 2018	11.47 Mgal/d
Error permit decision	24%
Error 2018 KCF evaluation	57%

There are three general methods for estimating the amount of water needed for dewatering of a quarry. One is a water balance calculation method consisting of applying effective recharge rates to an area of influence around the quarry. A second water balance method involve measuring or estimating the components of the water balance in a pit and using them in a water balance equation to calculate the associated water volume. Where possible, the second water balance calculation should be applied to the mining pits, rather than the entire mine site which may include additional complex water processes. This appears to be the method use by KCF, except the estimated component flows were matched to the amount of reported water pumped from the Frederick Quarry and then applied to the existing and planned mined areas. Numerical groundwater models can be used to represent complex groundwater systems; however, it should be noted that, if simulations are to be accurate, the data requirements for numerical models are usually high and can also be demanding computationally; consequently, MDE has rarely required their use for permit applications. Analytical groundwater models are more suited to simple mine situations to overcome the data requirements and costs associated with numerical models. Analytical solutions, specifically developed to estimate the fluxes of associated water to mines, such as described by Marinelli and Niccoli (2000), are commonly used for estimating groundwater flow to mines. Analytical groundwater solutions have many simplifying assumptions, commonly including steady state conditions and uniform aquifer properties, but natural hydrogeological systems include complexities that may violate the simplifying assumptions of analytical models. For that reason, an analytical method that is chosen can potentially provide relatively low accuracy estimates. As with the first water balance method, both numerical and analytical methods include recharge calculations within the area of influence of the quarry.

To use a hydrogeological water balance method, the capture zone of the quarry needs to be determined. In the case of the long-term testing of the Beaver Creek West Quarry, the capture zone was determined by measuring water levels in 12 observation wells and the zone of influence followed the local topography. At the Rockdale Quarry, a trough of depression was formed along the strike orientation of the St. Paul Group. At the Boonsboro and Security quarries, the zones of influence tended to follow topography along line sinks were formed by minor stream tributaries.

Impacts to Carroll Creek in Frederick City depend on the amount of flowing water needed to protect downstream habitat. The watershed is underlain about 56% carbonate rocks and the remainder crystalline and consolidated sedimentary rocks. The nearest comparable watersheds are the nearby Ballenger Creek, with about 40% (+/- 5-10%) carbonate rocks, and Antietam Creek at Sharpsburg, Washington County, with 64% carbonate rocks (Duigon and Dine, 1987). Carroll Creek, immediately upstream of the City's WWTP, was observed by the author to have only pooled water with no detectable flow on September 19, 2002, Figure 2. On the same date, flows measured at the USGS gage sites of Ballenger Creek (01643125, D.A.-20.2 mi^2, partial record, 1977-2002) and Antietam Creek (01619500, D.A.=281 mi^2, continuous record 1929-2022) were 3.58 cfs (0.177 cfsm) and 49.8 cfs (0.177 cfsm), respectively. At the unit flow rate of 0.177 cfsm, it is likely that 3.03 cfs or 1.96 Mgal/d was lost in the Carroll Creek 17.1 mi^2 watershed above the Frederick City WWTP. That flow was comparable to the 2.3-2.5 Mgal/d withdrawn by the Frederick Quarry in August and September 2002.

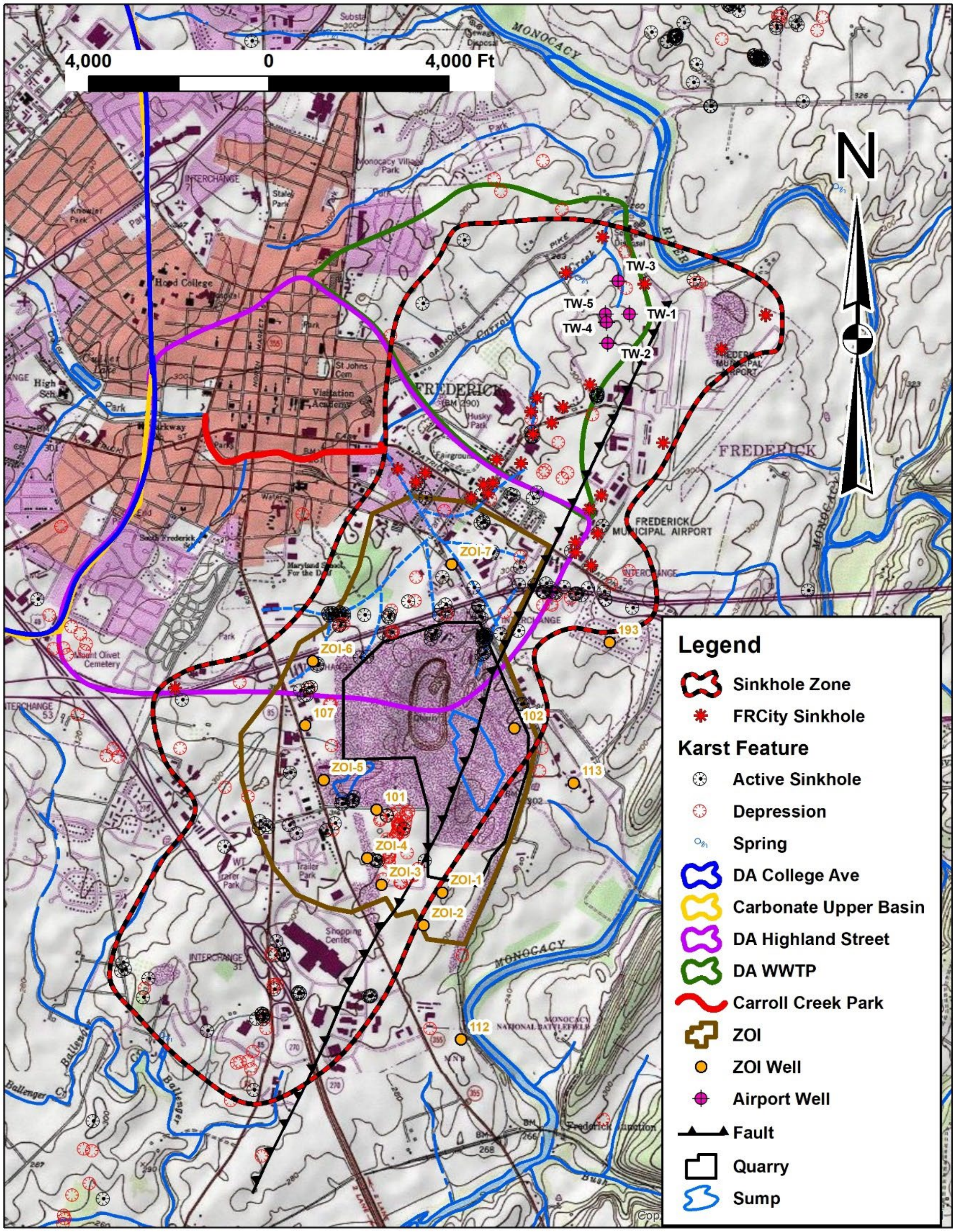

Figure 2. Topographic map in the vicinity of the Frederick Quarry. Shown are karst features from Brezinski (2004), sinkhole location provided by Frederick City DPW, a zone delineated by the sinkholes, drainage areas (DA) for segments of Carroll Creek, Carroll Creek Linear Park, the quarry ZOI, ZOI and airport observation wells, a major fault, and the quarry boundary and sump. Dashed blue lines are Carroll Creek drainage features delineated by Doctor et al. (2015).

On 29 December 2004, Dick Lucas and John Smith (MDE-WSP) measured flows in Carroll Creek at three sites, immediately above College Avenue (10.05 cfs), immediately below Highland Street (13.1 cfs) and just above the Frederick City WWTP access road (12.96 cfs), Figure 2 and Table 3. The quarry pumpage in December 2004 was 2.7 Mgal/d. The flow measured at the Antietam Creek gage on that date was 276 cfs or 0.98 cfsm. If that unit flow were applied to the drainage area above the WWTP (17.2 mi^2), the result is 16.86 cfs, indicating that 3.90 cfs or 2.5 Mgal/d were lost in that watershed, which is again comparable to the 2.7 Mgal/d pumped from the quarry in December 2004.

Table 3. Stream flow measurements taken in Carroll Creek on December 29, 2004.

Location	D.A (ac)	D.A (mi^2)	D.A (mi^2)	Carbonate	flow (cfs)	cfsm	D.A (mi^2)	Δflow (cfs)	Δcsfm
	segments	segments	Cumulative	%	12/29/2004		segments		
Above College Ave.	8,658	13.53	13.53	33	10.05	0.74	13.53	10.05	0.74
College Ave. to Highland St.	1,634	2.55	16.15	100	13.1	0.81	2.55	3.05	1.20
Highland St. to FR City WWTP	718	1.12	17.2	100	12.96	0.75	1.12	-0.14	-0.13*
Total above WWTP	11,010	17.2		56					

* expected gain = 1.20 + 0.13 cfsm * 1.12 mi^2 = 1.49 cfs or 0.96 Mgal/d.
Flow 12/29/2004 Antietam Creek gage (01619500) 276 cfs or 0.98 cfsm.
Estimated flow at WWTP at 0.98 cfsm = 16.86 cfs; loss = 16.86-12.96 cfs = 3.9 cfs or 2.52 Mgal/d.
Estimated loss at Highland St. = 2.52-0.96 Mgal/d or 1.56 Mgal/d.
Frederick Quarry pumpage December 2004 = 84,018,000 gal or 2.71 Mgal/d.
Stream dry end of drought September 2002 at WWTP

There, however, are complicating factors in determining the losses between College Avenue and Highland Street. Due to massive floods in the 1970's, 1.3 miles of underground conduits (4 @ 20 ft by 20 ft) were constructed by the early 1990's for flood control, with a linear park on top of the conduits. In addition, a substantial area of the watershed between College Avenue and Highland Street has been covered by impermeable surfaces of downtown Frederick City. This may not have been a limiting factor during the 2002 and 2004 flow measurements, since that area only makes up 15% of the total watershed and the remainder is relatively undeveloped, and flows were likely unaffected by storm events.

To determine if the comparable loss of flow in Carroll Creek and the withdrawals from the quarry are not just a coincidence, other factors should be considered. The Frederick Quarry is in the upper reaches of an unnamed tributary of Carroll Creek. As such, the quarry only has a small potential topographic drainage area. Some of the features that might reflect the capture zone for quarry dewatering are shown on a topographic map, Figure 2. The highest concentration of sinkholes in Frederick County occur in the vicinity of the Frederick Quarry. A sinkhole zone is outlined on the map that has an area of 2972 ac (4.6 mi^2) and includes about one-half of the Carroll Creek watershed below Highland Street. It includes karst features from Brezinski (2004) with added sinkholes outside of the Zone of Influence (ZOI) from a 2003 sinkhole map provided by the Frederick City Government. Not included were 250 sinkholes (30 pre-construction) reported by KCF Groundwater, Inc. (2015) related to the I70/MD 85 Interchange, MD355 and MD475 reconstruction project. The ZOI has an area of 1044 ac (1.6 mi^2) and was apparently based on dye trace results and possibly on the limits of drawdown estimated from water levels measured in monitoring wells. The area of the quarry is 346 ac (0.54 mi^2) and includes the 214 ac (0.33 mi^2) mined in 2018 indicated in the KCF 2018 report. The airport wells are included because one well (TW-3) had a static water level 28 ft below the Monocacy River at the confluence with Carroll Creek and 38 ft below

Carroll Creek near the Frederick City WWTP. A second well (TW-1) had a static water level 15 ft below the Monocacy River at the confluence with Carroll Creek and 25 ft below Carroll Creek at the WWTP. The same features are shown on the geologic map, Figure 3. Man-induced sinkholes can especially be related to groundwater pumping, and construction and development practices, and may also form when natural water-drainage patterns have been changed. From the geologic and topographic maps, these are all possible factors, as the sinkholes in the study area are distributed along the strikes of the Frederick and Grove limestones, drainage features and Interstate Route 70. Changes caused by pumping of groundwater from the quarry and changes in drainage patterns by land development and road construction (by diverting drainage over openings in bedrock) likely caused the formation of sinkholes in the study area. Newton (1981, 1987) identified more than 850 sites of sinkhole development in 19 States, with more than a total of 6,500 sinkholes or related features. Of those, 4000 were recorded in Alabama between 1900 and 1980, most which occurred after 1950, and only 50 were related to natural events.

Except for 2010, the trend of the water withdrawals from the Frederick Quarry follows that of the Beaver Creek East Quarry, Figure 4. The operator at the Beaver Creek Quarry indicated that the lower benches were not worked in 2009, accounting for the low water use in that year. This suggested that the lower benches were mined during those years with high water use. When Bluegrass Materials Company acquired the quarry from the previous operator, they raised some questions about how the water withdrawals were calculated, which were brought to MDE to get a better understanding of how that water should be calculated. Guidance appears to have been given by MDE during a meeting; however, no record could be found about those instructions. The operator indicated during testimony in a mining permit contested case that the differences in reporting were primarily by how precipitation and recycled water were accounted for. The calculation methodology changed, based on the guidance from MDE, which prompted the need for a permit modification. Table 1 indicates that the total of groundwater and spring recharge to the quarry is equal to 95% of the total water withdrawn, suggesting that there were relatively minor differences in reporting between the two operators.

As with the Beaver Creek Quarry, there is no correlation between the water withdrawals and stone production at the Frederick Quarry, Figure 5. The water use at the Beaver Creek East Quarry was high when the lower bench was mined and low when only the upper bench or benches were mined. Although no record could be found in the water use permit file, this was probably also the case at the Frederick Quarry. Testimony in the mining permit contested case indicates that the Frederick Quarry mine sump was allowed to recover during the low water withdrawal period. Since production remained relatively high during the the same period, this would suggest that only upper benches were mined.

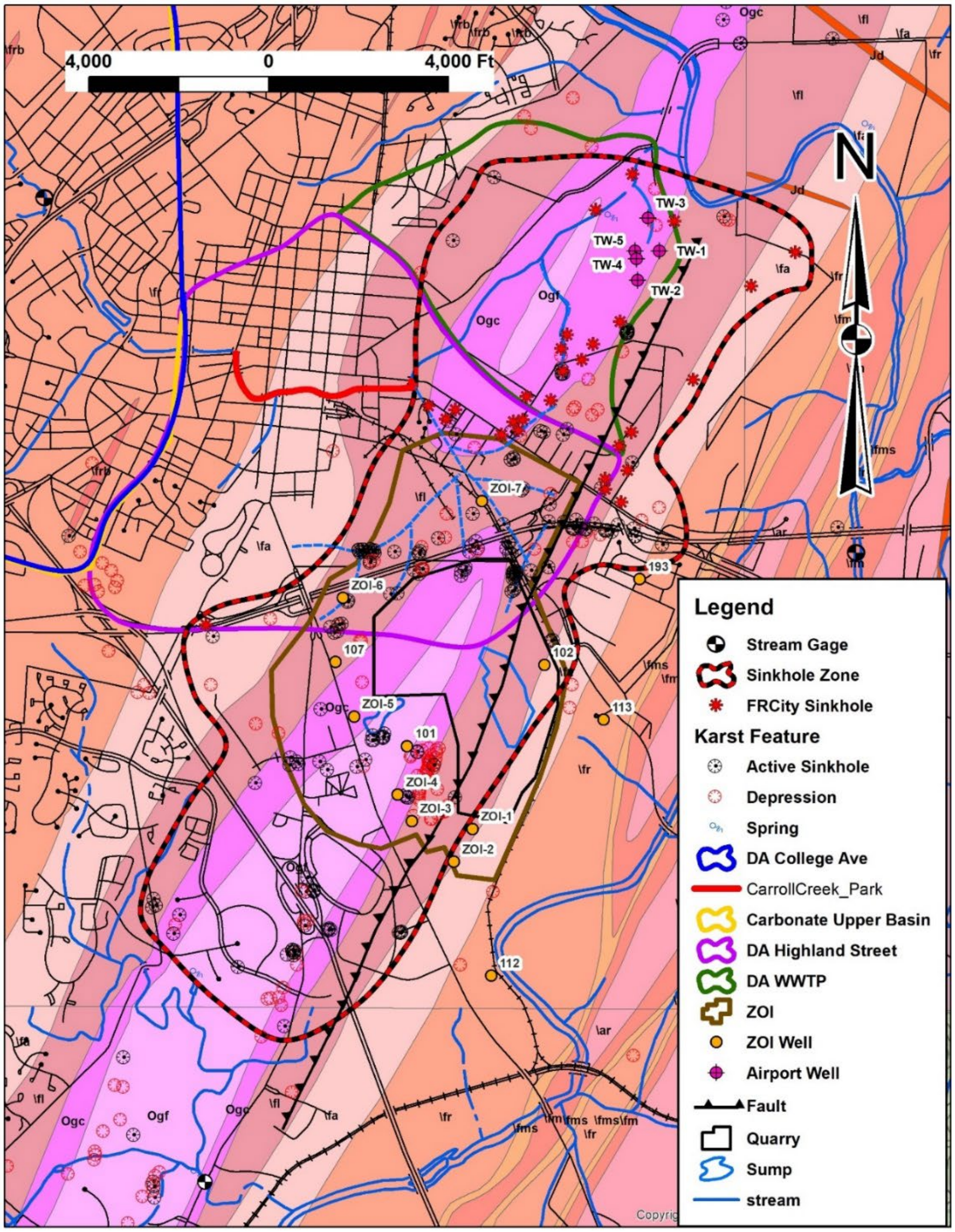

Figure 3. Geologic map in the vicinity of the Frederick Quarry. Shown are karst features from Brezinski (2004), sinkhole location provided by Frederick City DPW, a zone delineated by the sinkholes, drainage areas (DA) for segments of Carroll Creek, Carroll Creek Linear Park, the quarry ZOI, ZOI and airport observation wells, a major fault, and the quarry boundary and sump. Lithologic units within the Sinkhole Zone: Grove Limestone, Ogc-Ceresville Member, Of-Fountain Rock Member; Frederick Limestone, Va-Adamstown Member, Vl-Limekiln Member, Vr-Rocky Springs member. Dashed blue lines are Carroll Creek drainage features delineated by Doctor et al. (2015).

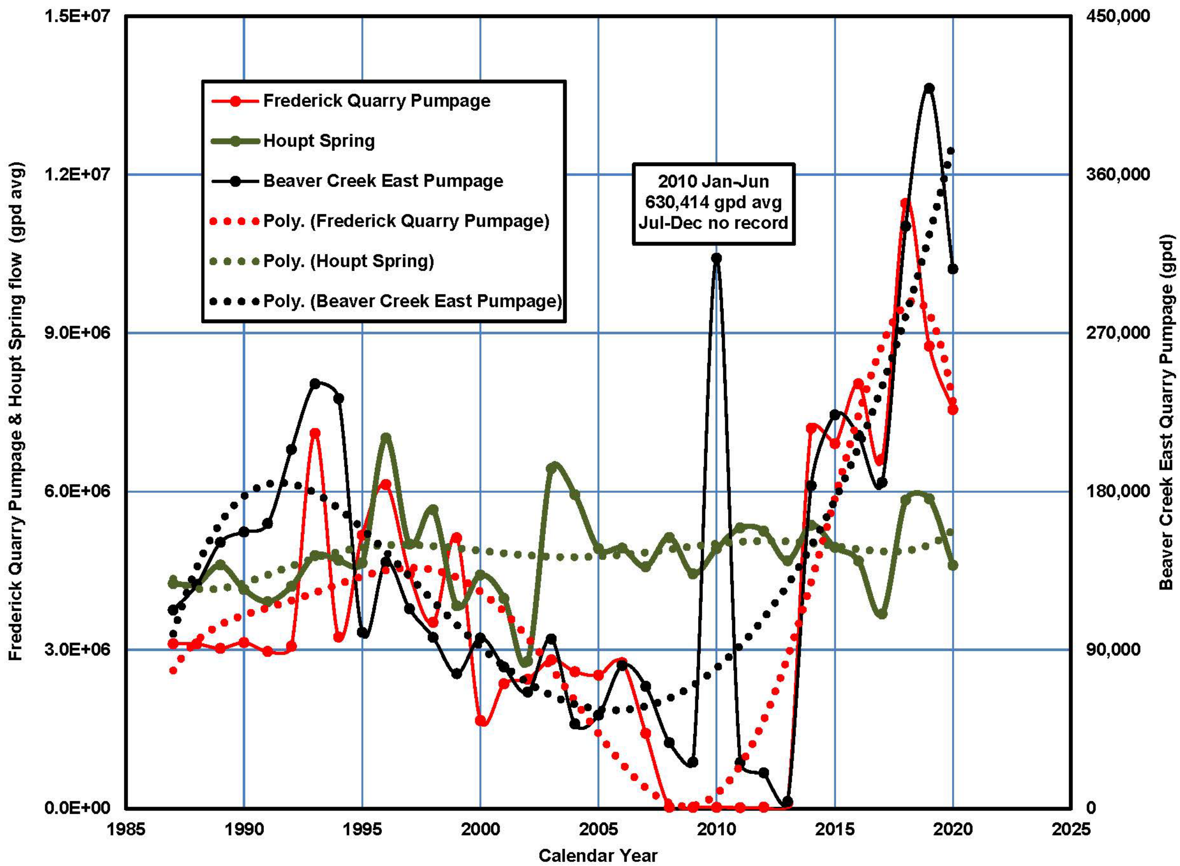

Figure 4. Annual averages for the Beaver Creek East and Frederick quarries pumpage, and Albert Powell Fish Hatchery (Houpt Spring) spring flow: 1987 to 2020.

As the KCF 2018 report indicates, 95% of the inflow into the quarry is groundwater recharge, either by diffuse or spring flow, a water balance can then be calculated for the various potential capture zones and compared to reported water withdrawals to determine which is the most likely capture zone. Table 4 shows the results of those calculations. The years chosen for the analysis were based on several reasons. 1999 and 2000 was chosen since those were the years that the ZOI was delineated. 2002 and 2004 were when flows were observed or measured in Carroll Creek. 1996, 2003 and 2018 were exceptionally wet years, when water withdrawals were expected to be at their highest levels. Finally, 1990 was chosen as a typical average year. Baseflow or effective recharge was estimated from hydrograph separations of stream flow data measured at Antietam Creek (Sharpsburg) and Houpt Spring (Albert Powell Fish Hatchery), Figure 6. The baseflow indices (baseflow to total flow) are 0.85 and 0.99 for Antietam Creek and Houpt Spring, respectively. While the unit rates of both sources matched during average flow conditions, the Antietam Creek values were about 50% higher during wet years. The Halford and Meyer (2000) study provided a possible explanation for that difference. They found that in the Suwannee River karst basin, hydrograph separation analyses overestimated net groundwater discharge by a factor of 2 because the effects of bank storage could not be differentiated from areal recharge.

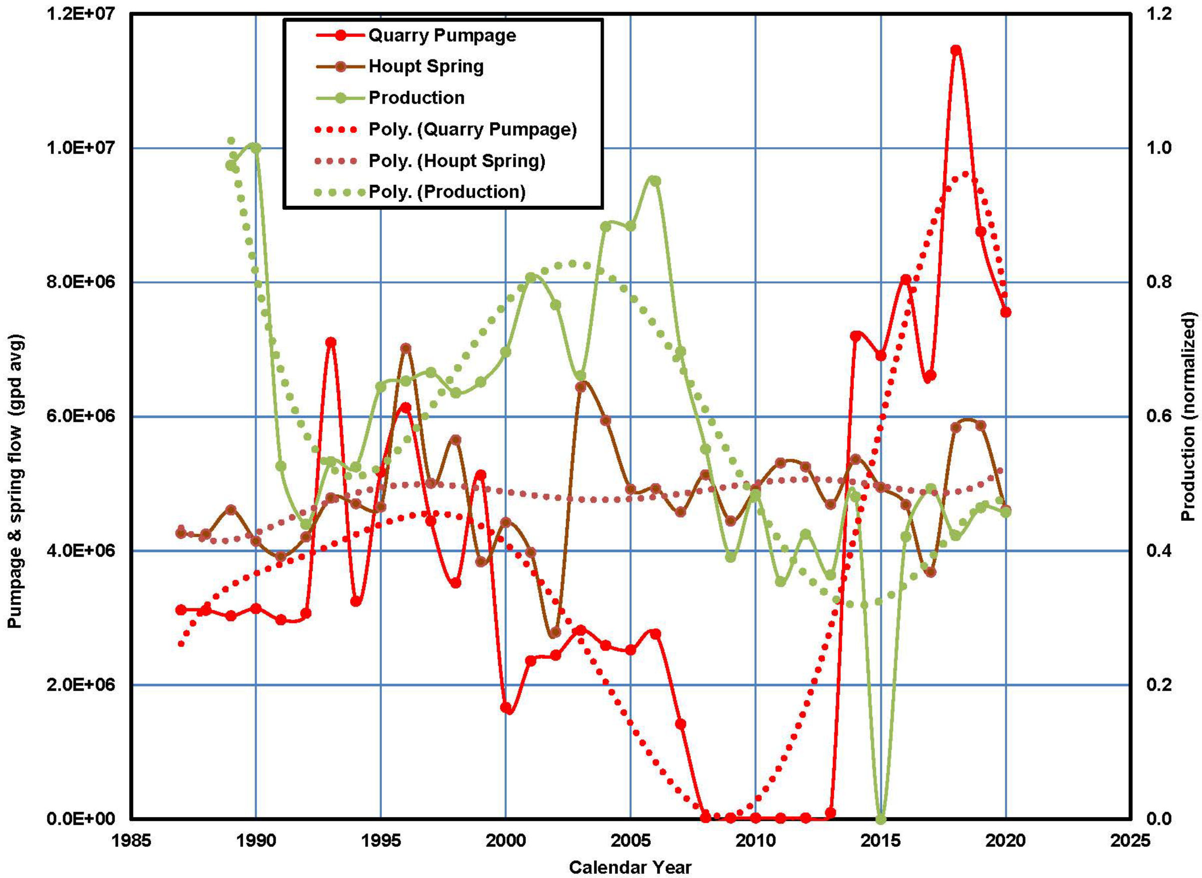

Figure 5. Annual averages for the Frederick Quarry pumpage and normalized production: 1987 to 2020.

Table 4. Water balance calculations in the Frederick Quarry potential capture zones (all values in gpd avg, except where indicated).

Recharge Area	Acres	1990	1996	1999	2000	2002	2003	2004	2018	
Mined Area	214	163,924	427,572	120,910	176,764	79,394	376,854	278,946	392,690	
ZOI	1044	799,704	2,085,912	589,860	862,344	387,324	1,838,484	1,360,841	1,915,740	Antietam Creek
Sinkhole Zone	2972	2,276,552	5,938,056	1,679,180	2,454,872	1,102,612	5,233,692	3,874,002	5,453,620	Effective recharge
Pumpage	gpd avg	3,139,118	6,132,743	3,838,346	4,422,728	2,446,356	2,815,479	2,590,650	11,460,274	
Mined Area	214	168,846	286,118	156,006	179,974	113,634	262,364	242,248	237,968	
ZOI	1044	823,716	1,395,828	761,076	878,004	554,364	1,279,944	1,181,808	1,160,928	Houpt Spring
Sinkhole Zone	2972	2,344,908	3,973,564	2,166,588	2,499,452	1,578,132	3,643,672	3,364,304	3,304,864	Effective recharge
Pumpage	gpd avg	3,139,118	6,132,743	3,838,346	4,422,728	2,446,356	2,815,479	2,590,650	11,460,274	
Recharge Rate										
Antietam Creek	in/yr	10.3	26.86	7.6	11.1	4.99	23.67	17.52	24.66	
	gpd/ac	766	1998	565	826	371	1761	1303.5	1835	
Houpt Spring	in/yr	10.6	17.97	9.8	11.3	7.14	16.48	15.2	14.95	
	gpd/ac	789	1337	729	841	531	1226	1132	1112	

When the mined area is used, the results are unrealistically low, since the mined area is unrelated to the potential drainage area recharging the quarry. Application of the ZOI area produced better results, but the calculated recharge was still about 2-5 times less than the reported pumpage, except for 2018, which is discussed below. The best results were achieved when the drainage area of the sinkhole zone was used in the calculations. The Houpt Spring data provided the best overall results, likely because of the effects of bank storage in the Antietam Creek watershed. One obvious exception is that the pumpage in 2018 (11.5 Mga/d) far exceeds any of the calculated recharge values for discharge to the quarry. A possible explanation is that the excess withdrawals represented interception of stream infiltration, likely from the Monocacy River near the confluence with Carroll Creek. Deviations from the reported pumpage may also reflect changes in quarry operations. When pumpage exceeds the calculated recharge by more than the 10% withdrawn for other uses, this may be due to depletion of sump and aquifer storage when lowering the water level in the quarry. Recharge could exceed pumpage when the water level is recovering in the quarry and surrounding aquifer, due to replenishment of storage.

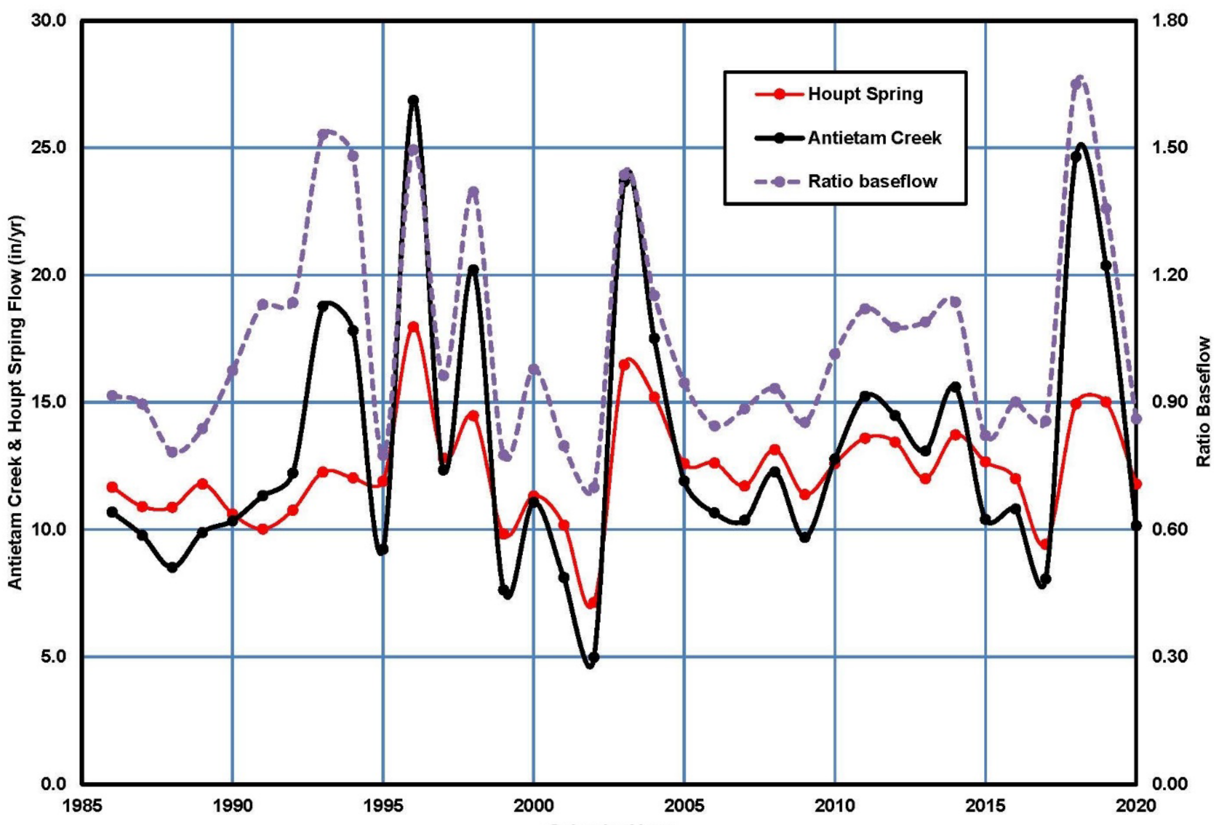

Figure 6. Annual average baseflow values for Antietam Creek (Sharpsburg) and Houpt Spring (Albert Powell Fish Hatchery) and the ratios of the baseflows for the period 1986 to 2020.

The KCF Groundwater, Inc. (2015) report was a re-evaluation and update of the ZOI for the Fredrick Quarry. Included were monitoring well hydrographs and water table maps for the period from 1996 through early 2014. The data between the quarry and the southern portion of Carroll Creek is limited to water levels in ZOI-7 located about 3300 ft north of the quarry sump, Figure 7. All the other water levels on the maps northeast of the quarry are control points used to construct computer-generated maps and do not represent actual measured water levels. Initially (1997 to 1999) the water level in ZOI-7 was nearly the same as that of Carroll Creek at Highland Street (278 ft MSL), which is about 3500 ft north of ZOI-7. The water level in the well declines steadily by about 90 ft between 1999 and 2006 and fluctuates between 70 and 90 ft of drawdown until the end of the record.

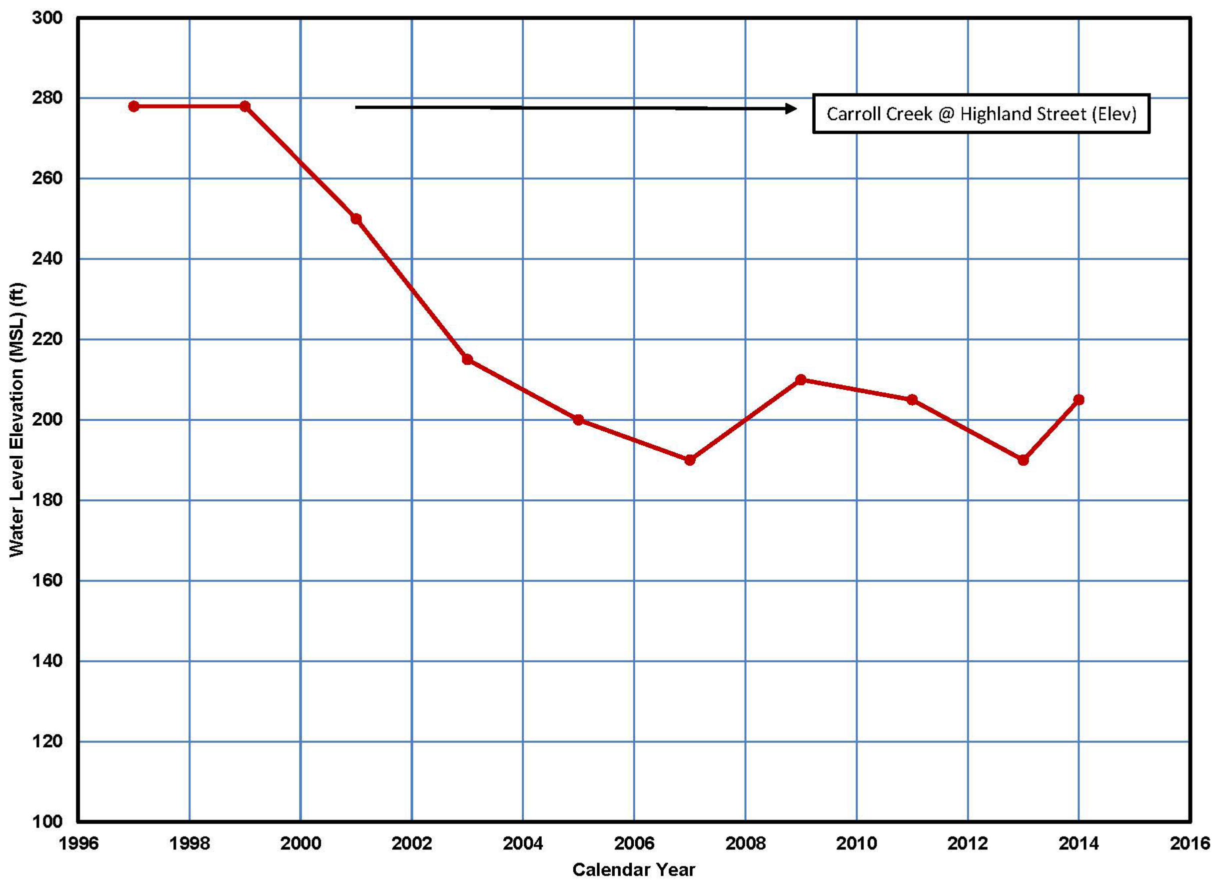

Figure 7. Hydrograph for the ZOI-7 monitoring well for the period 1997 to 2014. Elevation in ft (MSL).

Table 5. Location and elevation data for Frederick Airport test wells, measured on 09/29/2005, and points along Carroll Creek.

Location	Elev Topo map (ft)	SWL (ft) M.P. (2' ags)	SWL El (ft) Topo Map	Elev from Lat-long (m)	Elev from Lat-long (ft)	SWL El (ft) Lat-long	GPS Waypoint Name	GPS Waypoint Altitude (m)	GPS Waypoint Altitude (ft)	GPS Latitude	GPS Longitude
TW-3 Monocacy Blvd. Ext	265	54.6	212	82	269	214	9	68.1	223.6	39.4234	-77.3824
TW-1 Monocacy Blvd Ext	280	57.2	225	86.6	284	227	10	61.9	203.1	39.4214	-77.3815
TW-2 Monocacy Blvd Ext	305	16.8	290	102	335	318	11	92.9	304.8	39.4196	-77.3832
TW-4 Monocacy Blvd Ext	300	16.1	286	91.8	301	285	12	89.5	293.7	39.4209	-77.3833
TW-5 Monocacy Blvd Ext	292	26.0	268	90	295	269	13	89.0	292.2	39.4214	-77.3834
Monocacy River @ Carroll Creek	240			76	249					39.4272	-77.3796
Carroll Creek @ WWTP	250			81	266					39.4259	-77.3833
Carroll Creek @ Monocacy Blvd	250			73	240					39.4252	-77.3838
Carroll Creek @ Highland Drive	278			95	312					39.4159	-77.3972

* Longitude and Latitude Data collected with handheld GPS unit, Orthographic WGS84

**X and Y data are projected to Maryland State Plane meters and feet, NAD 1983

On September 29, 2005, Earth Data Inc. (2005) measured static water levels in a pumping test well (TW-1) and four observation wells (TW-2 to TW-4) at the Frederick Airport, Table 5 and Figure 8. The data in Table 5 highlighted in red represents surface elevations from a USGS topographic map and water levels measured by an electric log in the well boreholes. The remainder are topographic elevations and waypoint elevations determined from GPS data. While there are errors when the two sets of data are compared, the greatest appears to be related to the transposition of the GPS waypoint altitudes for the TW-1 and TW-3 data. In addition, the USGS map elevations are based on a vertical datum tied to the geoid (mean sea level) and water levels measured by electric probe are highly accurate. It is not uncommon for satellite heights to be off from map elevations by 10 to 20 m (50-70 ft). For these reasons, the USGS map elevations and electric probe measurements are used to determine the elevations of the water levels in the airport test wells.

The airport test well water levels were added to the KCF 2005 water table map, providing additional data points northeast of the quarry, Figure 8. The KCF water level elevation contours were extended manually. To honor each data point, the contours had to be extended downstream in Carroll Creek until meeting the tributary connected to the airport test wells. This interpretation suggests that a trough of depression initially expanded down the southwest tributary to Carroll Creek until reaching the main stem near the east end of Carroll Creek Linear Park. At that point it then expands down Carroll Creek towards the Monocacy River and the tributary connecting to the airport wells. This seems reasonable since this is the same reach where diminished flows occurred in 2002 and 2004 and confirms those observations. In addition to Carroll Creek, drawdowns due to quarry dewatering have been observed to follow stream channels at the Beaver Creek West, Boonsboro, and Security quarries and during a long-term aquifer test of a high-capacity limestone well in the Frederick City Fredericktowne Park. Using the outermost closed contour, a capture zone for quarry dewatering was delineated with an area (3,466 ac) overlapping and like that of the sinkhole zone (2972 ac). The overlap mainly occurs in the areas of the Frederick and Grove limestones, Figure 9, where most of the sinkholes occurred, suggesting that the sinkholes required the lowering of the water table and that lithologic formations susceptible to sinkhole development be present. When the water table capture zone is added to the previous water balance calculations, Table 6, and a simple error analysis is conducted, the effective recharge from the water table capture zone provides the best overall fit to the reported pumpage data. It is noted that the capture zone includes nearly all the drainage area of Carroll Creek below College Avenue, indicating that quarry dewatering could capture most of the baseflow discharged to the lower portion of Carroll Creek and account for the low flows observed during 2003 and 2004. As previously stated, the pumpage in 2018 (11.5 Mga/d) still far exceeds any of the calculated recharge values for discharge to the quarry and could reflect water diverted from the Monocacy River.

Table 6. Revised water balance calculations from Table 4 for the Frederick Quarry potential capture zones (all values in gpd avg, except where indicated). Capture zone from the water table map, Figure 8, added to table.

Recharge Area	Acres	1990	1996	1999	2000	2002	2003	2004	2018	
Mined Area	214	163,924	427,572	120,910	176,764	79,394	376,854	278,946	392,690	
ZOI	1044	799,704	2,085,912	589,860	862,344	387,324	1,838,484	1,360,841	1,915,740	Antietam Creek
Sinkhole Zone	2972	2,276,552	5,938,056	1,679,180	2,454,872	1,102,612	5,233,692	3,874,002	5,453,620	Effective recharge
% error		38	3	129	80	122	-46	-33	110	
Capture Zone	3466	2,654,956	6,925,068	1,958,290	2,862,916	1,285,886	6,103,626	4,517,931	6,360,110	
% error		18	-11	96	54	90	-54	-43	80	
Pumpage	gpd avg	3,139,118	6,132,743	3,838,346	4,422,728	2,446,356	2,815,479	2,590,650	11,460,274	
Mined Area	214	168,846	286,118	156,006	179,974	113,634	262,364	242,248	237,968	
ZOI	1044	823,716	1,395,828	761,076	878,004	554,364	1,279,944	1,181,808	1,160,928	Houpt Spring
Sinkhole Zone	2972	2,344,908	3,973,564	2,166,588	2,499,452	1,578,132	3,643,672	3,364,304	3,304,864	Effective recharge
% error		33.9	54.3	77.2	76.9	55.0	-22.7	-23.0	246.8	
Capture Zone	3466	2,734,674	4,634,042	2,526,714	2,914,906	1,840,446	4,249,316	3,923,512	3,854,192	
% error		14.8	32.3	51.9	51.7	32.9	-33.7	-34.0	197.3	
Pumpage	gpd avg	3,139,118	6,132,743	3,838,346	4,422,728	2,446,356	2,815,479	2,590,650	11,460,274	
Recharge Rate										
Antietam Creek	in/yr	10.3	26.86	7.6	11.1	4.99	23.67	17.52	24.66	
	gpd/ac	766	1998	565	826	371	1761	1303.5	1835	
Houpt Spring	in/yr	10.6	17.97	9.8	11.3	7.14	16.48	15.2	14.95	
	gpd/ac	789	1337	729	841	531	1226	1132	1112	

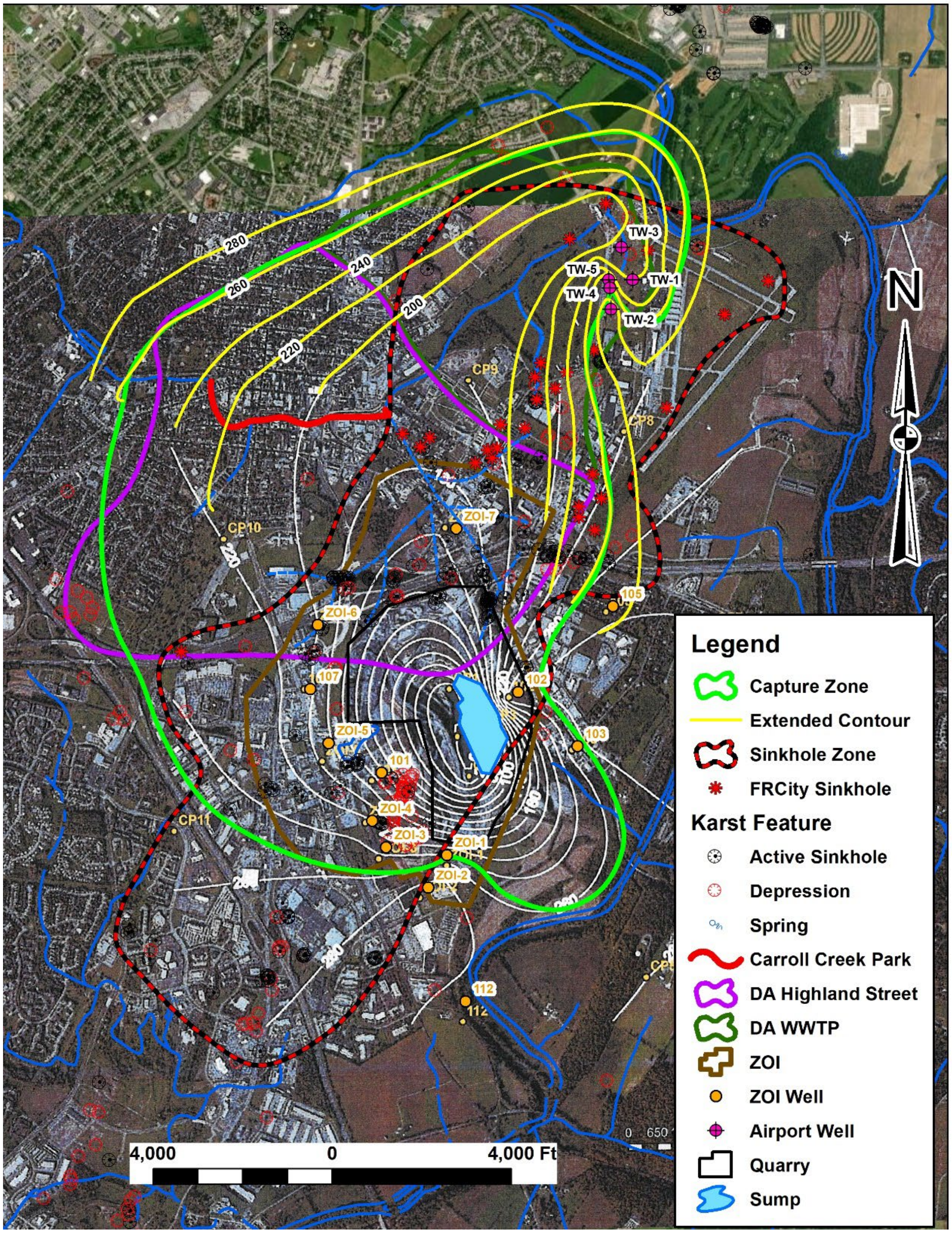

Figure 8. Aerial imagery map in the vicinity of the Frederick Quarry. Shown are karst features from Brezinski (2004), sinkhole location provided by Frederick City DPW, a zone delineated by the sinkholes, drainage areas (DA) for segments of Carroll Creek, Carroll Creek Linear Park, the quarry ZOI, ZOI and airport observation wells, the quarry boundary and sump. The capture zone was derived by overlaying a KCF 2005 water table map and extending the contours using water levels measured in the airport test wells. Dashed blue lines are Carroll Creek drainage features delineated by Doctor et al. (2015).

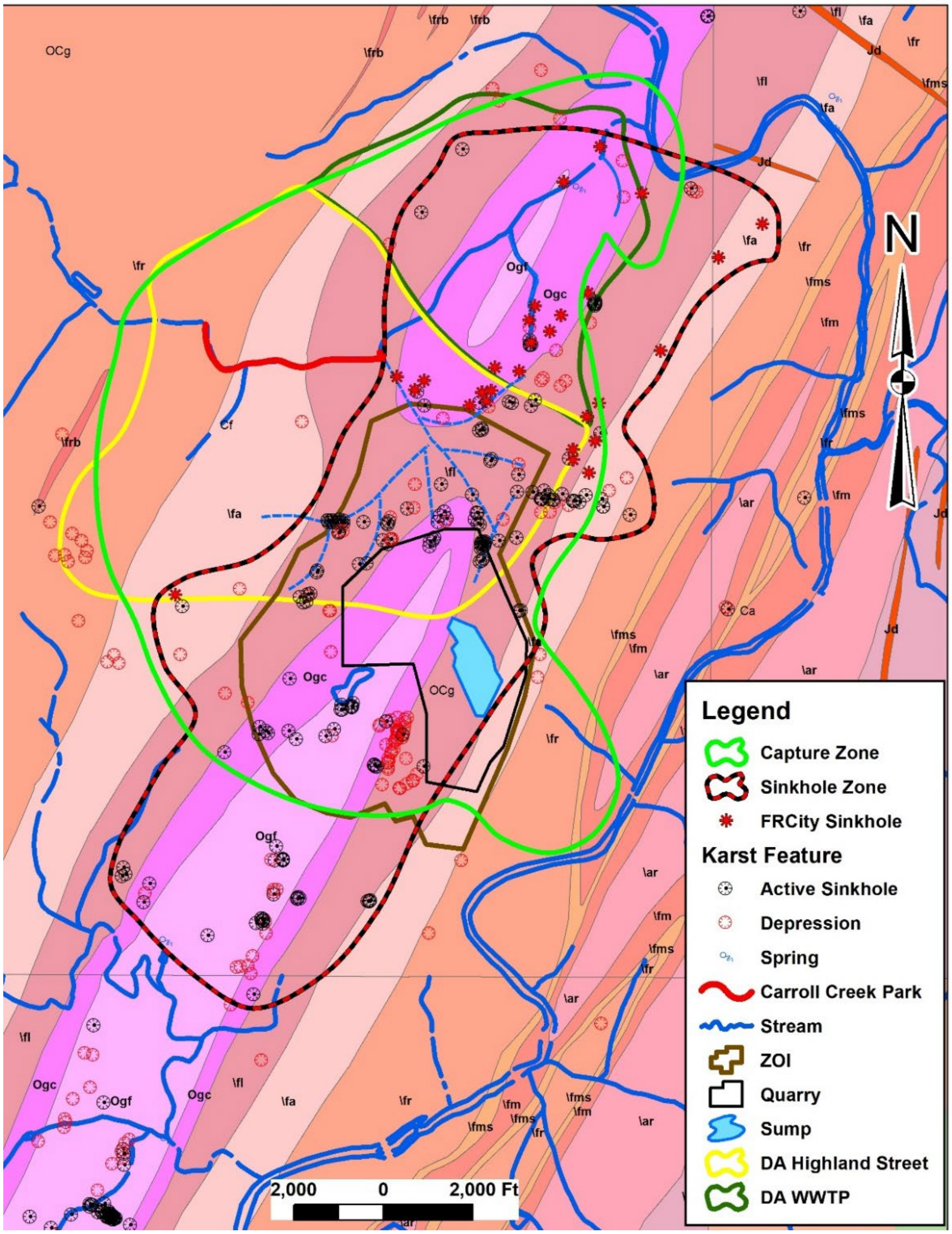

Figure 9 Geologic map in the vicinity of the Frederick Quarry. Shown are karst features from Brezinski (2004), sinkhole location provided by Frederick City DPW, a zone delineated by the sinkholes, drainage areas (DA) for segments of Carroll Creek, Carroll Creek Linear Park, the quarry ZOI, the quarry boundary and sump, The capture zone was derived by overlaying a KCF 2005 water table map and extending the contours using water levels measured in the airport test wells Lithologic units within the Sinkhole Zone: Grove Limestone, Ogc-Ceresville Member, Of-Fountain Rock Member; Frederick Limestone, Va-Adamstown Member, Vl-Limekiln Member, Vr-Rocky Springs member. Dashed blue lines are Carroll Creek drainage features delineated by Doctor et al. (2015).

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Medford Quarry Case Study

Medford Quarry was initially owned and operated by Teeter Stone Inc. The Teeter family first conducted a business which consisted of farming, quarrying, hauling, and road construction that included parts of the Pennsylvania Turnpike. The quarries were in Gettysburg and Fairfield, Adams County, Pennsylvania. The company was incorporated as John S. Teeter & Sons in 1936 and quarry operations were expanded by leasing the Hyde Quarry (Carroll County, Maryland) in the late 1940's. All the quarries were then operated under the Teeter Stone, Inc. ownership. In 1957, the company closed the Hyde Quarry and moved operations to the present Medford Quarry location.

Prior to about 1989, quarry withdrawals were determined by law and regulation to be reasonable, even if they caused nearby water supplies to go dry, had diminished yields or experienced water quality problems. That policy was defended by the Maryland Department of Natural Resources, Water Management Administration (DNR WMA) by citing the 1968 Finley vs Teeter Stone Company court decision, which was based on both "English" law (absolute ownership) and "American" law (reasonable use). The case concerned withdrawals for dewatering of the Medford quarry causing a diminished or lost water supply and development of sinkholes on the adjacent Finley 284-ac farm, Figure 10. The court decided that the withdrawal by the quarry was a reasonable beneficial use of water on the quarry property and there was no interference with lateral support under its interpretation of the law. The court indicated that any remedy for replacing impacted water supplies would require a change of the Maryland Law by the general assembly. Legislation requiring permits for surface mines was passed in 1975. Changes of the State regulations were made for water use in 1989, which adopted most of the elements of the Restatement (Second) of Torts, and in 1991 for surface mines ("Zone of Influence" or ZOI in karst terrain), so that quarries could be held liable for mitigation of impacts caused by dewatering activities.

Ultimately the Teeter family corporation was dissolved, and all three quarries were sold. The Genstar Stone Product Company eventually bought the Medford Quarry in 1986 and then sold it to Bluegrass Materials Company/LLC in 2014.

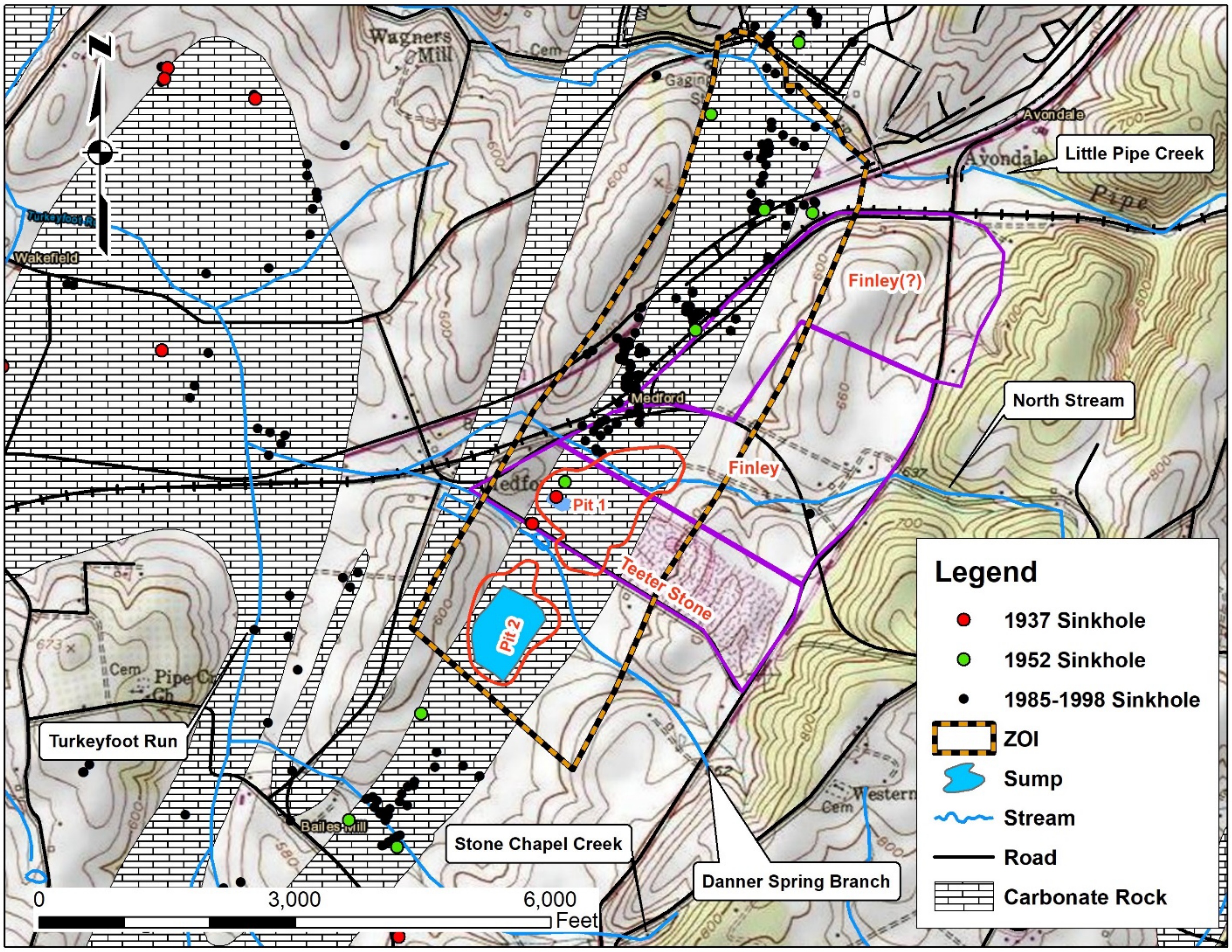

Figure 10. Topographic map overlain by carbonate rocks of the Wakefield Valley related to the 1968 Finley vs Teeter Stone Co. court case. The 1937 (Carroll County sinkhole database) and 1952 sinkholes (MDE files, supplied by Medford Quarry) were interpreted from aerial photos. The 1985-1998 sinkholes were taken from the Carroll County Government sinkhole database. Excavation of Quarry pit 1 started in 1957, while pit 2 was first developed in 1977.

The Medford Quarry ZOI report (Mauersburg, 1997) reviewed the results of numerous scientific studies on the potential environmental impacts of dewatering by the quarry. Dunn Geoscience (1988) reviewed four historical air photos (1952, 1963, 1970 and 1980) for sinkhole development. Only three sinkholes pre-dated quarry operations (1952 photo), two about 4000 feet southeast of pit 2 and the third about 3000 ft to the west of the pit. A 1987 fracture trace map shows 5 sinkholes south of the quarry and 8 to the north. The most recent ones (1980-1987) were located to the north of the quarry. From the Carroll County database, there were 119 sinkholes within the ZOI area, including 15 on the northwest corner of the Finley farm during the period 1985 to 1998. While there are some discrepancies in the locations of sinkholes in the area between the various sources, few sinkholes were present prior to commencement of quarry operations and most occurred after the completion of the Dunn Geoscience (1988) study. This suggests that sinkholes on the Finley property were the result of dewatering of the Teeter Stone (Medford) Quarry. Other factors often considered as causing sinkholes are land development and road construction. A review of the 1952 and present-day aerial photos indicated that there has been no significant development in the study area and the only significant road construction occurred with the relocation of MD Route 31 which was completed during the period of 1962 to 1966.

On March 31, 1994, a fatal accident occurred after a sinkhole opened in the westbound lane of MD Route 31, when a Westminster WWTP employee drove into the hole. In late October 1994 dye was injected into the sinkhole by Dr. Quinlan, about 2000 ft northeast of the quarry, but no dye was recovered at any of the monitoring points, including several in the quarry. During an investigation of surface water influence on Westminster's Wakefield Valley public supply wells, dye was injected in a sinkhole on July 13, 1994, along Copps Branch, more than one mile northeast of the quarry, with a major slug of the tracer arriving in the spring discharge located in quarry pit 1, Steinfort (1994). Optical brightener sampling by Aley (1990) during the period 11/08/1988 to 11/15/1988 suggested there was a gradient or flow path from the Westminster WWTP discharging to Little Pipe Creek then to quarry pit 1. Conversely, optical brighteners were not detected in samples taken from quarry pit 1 during the period 7/24/1989 to 7/27/1989. Water level data from a 29-well monitoring network in the Wakefield Valley have been recorded and maintained by Carroll County Government since April 1994, Figure 11. Most of the wells were used during the 1997 Medford Quarry ZOI investigation. Later three wells (WV-19a, WV-28 and WV-29) were added, four wells were abandoned (WV-3, WV-17, WV-18, and WV-19) and two were not monitored (WV-25 and WV-pipe). Figure 12 is a map of water levels from the monitoring wells recorded on 12/15/2017. The contours prepared by Carroll County Government on that date were open to the northeast of the quarry and were extended further to the northeast as part of the present study by honoring the slopes of the existing contours. This produced an anisotropic trough of depression typical of a fractured rock aquifer. A capture zone was defined by the last closed contour (elevation 525 msl or mean sea level) and provides a mechanism to explain why dye was not recovered in the quarry during the October 1994 dye trace of the MD Route 31 sinkhole. Dr. Quinlan suggested that the lack of recovery of dye during his test was due to either 1) the dye was missed or came through at an unmonitored location or 2) it did not reach the water table, Mauersburg (1997). Another possibility is based on the nature of groundwater flow in fractured crystalline rock aquifers. In theory flow is linear in the vicinity of a discrete vertical fracture but becomes radial as distance from the fracture increases. Flow in the matrix is diffuse through non-directional micro-fracture networks and is much slower than through the primary fracture. It is then possible that there was no direct hydraulic connection between the MD Route 31 sinkhole injection point and the primary fracture or conduit, but flow through the aquifer matrix was diffuse and slow causing dispersion and/or absorption of the dye tracer.

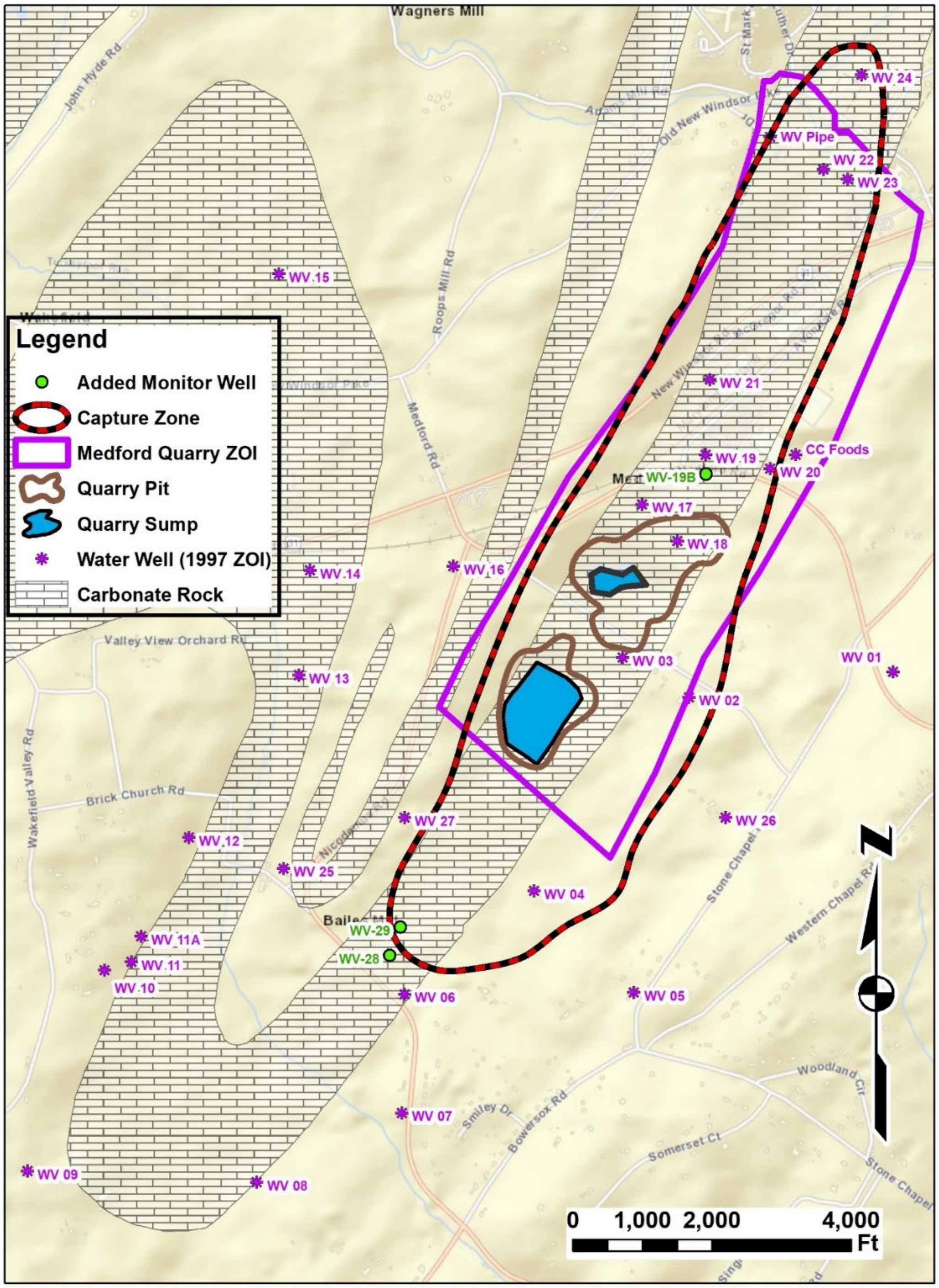

Figure 11. Road map, with carbonate geology, of the Medford Quarry area, with the locations of the Carroll County Government monitoring wells.

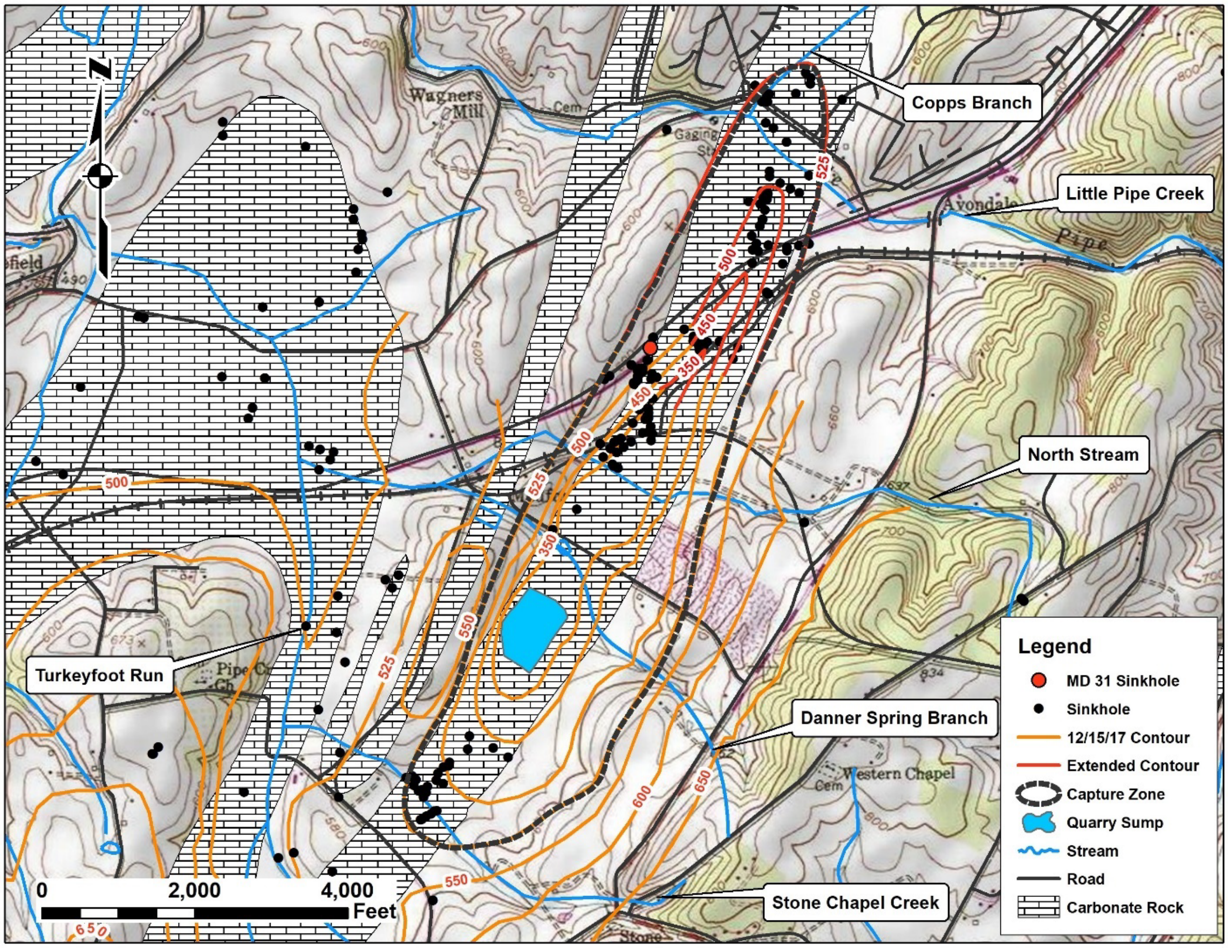

Figure 12. 2017 water table map constructed on an USGS topographic map, with carbonate geology added. The capture zone is defined by the last closed contour (elevation 525 ft msl).

Previously, on 3/3/1987, R.E. Wright Associates measured water levels in 15 commercial, industrial, and residential wells and one well at the WWTP, Haufler (1987). From those data, they constructed a water table map, Figure 13. The orientation of the trough is like that of the 2017 water table map produced in the present study, except that the area of the capture zone (359 ac) is smaller that of the 2017 map (472 ac). This seems reasonable since the trough of depression likely would have expanded over time as mining proceeded.

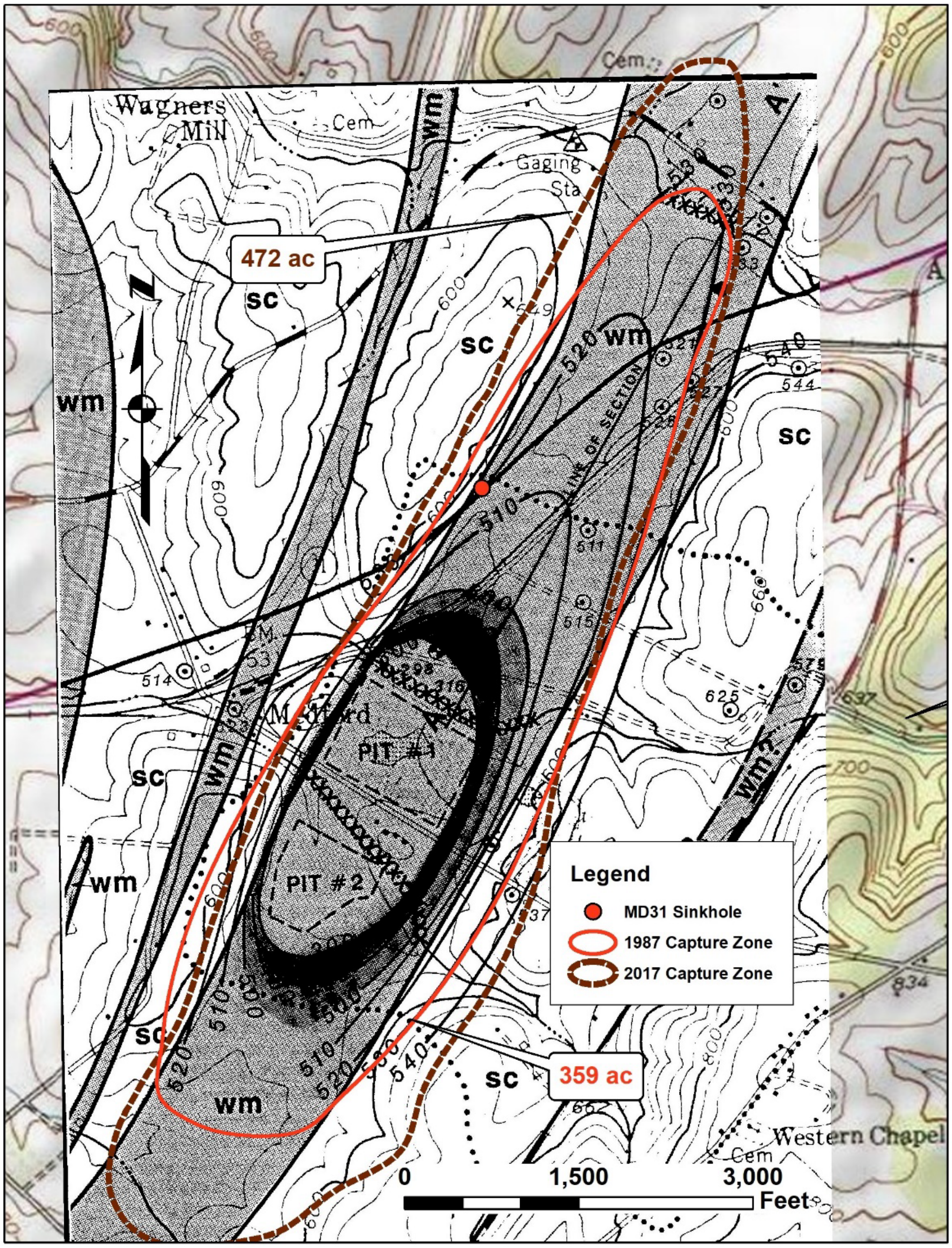

Figure 13. 1987 R.E. Wright Associates, Haufler (1987), water table map constructed on an USGS topographic map, The 1987 capture zone (359 ac) is defined by the last closed contour (elevation 530 ft msl). The 2017 capture zone (472 ac) is taken from Figure 3 and defined by the last closed contour (elevation 525 ft msl).

Table 7. 1989 seepage runs of Turkeyfoot Run and its tributaries.

Map No.	Site No.	Stream	Date	Area	Area	Flow	Flow	Unit Flow	DA incr	Flow incr	Flow incr	Western Run
				ac	mi^2	Mgpd	cfs	cfsm	mi^2	cfs	cfsm	cfsm
1	1	North Stream	7/25/1989	201	0.314	0.094	0.145	0.46	0.314	0.145	0.46	1.47
3	2	North Stream	7/25/1989	341	0.533	0.11	0.170	0.32	0.219	0.025	0.11	1.47
4	3	North Stream	7/25/1989	347	0.542	0.085	0.132	0.24	0.009	-0.038	-4.22	1.47
5	4	Danner Sp Br	7/25/1989	103	0.161	0.149	0.231	1.43	0.161	0.231	1.43	1.47
6	5	Danner Sp Br	7/25/1989	153	0.239	0.121	0.187	0.78	0.078	-0.044	-0.56	1.47
7	6	Danner Sp Br	7/25/1989	280	0.438	0.86	1.331	3.04	0.199	1.144	5.75	1.47
9	7	Stone Chapel Crk	7/25/1989	36	0.056	0.019	0.029	0.52	0.056	0.029	0.52	1.47
10	8	Stone Chapel Crk	7/25/1989	346	0.541	0	0.000	0.00	0.485	0.000	0.00	1.47
14	9	Turkeyfoot Run	7/26/1989	1005	2.242	0.601	0.930	0.41	2.242	0.930	0.41	1.42
15	10	Turkeyfoot Run	7/26/1989	1498	2.636	0.801	1.239	0.47	0.394	0.309	0.78	1.42
N/A	11	Railroad Basin	7/25 - 7/27	89	0.139	0	0.000	0.00	0.139	0.000	0.00	1.39
N/A	12	Quarry Pit 1	7/25 - 7/27	N/A	N/A	1.061	1.642	N/A	N/A			
N/A	13	Quarry Pit 2	7/25 - 7/27	N/A	N/A	0.296	0.458	N/A	N/A			
		Total Pit1 + Pit2	7/25 - 7/27	N/A	N/A	1.357	2.100	N/A	N/A			

Synoptic flow measurements were taken in the Turkeyfoot Creek watershed on July 25-26, 1989, (Aley, 1990). Table 7 and Figure 14 show the unit flows taken on those dates and indicate that there were substantial reductions in flows in the North Stream, Danner Spring Branch and Stone Chapel Creek, all of which are within the capture zone of the quarry. The flow in the main Turkeyfoot Run tributary appeared to be unaffected by quarry withdrawals, probably because that tributary is outside of the quarry capture zone. Applying upstream unit flows it was estimated that the average flows discharged from the quarry (July 25-27) at site 6 were about 23 % higher than the natural flows in the water captured from the three tributaries. The additional flow is possibly water diverted from Little Pipe Creek. Previously discussed fluorescent dye trace studies indicated that that there was a connection between Little Pipe Creek and inflow to the quarry, but the quantity of water diverted was not determined. Chloride and Fluoride data from 10/07/2002 to 10/11/2002 provided by Stearns & Wheler, LLC, Studevant (2003), were used to determine if there was a hydraulic connection and how much water likely was flowing from the WWTP discharge to Little Pipe Creek then to the quarry. The Chloride concentrations were 44 mg/L, 69 mg/L and 122 mg/L in Westminster's Wakefield well (background), the quarry and the WWTP, respectively. If the concentration is assumed to be proportional to flow, the amount diverted follows:

Flow Contribution = [$(\text{Chloride}_{\text{Quarry}})$-$(\text{Chloride}_{\text{Background}})/(\text{Chloride}_{\text{WWTP}})$]
= 60 mg/L – 44 mg/L/122mg/L = 20%.

The concentrations of Fluoride were 0.1 mg/L, 0.13 mg/L and 0.1 mg/L in Westminster's Wakefield well (background), the quarry and the WWTP. A review of all the Westminster well data indicated the background concentration was 0.08 mg/L. If the concentration is assumed to be proportional to flow the amount diverted follows:

Flow Contribution = [$(\text{Fluoride}_{\text{Quarry}})-(\text{Fluoride}_{\text{Background}})/(\text{Fluoride}_{\text{WWTP}})$]
= 0.13 mg/L – 0.08 mg/L/0.41 mg/L = 12%.

Considering that the Turkeyfoot Run flows were measured in 1989 and the Chloride and Fluoride samples were taken in 2002, there is a reasonable match between the two sets of values when estimating the contribution of Little Pipe Creek flow to the quarry discharge.

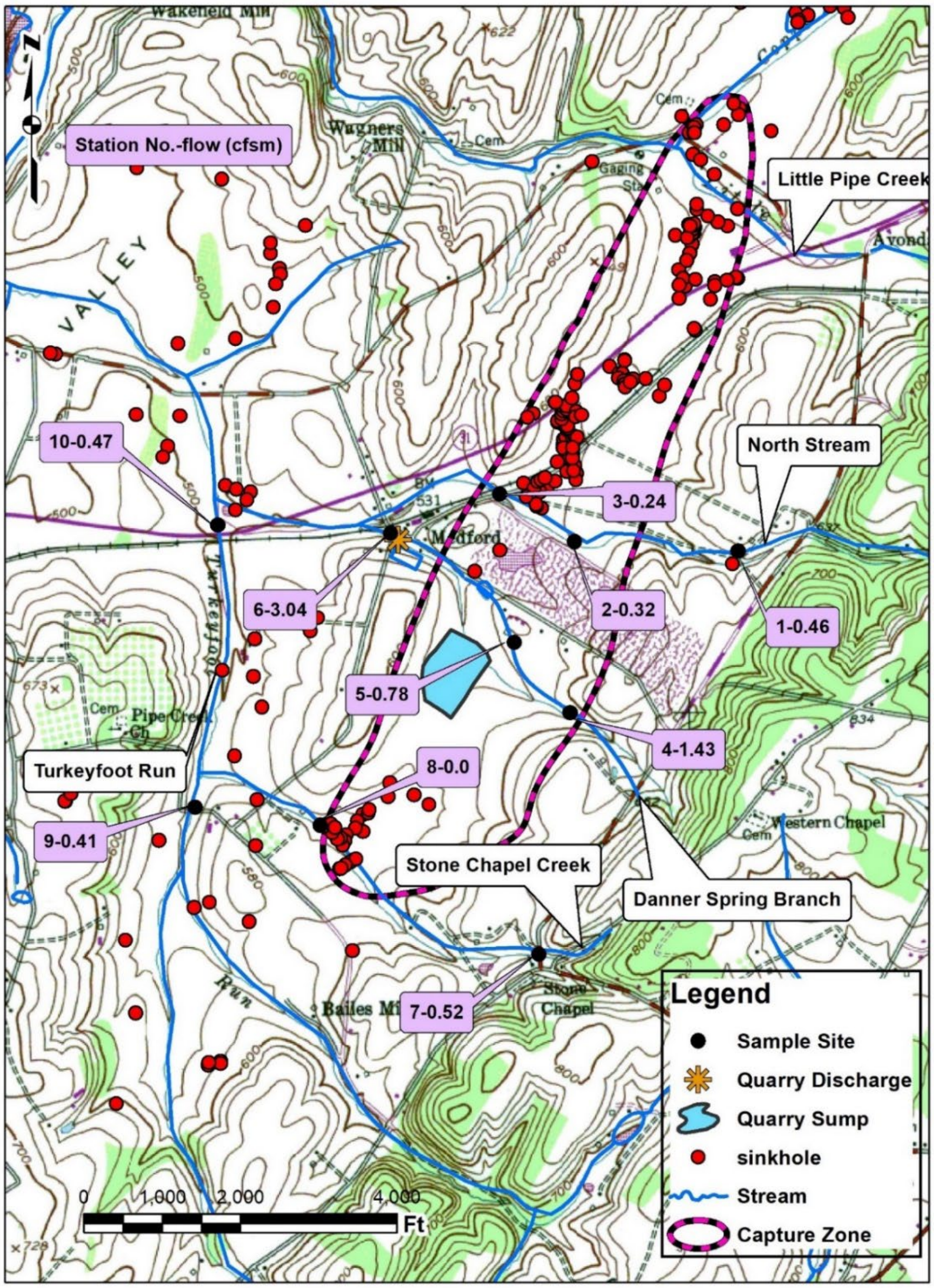

Figure 14. Topographic map with the results of the 1989 seepage runs of Turkeyfoot Run and itstributaries and the Medford Quarry capture zone.

Table 8. 2007 KCI MBSS data collected in Turkeyfoot Run and its tributaries.

Map No.	Site No.	Spring Date	BIBI	Rating	Summer Date	FIBI	Rating	CIBI	Discharge (cfs)	D.A. (ac)	Discharge (cfsm)	Western Run (cfs)	Western Run (cfsm)	Antietam Crk (cfs)	Antietam Crk (cfsm)	PHI	Rating
North Branch																	
16	M1	5/24/2007	4.00	Good	8/28/2007	3.33	Fair	3.67	0.07	258	0.17	18.2	0.304	142	0.505	61.1	Degraded
15	M2	5/24/2007	3.75	Fair	8/28/2007	3.33	Fair	3.54	0.13	311	0.27	18.2	0.304	142	0.505	54.9	Degraded
14	M3	5/24/2007	2.75	Poor	8/24/2007	3.33	Fair	3.04	0.31	402	0.49	22.6	0.378	153	0.544	44.6	Severely Degraded
13	M11a	5/29/2007	3.00	Fair	8/29/2007	3.33	Fair	3.17	0.07	463	0.10	18.0	0.301	142	0.505	58.2	Degraded
Danner Spring Branch																	
12	M4	5/29/2007	2.00	Poor	N/R(0)	N/R(0)	Poor	2.00	0.24	116	1.32	No fish found				61.5	Degraded
11	M5	5/29/2007	2.50	Poor	N/R(0)	N/R(0)	Poor	2.50	0.16	176	0.58	No fish found				66.2	Partially Degraded
10	M13	5/29/2007	2.25	Poor	N/R(0)	N/R(0)	Poor	2.25	N.A.	298	N.A	No fish found-subsurface flow beneath rip-rap				52.2	Degraded
9	M6	5/23/2007	2.00	Poor	8/29/2007	3.33	Fair	2.67	0.08	240	0.21	18.0	0.301	142	0.505	39.1	Severely Degraded
Confluence																	
2	M12	5/23/2007	2.75	Poor	9/17/2007	4.00	Good	3.38	0.25	909	0.18	14.2	0.237			44.2	Severely Degraded
Turkeyfoot Run																	
4	M9	5/23/2007	2.75	Poor	8/23/2007	3.67	Fair	3.21	0.8	1121	0.46	24.1	0.403	178	0.633	56.1	Degraded
3	M10	5/23/2007	3.00	Fair	9/18/2007	4.00	Good	3.50	0.35	1687	0.13	13.9	0.232	100	0.356	42.8	Severely Degraded
1	M8	5/30/2007	2.75	Poor	8/31/2007	3.67	Fair	3.21	1.22	2845	0.27	17.0	0.284	139	0.495	38	Severely Degraded
Stone Chapel Creek																	
8	M7	5/24/2007	3.25	Fair	N/R(0)	N/R(0)	Poor	(1.63)	0.03	85	0.23	No fish found				37.3	Severely Degraded
N/A	Control	5/30/2007	3.00	Fair	9/25/2007	4.33	Good	3.67	0.75	3524	0.14	12.0	0.201	90	0.320	54.5	Degraded

PHI Scoring	
Score	Narrative Rating
81-100	Minimally Degraded
66.0-80.9	Partially Degraded
51.0-65.9	Degraded
0-50.9	Severely Degraded

BIBI/FIBI/CIBI(IBI) Scoring	
Score	Narrative Rating
5.00-4.00	Good
3.99-3.00	Fair
2.99-2.00	Poor
1.00-1.99	Very Poor
Less than 3 years of data Minimum acceptable scores BIBI=2.65 and FIBI=2.50	

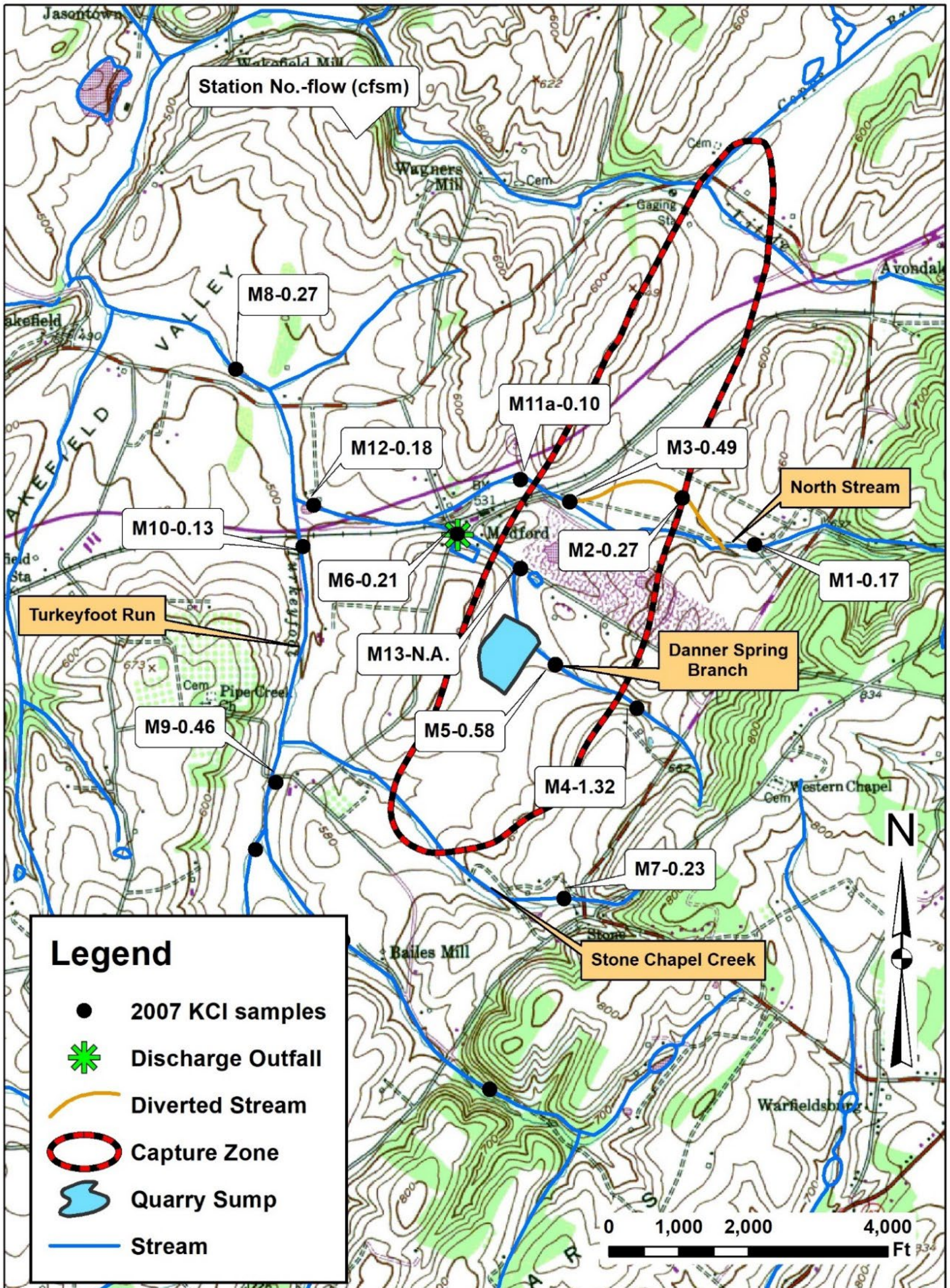

Figure 15. Topographic map with 2007 KCI MBSS sample sites and seepage run results.

The WMA-WSP received a report required as part of a permit application from the KCI Technologies, Inc. (KCI) dated January 2008 and titled "Biological Monitoring and Assessment of Cranberry Branch and Turkeyfoot Run, Cranberry Water Treatment Plant and Medford Quarry, Carroll County, Maryland". Table 8 and Figure 15 show the unit flows measured by KCI at each sampling site in the Turkeyfoot Run watershed. KCI indicated the flows were measured at each site in conjunction with fish sampling between August 23, 2007, and September 27, 2007. They were not synoptic values and caution is needed when using such data to interpret the effects of quarry dewatering on stream base flow. The quarry withdrawals were 1.8 Mgd avg and 1.3 Mgd avg during the dry year 2007 and the wet 1989, respectively. This suggests that the withdrawals in 2007 could have had an even greater effect on stream flow than the substantial impacts caused by the withdrawals in 1989.

There is no direct correlation between the 1989 and 2007 data. The North Stream is losing in 1989, but gaining in 2007, possibly because of storm runoff or the construction of the diversion channel around the north side of the quarry. The unit flows in 1989 (1.33 cfs) at site M6 (Danner Spring Branch) are much higher than those in 2007 (0.08 cfs), suggesting that Site M6 was upstream of the quarry discharge in 2007, as was verified in the KCL report. The unit flows increased between M9 and M10 in 1989 and decreased in 2007 between those two sites. One explanation for this is that the quarry trough of depression expanded between the two periods and was capturing flow from the main stem of Turkeyfoot Run in 2007; however, the flow measurements were taken nearly a month apart and there was a substantial reduction in the flows in Western Run between the dates of the measurements in Turkeyfoot Run. In addition, subsequent 2017 water table mapping, Figure 15, indicated that the capture zone did not reach the main stem of Turkeyfoot Run. No downstream measurement was taken in Stone Chapel Creek in 2007, but, based on the 1989 data and 2009 measurements that followed, it is reasonable to assume that the stream may have gone dry at that point. As with the 1989 data, the flows decrease downstream in Danner Spring Branch by about 50% from outside of (M4) to the middle of the trough of depression (M5). Flow at site M13 was subsurface beneath a rip-rap substrate and could not be measured.

Physical Habitat Index (PHI)

Six sites (M3, M6, M7, M8, M10 & M12) each had a severely degraded PHI rating. All, except site M3, which was in a gaining stream reach that was likely related to construction of the North Stream diversion channel, are outside or on the edge of the capture zone of the quarry. They are all near roads suggesting that proximity to the roads was the probable cause of the degraded conditions.

Benthic Index of Biotic Integrity (BIBI)

Site M1 had a good BIBI rating. Four other sites (M2, M7, M10 & M11a) had fair ratings. These five sites are all effectively outside of the influence of the quarry dewatering trough of depression. Eight other sites (M3, M4, M5, M6, M8, M9, M12 & M13) had poor BIBI ratings. Sites M4, M6, M8 and M9 are outside of the influence of the quarry and M3 was in a gaining stream reach. Sites M5 and M13 are within the capture zone of the quarry. In addition, sites M3, M6, M8, M9, & M12 are near roads, but, also, are sites M7, M10, M11a which all had fair ratings. These data would suggest proximity to roads may have been the primary factor affecting the BIBI indices, with quarry operations as a secondary cause.

Fish Index of Biotic Integrity (FIBI)

Sites M10 and M12 each had good FIBI ratings. Both are outside of the influence of quarry dewatering. Sites M1, M2, M3, M6, M8 & M9 had fair FIBI ratings. Sites M6, M8 and M9 are outside of the trough of depression. The 1989 flow data indicate that unit flows steadily declined between M1 and M3, suggesting that the decrease was due to quarry dewatering. The flows increased downstream in the North Stream in 2007, which may have been the result of storm runoff or construction of the North Stream diversion channel around the quarry. This may have allowed fish to pass upstream during a period of elevated flows or through the diversion channel. Sites M4, M5, M7, and M13 were not rated, because no fish could be found at those stations. There was no flow in Stone Chapel Creek downstream of site M7 in the wet year 1989, which was most likely the case during the dry year of 2007. In both years, the unit flows declined sharply downstream in Danner Spring Branch and there was no surface flow in a rip-rap lined channel at site M13. The most likely reason for the lack of fish in Danner Spring Branch and Stone Chapel Creek are barriers related to quarry operations that restricted fish passage.

Water Quality

KCI indicated that Turkeyfoot Run was a Class I stream, because it is a tributary of Double Pipe Creek. Double Pipe Creek is a tributary of the Monocacy River and, as such, it and Turkeyfoot Run are Class IV-P streams. The standards for Use IV-P waters are the same as Use I, except for temperature (75^0 vs 90^0 F) and additional toxic substance criteria.

KCI identified turbidity, pH, and nitrite levels as being the water quality parameters of concern during their Medford Quarry study. Turbidity was higher during the spring sampling period than the summer one, likely due to greater surface runoff. The highest levels in the spring were measured at sites M5, M6, M9, M11a, M12 & M13, while the lowest levels were at M1-4, M7, M8 & M10. The higher levels, except site M9, were in the vicinity of the quarry or immediately downstream of the discharge, while the lower levels were generally outside of the influence of the quarry or along the North Stream diversion channel. During the lower turbidity summer, the highest levels occurred at sites M5, M6 & M8, while the lowest levels were at M2, M4, M7, M9 & M10. In this case, the higher levels were in the vicinity of the quarry or downstream of the discharge, while the lower levels were outside of the influence of the quarry or in the diversion channel. During the two sampling periods, two sites, M5 & M6, were consistently high, while four, M2, M4, M7 & M10 were consistently low. Again, the higher levels were near the quarry and the lower ones outside of the quarry's influence.

Sites with slightly elevated pH levels were M2, M4, M5, M8 & M10. All, except M5, are outside of the influence of the quarry, suggesting that the high pH levels were probably related to the calcareous nature of an aquifer partially feeding the streams.

High nitrite levels observed at sites M9 and M10, both outside of the influence of the quarry, were probably due to farming activity.

Summary of biological monitoring data

Proximity to roads appears to be the reason for degraded PHI conditions. The lack of fish in Danner Spring Branch and Stone Chapel Creek is probably related to lack of flow or barriers to passage related to quarry operations. It appears that stream segments with low BIBI indices may have been due to both proximity to roads and the effects of quarry dewatering. The slightly elevated pH levels at several sites likely were related to the calcareous nature of an aquifer partially feeding the streams. High nitrate levels at two sites were probably related to farming activity.

Table 9. 2009 seepage runs in Turkeyfoot Run and its tributaries.

Map No.	Station	Date	D.A	D.A.	Flow	Unit flow	D.A. incr	Flow incr	Flow incr	Western Run	Antietam Crk	
			acres	mi^2	cfs	cfsm	mi^2	cfs	cfsm	cfsm	cfs	
9	S1	9/25/2009	86	0.14	0.13	0.93	0.14	0.13	0.93	0.80	0.43	dry downstream
												Total D.A. 0.52 mi^2
13	T4	10/6/2009	339	0.53	0	0.00	0.53	0	0.00	0.635	0.37	
11	T6	10/6/2009	364	0.57	0.54	0.95	0.57	0.54	0.95	0.635	0.37	T5-T6 tributary probably
12	T5	10/6/2009	545	0.85	0.94	1.11	0.28	0.40	1.43	0.635	0.37	captures flow from
14	T3	10/6/2009	1005	1.57	1.38	0.88	0.72	0.44	0.61	0.635	0.37	S1&T4 tributaries
15	T2	10/6/2009	1498	2.34	2.08	0.89	0.77	0.7	0.91	0.635	0.37	
17	T1	10/6/2009	2700	4.22	13.96	3.31	1.88	11.88	6.32	0.635	0.37	Discharge
5	D1	9/25/2009	92	0.14	0.42	3.00	0.14	0.42	3.00	0.80	0.43	
6	D2	9/25/2009	149	0.23	0.33	1.43	0.09	-0.09	-1.00	0.80	0.43	
7	D3	9/25/2009	298	0.47	0	0.00	0.24	-0.33	-1.38	0.80	0.43	
8	D4	9/25/2009	332	0.52	0.65	1.25	0.05	0.65	13.00	0.80	0.43	Leakage/Discharge
1	N1	10/5/2009	270	0.42	0.22	0.52	0.42	0.22	0.52	0.65	0.37	
2	N2	10/5/2009	325	0.51	0.21	0.41	0.09	-0.01	-0.11	0.65	0.37	
3	N3	10/5/2009	405	0.63	0.17	0.27	0.12	-0.04	-0.33	0.65	0.37	
4	N4	10/5/2009	462	0.72	0.16	0.22	0.09	-0.01	-0.11	0.65	0.37	
8	D4	11/9/2009	332	0.52	0.7	1.35		N/A		1.19	0.48	
4	N4	11/9/2009	462	0.72	1.13	1.57		N/A		1.19	0.48	
16	C1	11/9/2009	955	1.49	10.36	6.95	0.77	8.53	11.08	1.19	0.48	Discharge
15	T2	11/9/2009	1498	2.34	6.74	2.88	2.34	6.74	2.34	1.19	0.48	
17	T1	11/9/2009	2700	4.22	21.71	5.14	1.88	14.97	7.96	1.19	0.48	Discharge

S1 - Stone Chapel Creek
D1-4, C1 - Danner Spring Branch
N1-4 - North Stream
T1-6 - Turkeyfoot Run

Since the 2007 streamflow measurements were not synoptic, the permittee was required to take additional measurements as a permit condition that were completed in 2009, Table 9 and Figure 16. In that case, the units flow declined by 58% and 100% in the North Stream and Danner Spring Branch, respectively: however, the zero flow at site D3 Danner Spring Branch occurred in the same area as the 2007 site M13, where flows could not be measured due to subsurface flow beneath riprap. There were no downstream measurements in Stone Chapel Creek; however, the flows measured in 1989 and the lack of fish in 2007 suggest that the stream was likely dry during the 2009 study. There was a decline in the unit flow between T5 and T3 in Turkeyfoot Run. One explanation is that there was no flow at site T4 on a tributary to Turkeyfoot Run, which accounts for 33% of the drainage area at site T3. If the drainage area at T4 were subtracted from the areas at T3 and T2, then the unit flows would be 0.95 cfsm, 1.11 cfsm, 1.38 cfsm and 1.14 cfsm in downstream order from T6 to T2, which is consistent with a naturally flowing stream in a karst area. Since T4 was well outside of the quarry capture zone, there must be another reason for the lack of flow in that stream. On possible explanation is that there was thieving of water or a diversion from the unnamed tributary to the main channel of Turkeyfoot Run between T5 and T3, which is known to occur in karst areas.

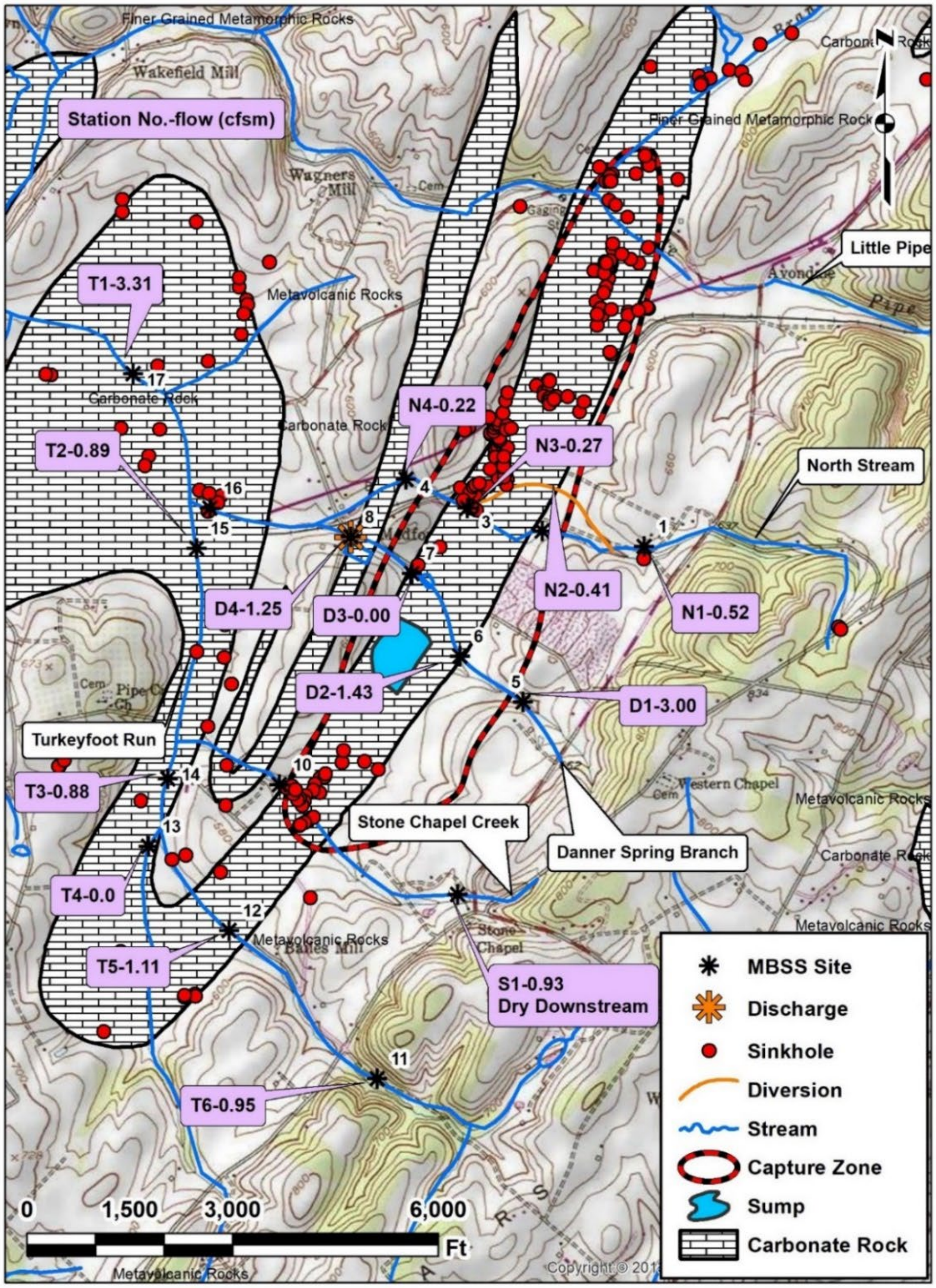

Figure 16. Topographic map, with carbonate geology and the 2009 seepage run results.

Separate seepage run and dye trace studies were completed in Copps Branch and Little Pipe Creek in 1994 and 2002, respectively, Figure 17. The 1994 investigation was completed by the MDE Water Quality Monitoring Program, (Steinfort, 1994). Streamflow was measured at four locations from Fenby Farm Road to just above the confluence of Copps Branch with Little Pipe Creek, Table 10. The flow from site A to site B increased by an average of 16%, as would be expected in a downstream direction. There was a minimal change between sites B and C of 3%, but the sites were relatively close to each other. The flow then declined by 46% between sites C and D, due to capture by an open sinkhole.

On an unknown date, while flow was 1.5 cfs above the sinkhole, flow downstream was 1.0 cfs, indicating that the acceptance capacity of the sinkhole was 0.5 cfs. To establish why Copps Branch was a "losing stream", a dye trace was conducted on July 13, 1994, by injecting a 20% Rhodamine WT solution into the sinkhole. Charcoal packets were planted at multiple sites throughout Little Pipe Creek, several test wells and two spring discharges on the floor of Medford Quarry pit #1. There was no recovery of dye over the following two weeks at the Little Pipe Creek stations at: The abandoned USGS Avondale stream gage, Roops Mill Road at Adams Mill Road, John Hyde Road at Roops Mill Road, and the Hyde Quarry. A major slug of dye, about 10 times background level, arrived at the Medford Quarry pit #1 north spring discharge six days later, on July 19, 1994. The was no detectable dye at the south spring of pit #1, indicating that the two springs had different sources.

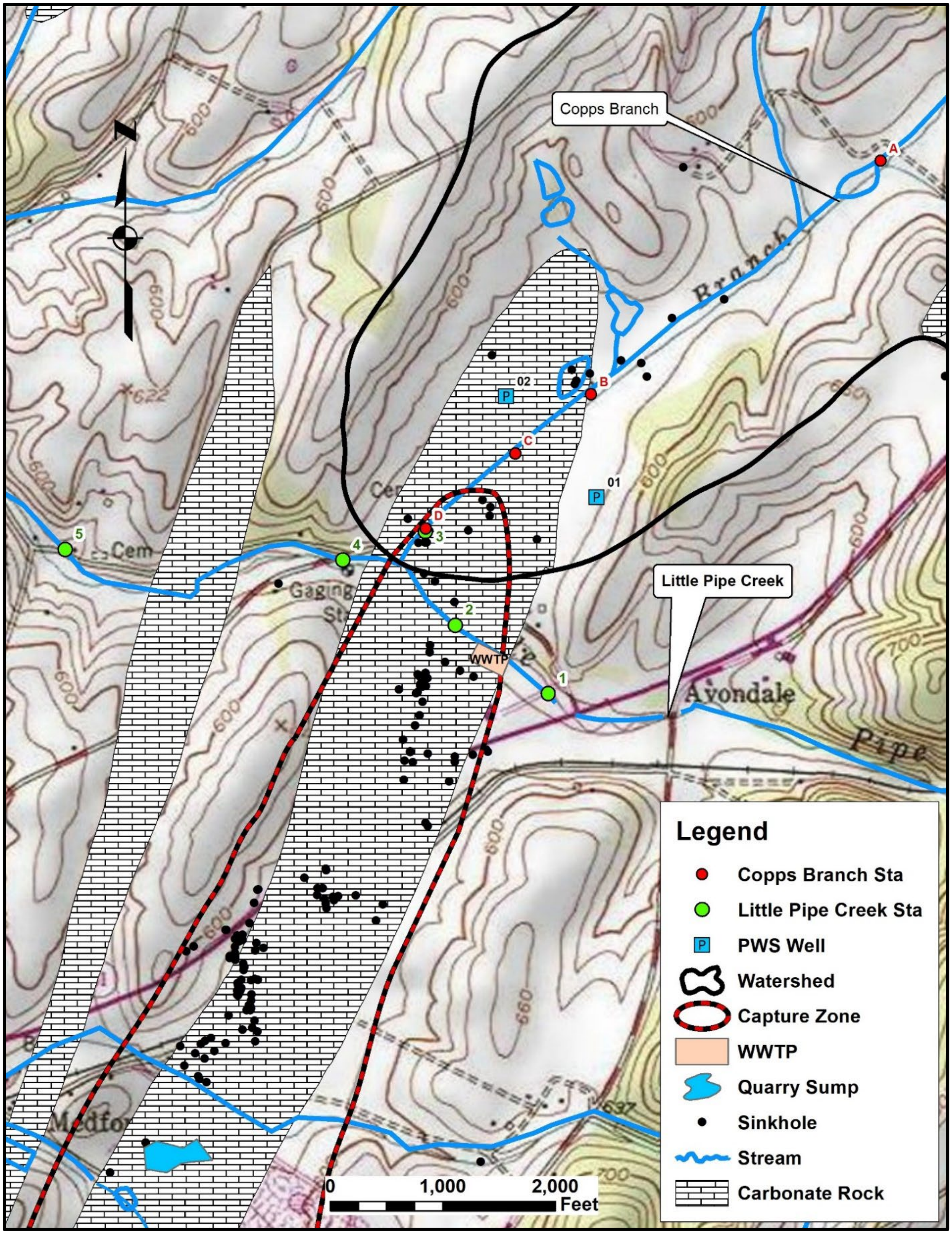

Figure 17. Topograhic map, with carbonate geology and the locations of the 1994 Copps Branch and 2002 Little Pipe Creek seepage run stations.

Table 10. 1994 seepage runs in Copps Branch.

Site	ID	5/27/1994	6/16/1994	6/18/1994	6/22/1994	Average	% Change
at Fenby Farm Road	A	0.426	0.388	0.577	0.448	0.460	
Upstream PW #1	B	0.523	0.447	0.618	0.547	0.534	16
Downstream PW #2	C	0.537	0.488	0.632	0.551	0.552	3
Upstream confluence with Little Pipe Creek	D	0.311	0.247	0.303	0.337	0.300	-46
		0 discharge 7/11/1994. 0.377 cfs flow into upstream sinkhole about 100 ft from MD 852. At undated flow of 1.5 cfs, with sinkhole open, 0.5 cfs flowed into sinkhole (acceptance capacity).					

In September 2002, Advanced Land and Water, Inc. (ALWI), Thomas and Eisner (2002), conducted stream flow measurements in Little Pipe Creek near the confluence with Copps Branch, Figure 17 and Table 11, followed up with a dye trace along the same reach of the creek with a recovery station in pit #1 of the quarry.

No flow was observed at station 3 (Copps Branch) on 8/29/2002 and that station was excluded from any further measurements. There was no record of any upstream flow measurements at station 3 that could be compared to the results of the 7/11/1994 MDE flow measurements (Steinfort, 1994) which indicated that there was upstream flow of 0.377 cfs when the stream was dry at station 3. It is noted that the times of 9/20/2002 measurements are probably in error. The time at station 1 may have been transposed from the earlier 9/6/2002 measurements. The later 9/20/2002 times are in order except for the AM/PM abbreviations. They are likely AM times, since most consultants tend to start work in early mornings.

Station 1 is immediately upstream of the Westminster WWTP and where natural flows in the creek (0.65 and 0.9 cfs) were measured. Most of the flows (72-76%) at station 2 were from the WWTP discharge. There were substantial declines (-12% and -41%) in flows between stations 2 and 4 that were in the same area as the quarry capture zone and sinkhole distribution trend, suggesting that quarry dewatering could have caused the lost flow. The flows then increase moderately (15%) and then substantially (51%) at station 5, which could either be the result of a natural gaining reach or a peak flow event moving through the stream reach. This could have been resolved by continuous flow measurements at each station or at the very least a continuous record of the WWTP discharge.

Table 11. 2002 seepage runs in Little Pipe Creek.

Station	Date	Time	Trial 1	Trial 2	Trial 3	Average	Change
			cfs	cfs	cfs	cfs	%
1	9/6/2002	11:25AM	0.79	0.53	0.62	0.65	-
	9/20/2002	11:25AM?	0.9	0.9	0.9	0.90	-
2	9/6/2002	1:30PM	3.7	3.81	3.3	3.60	-
	9/20/2002	7:30AM?	4	3.9	4.5	4.13	-
3	8/29/2002	N/R	0	0	0	0	-
4	9/6/2002	2:30PM	3.4	3.1	3.0	3.17	-12.0
	9/20/2002	8:30PM?	3.0	2.4	1.9	2.43	-41.0
5	9/6/2002	3:30PM	4.8	5.4	4.2	4.80	51.0
	9/20/2002	10:30PM?	2.7	2.8	2.9	2.80	15.0

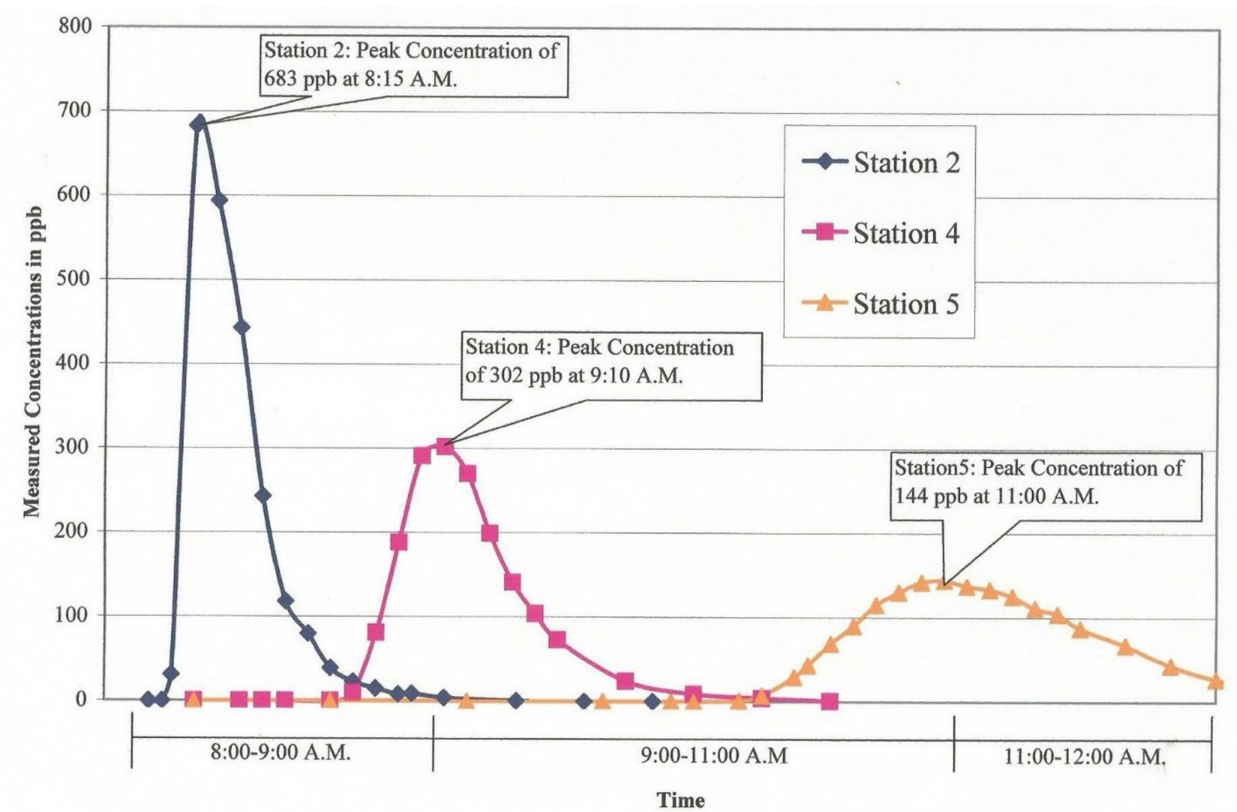

Figure 18. Histogram of initial dye concentrations in Little Pipe Creek on 9/12/2002. Reproduced from the ALWI, Thomas and Eisner (2002), report dated December 6, 2002.

Rhodamine WT dye was inserted into the WWTP aerator and released to Little Pipe Creek on 9/12/2002. Peak concentrations reached 683 ppb, 302 ppb and 144 ppb at stations 2, 4 and 5, respectively between 8:15 AM and 11 AM, Figure 18. Since fluorescent dyes are not conservative, the dye was probably lost downstream due to interaction with stream sediments by sorption and non-sorption mechanisms. Water samples were collected, and charcoal packets were deployed at the quarry during a 14-d monitoring period. The maximum concentration of dye at the quarry was 0.19 ppb on Day 13 or about 0.1% of the injected dye. An automatic sampler was also used to collect additional water samples with no detectable dye concentrations.

The substantial differences between the 1994 and 2002 dye trace studies of Little Pipe Creek/Copps Branch may be explained by a quantitative dye trace study conducted at the Security Quarry in Hagerstown. After a massive increase in pumpage at the quarry to 8.2 Mgd in December 2004, creek flow into a sinkhole on the opposite bank of Antietam Creek was dammed, which reduced the total flow to a cave on the quarry property by an estimated 30-50%. The dam was then partially opened, dye was injected into the sinkhole, and 69% of the dye was recovered discharging from the cave. The reported pumpage after the dye trace and probable repair of the sinkhole was reduced by 35%, which was within the estimated range of the reduced flow to the quarry cave when creek flow to the sinkhole was dammed. A second dye trace in Antietam Creek was conducted with a recovery at the cave of 0.12%. Since there was still a major inflow of water to the quarry, the low recovery rate from the creek trace was likely due to absorption by streambed sediments or by other chemical reactions.

At Little Pipe Creek, there was a substantial recovery of dye in the quarry that was injected in a sinkhole near the confluence of Little Pipe Creek during the 1994 trace, but no recovery in Little Pipe Creek. In 2002, dye injected at the WWTP was recovered at high, but diminishing downstream concentrations. There was a limited (0.1%) recovery at the quarry, which was likely due to sorption of the dye by stream sediments or clastic sediments in karst features or other chemical reactions.

A water balance analysis was performed to determine the sources of water for dewatering operations at the quarry. The key points to consider are that the seepage runs indicated that, within the capture zone of the quarry, Danner Spring Branch and Stone Chapel Creek went dry, and the Northern Stream flows were reduced by about 50%, while dye trace studies indicated that there was a possible hydraulic connection between Little Pipe Creek/Copps Branch and the quarry. The tributary watersheds were divided into sections, one each upstream of and one each within the capture zone of the quarry, Figure 19. The remainder of the contributing area included the area of the capture zone between the tributary basins and Little Pipe Creek/Copps Branch. Table 12 provides the results of the water balance analysis. The average of the unit flows from the 1989, 2007 and 2009 seepage runs were applied to the calculated drainage areas of each section of the three tributaries, while the unit flow for the North Stream was applied to the remainder of the capture zone toward Little Pipe Creek. Most of the water (53.4%) captured by quarry dewatering was from the spring fed Danner Spring Branch.

The water balance indicates that 96% of the total runoff within the capture zone and upstream tributaries is withdrawn by the quarry dewatering operation. To compare the amount of runoff captured to the pumpage from the quarry requires use of streamflow data from a USGS gaging station having a record from 1979 to 2021, or the period of reported water use at the quarry. The Little Pipe Creek gage (01640000) at Avondale has a short period of record (1947-1956) that does not overlap with the quarry pumpage. A 2008 informal AWLI report, Hammond (2009), correlated the Little Pipe Creek streamflow data, corrected for WWTP inflow, to the streamflow records for Slade Run at (01583000) at Glyndon. The result was a R^2 value equal to 0.84, indicating that the Slade Run data could be used for a longer period (1948-1980). That data; however, only can be compared to the first two years of quarry pumpage. Figure 20 is a chart of the average total runoff at both the Slade Run station at Glyndon and the Western Run station at Western Run for the period 1948 to 1980. There a good correlation between the two sets of data and since the Western Run gage data covers the period as the quarry pumpage (1979 to 2021) that stream flow data were used to estimate the amount of water captured by quarry dewatering activity. There is a good correlation between the pumpage and calculated captured runoff trendlines, Figure 21, except for the early few years which may be due to an end point error resulting from near record rainfall (59 in at BWI) in 1979. The result of the water balance analysis indicates that 78% of the pumpage comes from captured runoff from the upstream tributaries, while it is likely that the remaining 22% is diverted from Little Pipe Creek. This is consistent with the 20% of chloride recovered in the quarry pit during the 2002 Stearns & Wheler, Sturdevant (2003), dye trace of Little Pipe Creek and the arrival at the quarry of a major slug of Rhodamine WT after injection into a Copps Branch sinkhole during the 1994 MDE study.

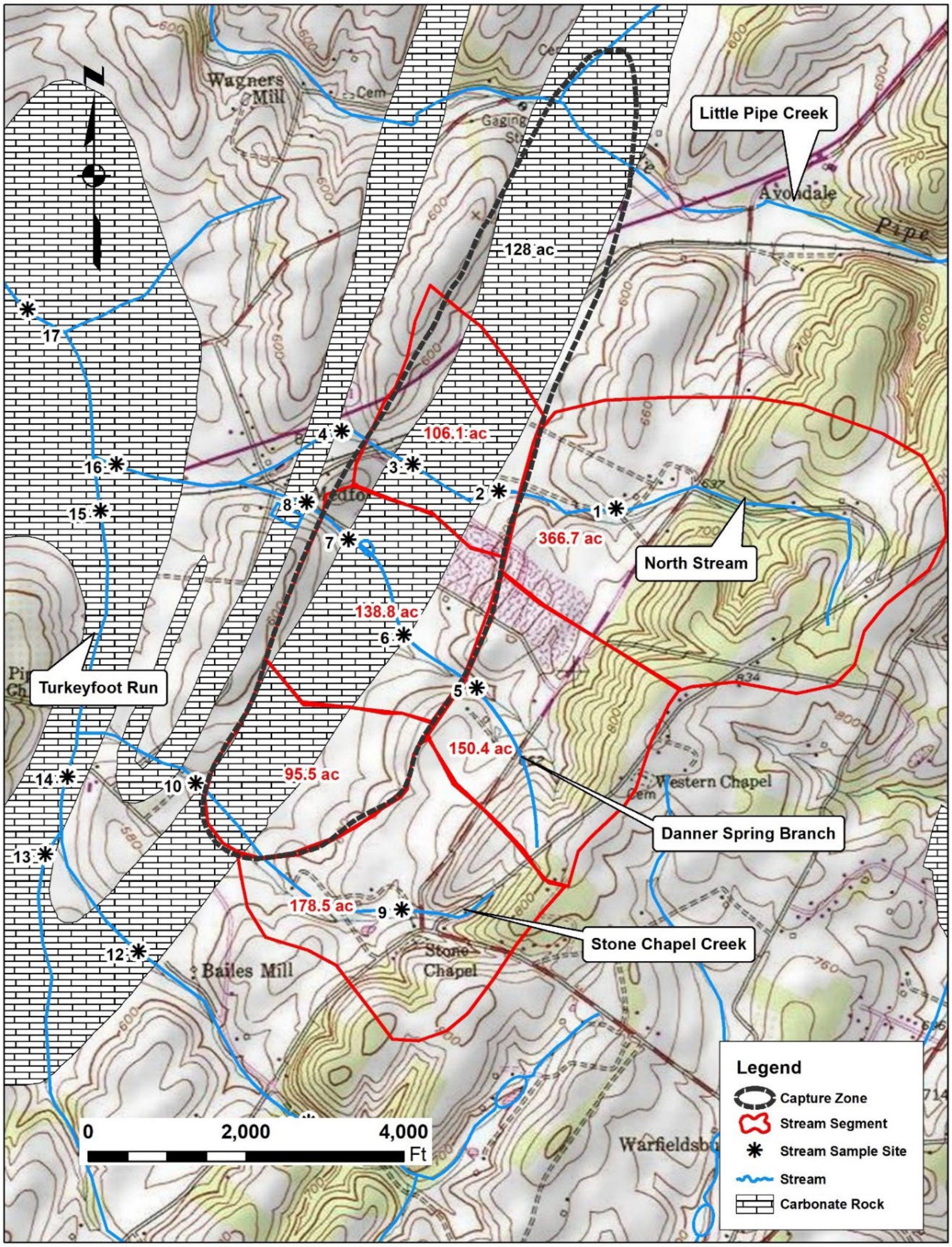

Figure 19. Topographic map with carbonate geology. Shown are the drainage areas of the stream segments used in the water balance analysis of the stream flows captured by dewatering of the Medford Quarry.

Table 12. Calculated stream flow captured by dewatering of the Medford Quarry.

Basin	D.A (ac)	D.A. (mi^2)	Unit Flow (cfsm)	Flow (cfs)	% Total
Upstream					
North Stream	336.7	0.53	0.39	0.205	23.0
Danner Spring Branch	150.4	0.24	1.92	0.451	50.6
Stone Chapel Creek	178.5	0.28	0.56	0.156	17.5
Remainder Capture Zone	128	0.20	0.39	0.078	8.8
Total	793.6	1.24		0.891	99.9
Downstream					
North Stream	106.1	0.17	0.19	0.032	100
Danner Spring Branch	138.8	0.22	0	0	0
Stone Chapel Creek	95.5	0.15	0	0	0
Remainder Capture Zone	128	0.20	0	0	0
Total	468.4	0.73		0.032	100
Total Loss (capture): 0.891 - 0.032 = 0.859 cfs or 96.4 % of total runoff					

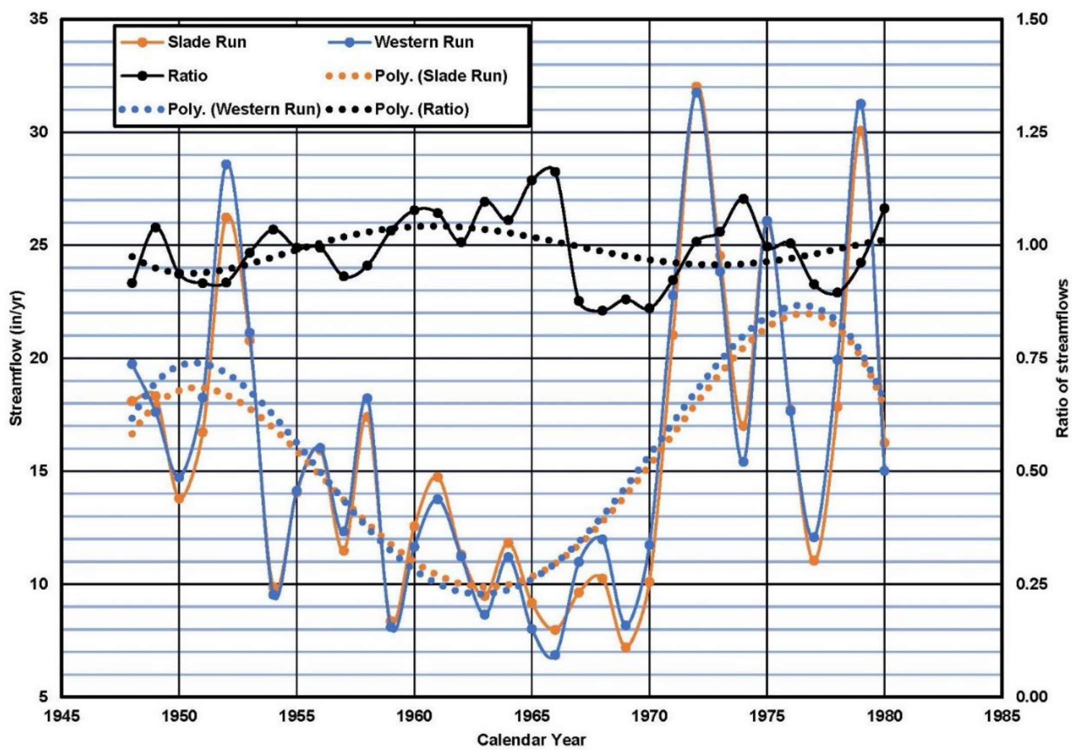

Figure 20. Comparison of the annual baseflows of Slade Run and Western Run during 1948-1980.

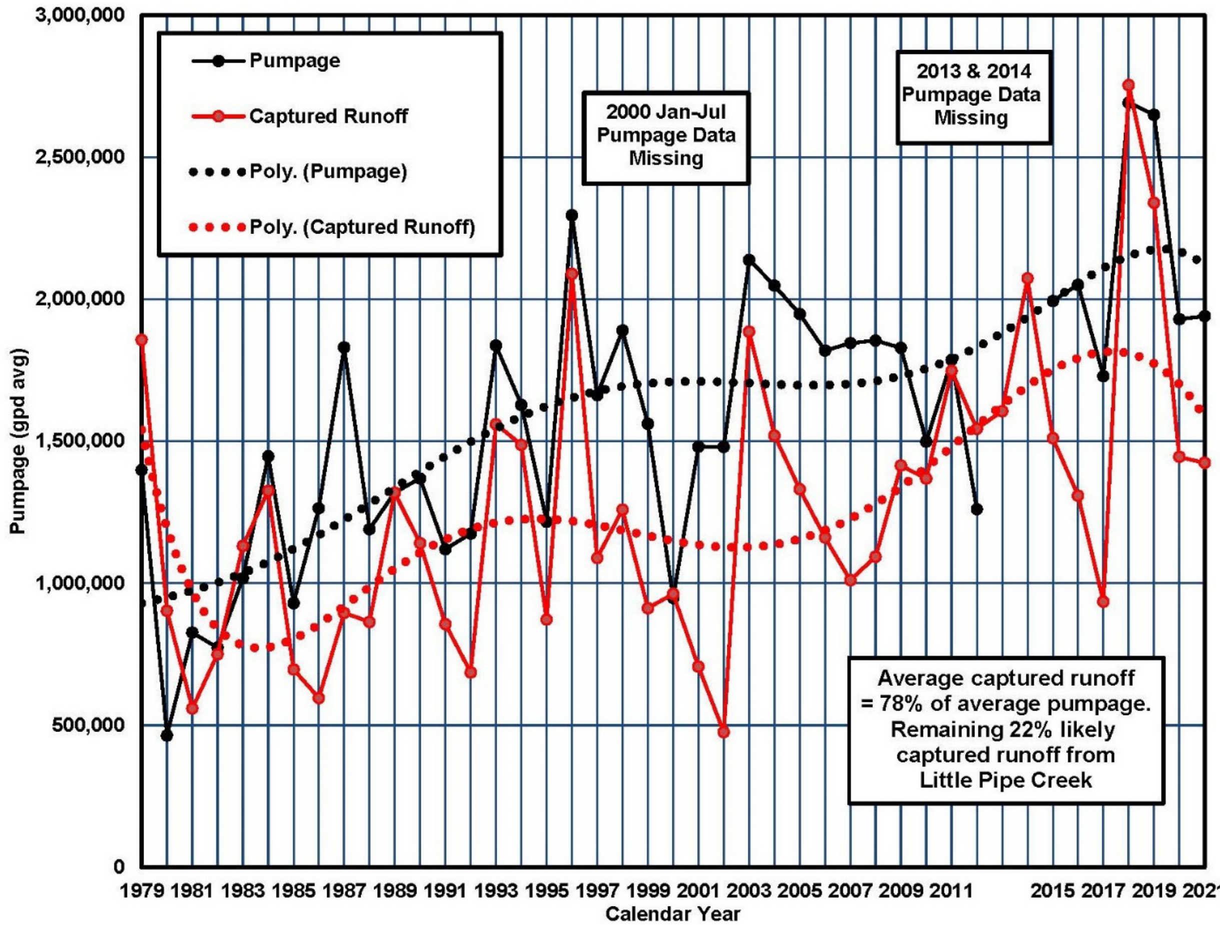

Figure 21. Comparison of the pumpage from the Medford Quarry and the calculated captured runoff due to dewatering of the quarry.

The available information on potential impacts to water wells due to dewatering of the Medford Quarry, Table 13, comes from three sources. The first two were joint public informational hearings on the water appropriation permit applications for the New Windsor and Medford quarries. The first hearing was held at the New Windsor Middle School on 5/24/1988 and the second at the West Middle School (Westminster) on 5/25/1988. The third source was the MDE Mining Program Well Interruption Database-ZOI. Initially, the property locations, except for that of Neil Ford, could not be determined; however, they were found through additional searches of the quarry water appropriation files.

Figure 22 shows the locations of four of the five wells, all which had reported problems. The fifth owner, Marlin Hoff, had three wells not shown of the map that were located 6 miles from the Medford Quarry which had no reported problems. Three wells (Purdum, Thompson and Ford) were located outside of both the capture zone and the 1997 ZOI of the quarry. The remaining well, Carroll County (CL CO) Foods was within the ZOI and just outside of the capture zone. The owner reported a reduced yield in 1986 that was still sufficient to meet water demand. There was no evidence that the well was replaced until possibly 1993. All the well problems occurred during the droughts of 1986, 1998 and 2002. In addition, all the wells were drilled into the crystalline, non-carbonate rock Wissahickon Formation, an aquifer that can produce low-yielding wells that are subject to decreased yields during droughts.

Also shown on the map is the 1500 ft zone used for water supply inventories during the water appropriation permit application process. There are 71 properties with wells on the 9/29/2009 inventory contained in the permit file, most which are east of the quarry, along Stone Chapel Road and West Chapel Road. The inventory did not include well location; however, it is likely only four wells (properties 1, 7, 10 and 11) were within the capture zone and ZOI. Other properties (12, 14, 16, 17 and 18) in the capture zone of ZOI were owned by the quarry operator. Other than the CL CO Foods well, no record could be found of any impacts to wells on the 2009 inventory.

Although there were no detailed investigations completed concerning impacts to individual wells, the available information indicates that droughts likely caused the reported well problems, not dewatering of the Medford Quarry.

Table 13. Well complaints made at public hearings or contained in Mining Program files related to dewatering of the Medford Quarry.

Name	Street Address	Town	Well Failure	Description - Solution	Replacement Well
			Date		Depth (≈ ft)
Purdam, James III	1531 or 1537 Nicodemus Road	New Windsor, MD 21776	1986	Well failure. No details	N/A
Hoff, Marlin	East side Hoke Road	New Windsor, MD 21776	N/A	West side of New Windsor. 6 miles from Medford Quarry. No record of water loss.	N/A
CL CO Foods	1333 Avondale Road	New Windsor, MD 21776	1986	Low yield. Deepened well	N/A
Thompson, James	1436 Nicodemus Road	New Windsor, MD 21776	8/3/1998	ZOI complaint. Well dry. 4 new wells drilled by Lafarge.	385
Ford, Neil	1431 Nicodemus Road	New Windsor, MD 21776	3/4/2002	ZOI complaint. No water	300

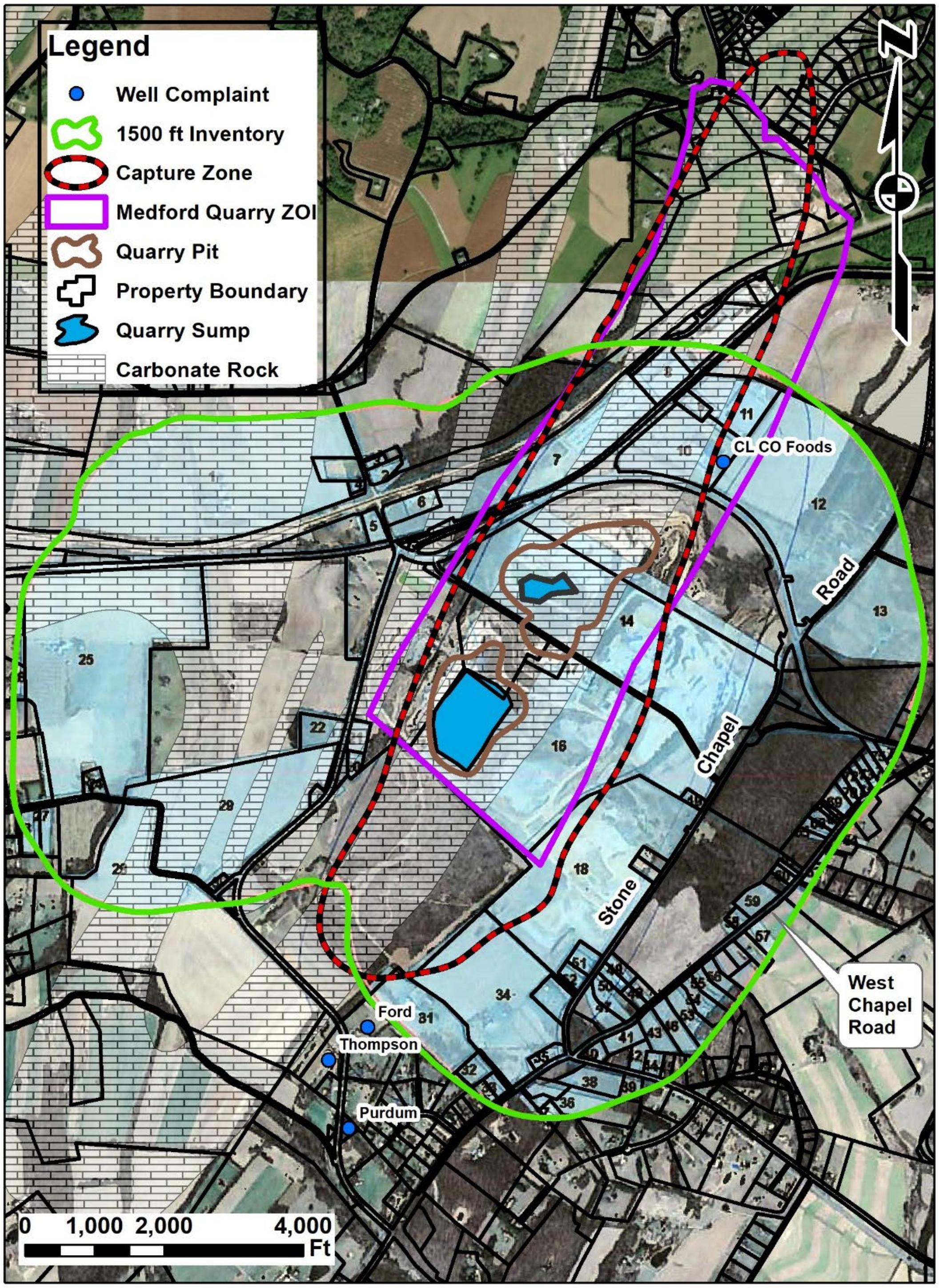

Figure 22. Aerial photos with carbonate geology overlain on 2009 water supply inventory and well complaints received by either the MDE Water Supply or Mining programs.

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