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Ohio Environmental Protection Agency

Gibsonburg Karst Investigation

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ABSTRACT

A ground water investigation was conducted in an unconfined Silurian dolomite aquifer in Gibsonburg, Ohio to help quantify ground water flow rates and gain a better understanding of the degree of karst development in the region. Since surficial karst features such as sinkholes, caves, and springs, were not apparent in the study area, dye traces were conducted using artificial injection and receptor sites, including public water system wells, monitoring wells, and quarries. Two fluorescein (uranine) dye traces were conducted under different public water system pumping scenarios. Dye was injected in a shallow monitoring well screened between 10 and 20 feet below ground surface. For the first dye trace, dye was detected in two of the three public water system wells monitored, at two monitoring wells, and in a quarry. The fastest measured flow rate was 3,500 feet/day, and represented flow to a monitoring well screened from 96 to 106 feet below ground surface that was within the zone of influence of the production wells. Results from the second trace indicated dye detections up to 20 times background levels in water samples from three of the five monitored public water supply wells and the quarry. Dye was first detected at Gibsonburg's well 7, 6.5 hours after injection, with a flow rate of 8,600 feet/day. Dye was also detected downgradient from the injection site at a quarry 8.5 hours after injection, representing a more ambient unstressed flow rate of 4,500 feet/day. This was the first hydrogeologic investigation in Ohio to utilize an artificial injection site and public water system well receptor sites and provides evidence that even though the area lacks surficial karst features, it still exhibits fast ground water flow rates indicative of a karst aquifer. Data from this study will be used to refine the drinking water source protection area for the Village of Gibsonburg and other public water systems utilizing this karst aquifer.

INTRODUCTION

Understanding the susceptibility and dynamics of Ohio's karst aquifers is necessary to help adequately protect the public water systems that rely on karst aquifers from contamination. The 1996 Amendments to the Safe Drinking Water Act required states to delineate drinking water source protection areas for all public water systems, including those located in karst aquifers. Ohio EPA initially utilized a semi-arbitrary fixed radius method to delineate protection areas for public water supplies located in karst settings. While the approach was consistently applied throughout the state, it was not scientifically rigorous. Now that Ohio EPA has completed the delineation requirements of the Safe Drinking Water Act, it is gathering additional data to help refine and improve upon the drinking water source protection areas delineated for public water supplies in vulnerable karst areas.

Literature suggests that the scientifically preferred method for delineating a public water system's drinking water source protection area in a karst region is to conduct a dye trace test and determine the ground water flow rates in the region (USEPA, 1997). Since conducting a dye trace at every public water supply in a karst region is impractical, Ohio EPA conducted representative investigations in several major karst regions where dye trace data was lacking. The information could then be extrapolated for the other public water supplies located within the region. Since very little information was available for some of the karst regions, the dye trace data was necessary to determine if porous media modeling assumptions were appropriate (minimal karst development) or if the groundwater traveled primarily via conduit flow. This information would be used to refine the existing drinking water source protection areas. The refined areas would offer improved protection to Ohio's public water supplies located in karst aquifers.

Previous Investigations

Historic data on flow rates are available for several Ohio karst aquifers and Ohio EPA collected data in two additional karst regions, but data was still lacking for the relatively flat-lying less-developed shallow unconfined Silurian dolomite aquifer in northwest Ohio (See Figure 1). Successful dye traces have been conducted by others in the Devonian carbonates of the Bellevue-Castalia karst plain (ODNR 1994), the Olentangy River Gorges (McCullough 2004), and the unglaciated karst escarpment in Pike County (Fields 2006). All of the documented dye traces yielded fast flow rates indicative of karst hydrogeology (over 500 feet/day in glaciated regions and 5,900 feet/day in unglaciated karst). Ohio EPA karst investigations in the Dissected Niagara Escarpment in Clark County in 2008 yielded flow rates ranging from 3,100 – 28,800 feet/day and a 2009 Ohio EPA investigation in the paleoreef carbonate ridge region of Wyandot and surrounding counties yielded flow rates ranging from 1,700 - 67,000 feet/day. Data on the less-developed Silurian dolomite aquifer in western Sandusky County and the surrounding karst region was not available. Since surficial karst features were absent or poorly developed in this region, it was questionable whether this area should even be classified as a karst aquifer.

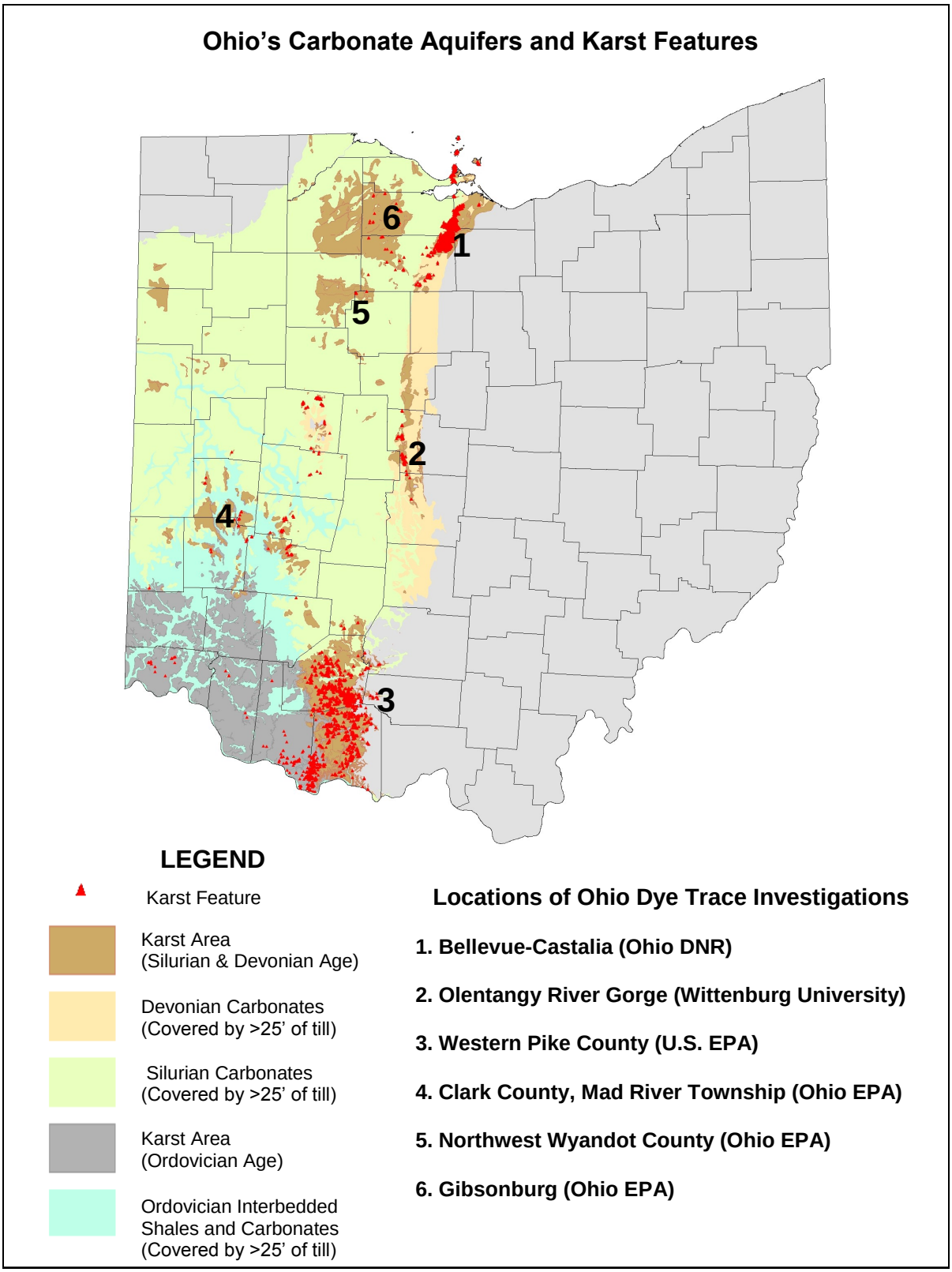


Figure 1. Ohio's Karst Geology and Locations of Dye Trace Investigations.

Purpose of Investigation

The purpose of this investigation was to assess the level of karst development and determine the ground water flow rates in the northwestern Ohio Silurian dolomite aquifer. Further, this was the first investigation to take place within a community water system's wellfield with deep wells. It would help determine whether karst flow was restricted to the uppermost portion of the aquifer or if flowpaths intersected deeper portions. Two fluorescein dye traces were conducted in March and June of 2009, with dye injected into a shallow monitoring well. Additional monitoring wells, public water supply wells, and quarries were utilized as potential receptor sites. The information gained from this investigation will be used to select appropriate drinking water source protection area delineation methods for public water systems located within the region. In addition, the information will be used to help better respond to ground water contamination events in the northwestern Silurian dolomite aquifer.

Physical Setting and Hydrogeology

The area under investigation is located in the Village of Gibsonburg, in Sandusky County. The study area lies on the boundary between the Sandusky and Cedar-Portage Hydrologic Unit Code 8 watersheds. There are no perennial streams located within the immediate study area. The headwaters to Nine Mile Creek and Wolf Creek are located approximately two miles to the northeast of the study area, Sugar Creek is located 2.2 miles to the northwest, and Mudd Creek is located 4.2 miles to the Southeast. The area is flat-lying, with a very slight grade northeast towards Lake Erie.

The aquifer in this region is made up of the undifferentiated Lockport dolomite (See Figure 2). The Lockport is described by the Ohio Department of Natural Resources as being fine-grained and massive with less fracturing and solution weathering than the other dolomites in Sandusky County (ODNR, 1991). Sinkholes and caves were not located within the immediate study area, but local dolomite quarries and well logs indicate that

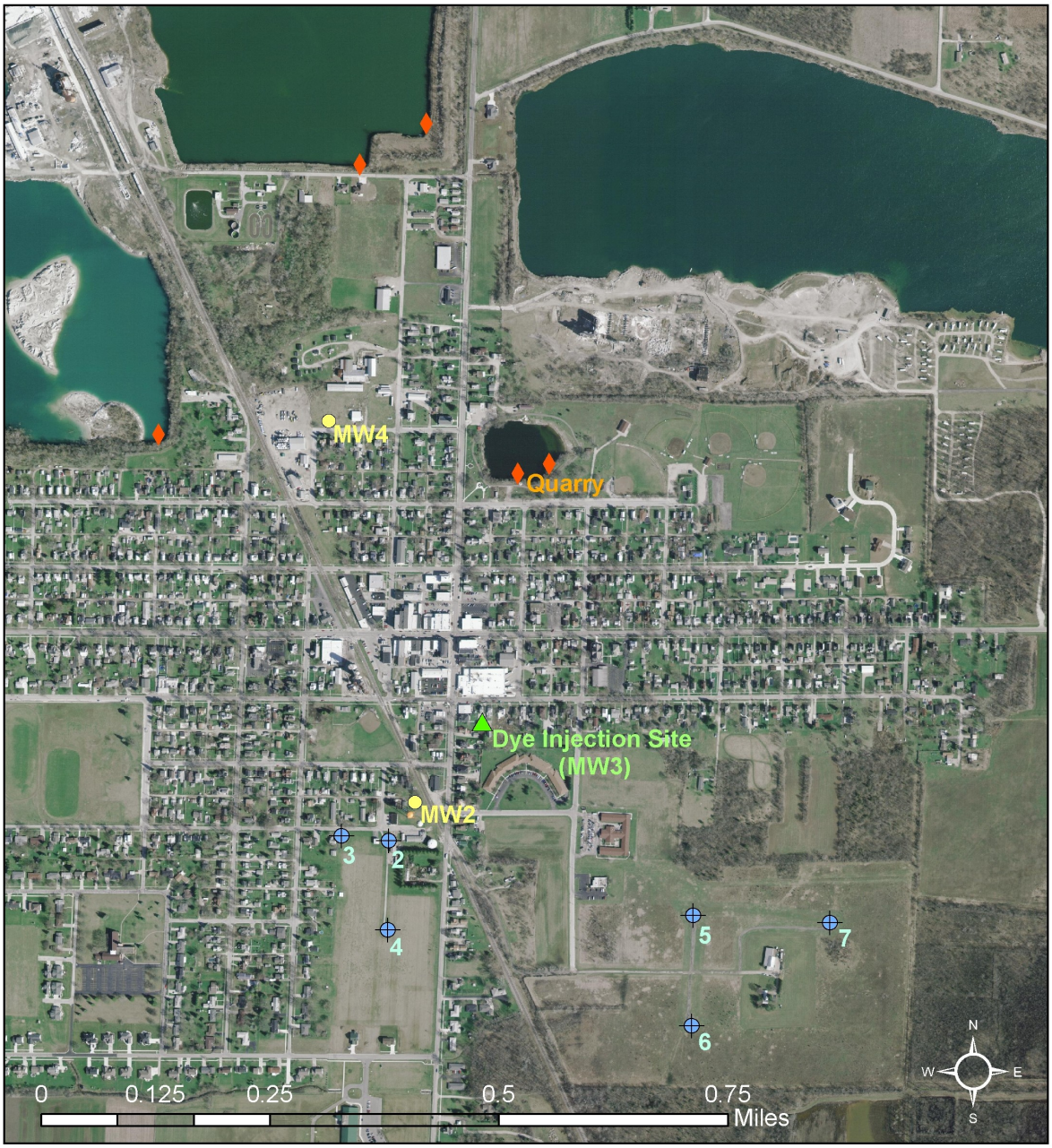
Figure 2. Exposed Lockport Dolomite at Gibsonburg. Pictures depict bedding planes, vertical fractures, and dissolution features observed at abandoned quarries in Gibsonburg, Ohio.

Indicate that the dolomite bedrock is fractured and close to the ground surface. Rock cores from four monitoring wells Ohio EPA drilled in Gibsonburg in 2008 indicate that the degree of fracturing in the formation is variable, but all cores exhibited some degree of intense fracturing (recovered core lengths less than 0.33 feet, with fragmented lengths averaging 0.1 -0.33 feet) even at depths up to 287 feet below ground surface. This degree of fracturing was higher than expected, based on prior descriptions for the Lockport formation. The Lockport may exhibit a higher degree of fracturing in all areas where the glacial cover is thin or absent. Water tables in this region are high, with static depths to water of four to twelve feet below ground surface.

The Village of Gibsonburg operates six public water supply wells in the region (See Figure 3). The wells pump an average of 401,000 gallons of water a day with a plant design capacity of 620,000 gallons/day. The water system serves a population of 2,450 residents. Wells range in depth from 293 to 342 feet below ground surface and have casing depths that vary from 26 to 67 feet. Table 1 provides a detailed description of both the Village's public water supply wells and four monitoring wells. Ground water flow is to the north-northeast towards Lake Erie, the regional discharge feature (See Figure 4). Localized flow, under pumping conditions, is somewhat radial towards the public water system wells.

Table 1. Well Construction Data.

Well Name	Depth to Bedrock (feet)	Total Depth (feet)	Casing Length (feet)	Casing Diameter (inches)	Pump Capacity (gpm)
Monitoring Well 1	4	300	291	2	N/A
Monitoring Well 2	12	106	96	2	N/A
Monitoring Well 3	7	30	20	2	N/A
Monitoring Well 4	9.5	60	50	2	N/A
Gibsonburg Well 2	Unknown	293	50	10	115
Gibsonburg Well 3	Unknown	313	67	10	221
Gibsonburg Well 4	Unknown	301	26	10	135
Gibsonburg Well 5	3	315	27	10	75
Gibsonburg Well 6	5	342	33.4	10	117
Gibsonburg Well 7	5	322	35.7	10	525



Legend

- Dye Injection Location (Monitoring Well #2)
- Gibsonburg's Public Water System Wells
- Ohio EPA Monitoring Wells
- Quarry Sampling Sites

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Figure 3. Study Area Map. Map depicts locations of dye injection site and ground water sampling locations.

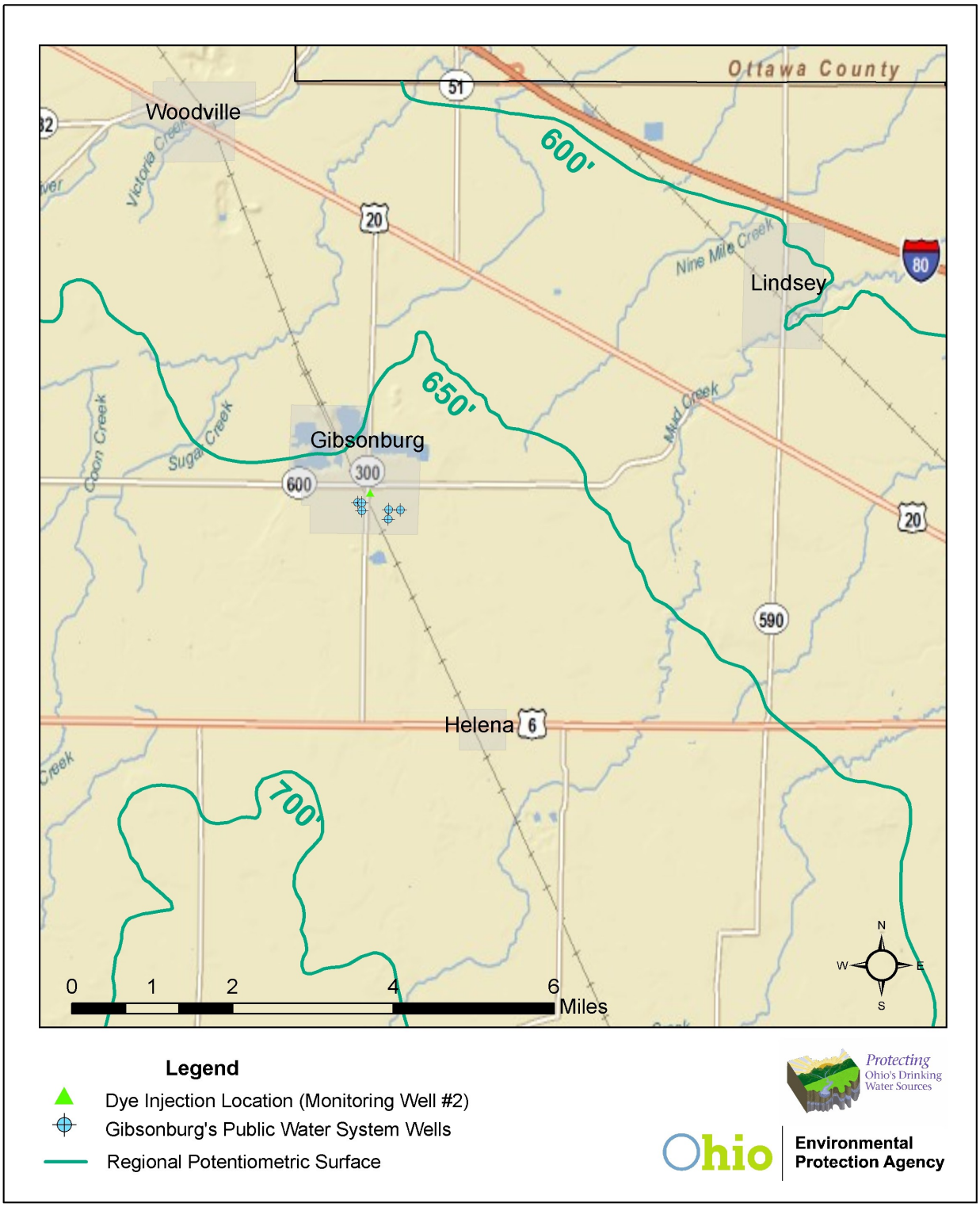

Figure 4. Regional Potentiometric Surface Map. Map created by the United States Geological Survey as part of the Regional Aquifer System Analysis project in 1994 using contemporaneously measured ground water levels.

METHODS

Wherever possible, the recommendations outlined in Alexander and Quinlan's "Practical Tracing of Groundwater with Emphasis on Karst Terranes" were used for this investigation (U.S. EPA, 1996). Fluorescein dye (also referred to as Uranine or Acid Yellow 73) was selected as a tracer because it is a conservative tracer and is considered to be non-toxic even at visibly detectable levels (Fields et. al., 1995).

An infiltration capacity test was performed at Ohio EPA monitoring well 3 to determine if it could be used as an injection site. Five hundred gallons of hauled water were injected into the monitoring well, at a sustained rate of 2.6 gallons per minute. This rate is considered adequate for a suitable injection location (Aley, 2002). The infiltration test was performed twenty days prior to dye injection.

After dye was injected in the monitoring well it was chased with approximately 300 gallons of water to ensure the dye was effectively flushed out of the well casing and into the aquifer. ISCO auto-samplers were used at primary sampling sites to collect water samples at regular intervals (See Figure 5). Water taps (pre-treatment) at each public water system well were left open and flowed into a water cooler set up as a sampling reservoir (See Figure 5). The overflow from the water cooler was directed outside of the well houses and gates. A Turner Designs Model 10-000 R fluorometer was used to analyze water samples in the field and lab for fluorescein dye concentration (See Figure 6).

Figure 6. Field Calibrating Fluorometer.

Charcoal dye detectors were used in more distant sampling sites and in conjunction with the auto-samplers to compare results from the two sampling methods (See Figure 7). The charcoal dye detector sampling method is a good

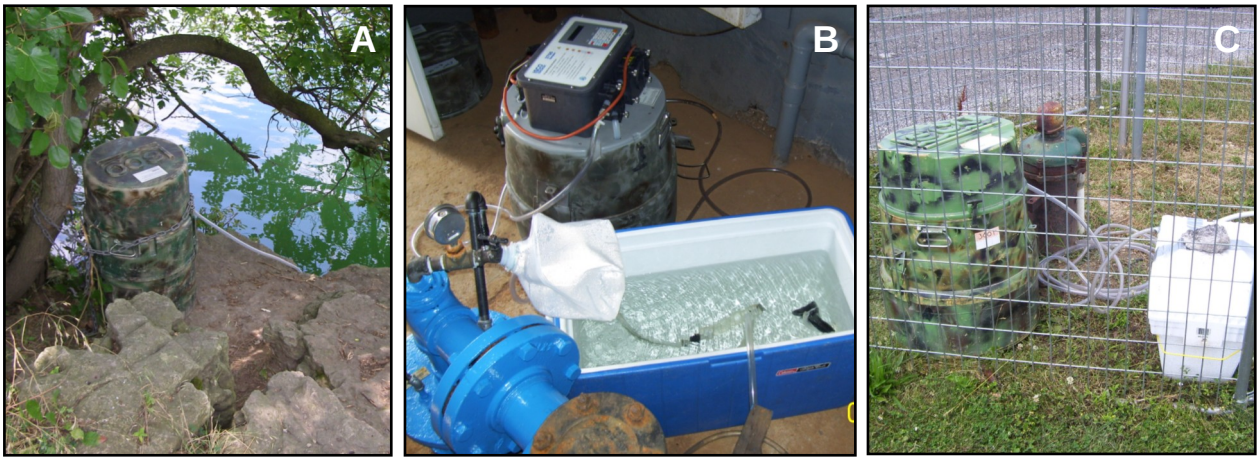

Figure 5. Automated Water Sample Collection Methods. A. Sampler at Williams Park Quarry. B. Sampler at Gibsonburg Well 2 (inside well house). C. Sampler at Gibsonburg Well 6 (inside fenced area).

back-up to discrete water sampling, because it represents a continuous sample and the method is more likely to detect dye in small quantities and not miss a slug of dye that is quickly passing through the aquifer. Dye detectors were constructed by stapling vinyl screening into double packets, filling each packet with two teaspoons of granulated activated charcoal, and securing them at the top with a paper clip. The dye detectors used to sample public water system well water were placed in the bottom of the cooler used as a temporary water storage basin. Stainless steel nuts were attached to dye detectors used in the monitoring wells and some quarries to act as sinkers. These detectors were attached to undyed monofilament fishing line and lowered to either the screened interval of the monitoring well or a few feet below the water surface in quarries. In streams and some quarries, the dye detectors were attached to either concrete blocks using copper wire or to smaller home-made concrete sampling devices often referred to as "gumdrops." Gumdrops were constructed out of quikrete and wire clothes-hangers and were anchored to a nearby tree with monofilament fishing line to ensure the dye detector did not drop deep into the quarry where it would not be retrievable. Concrete blocks used in streams were similarly anchored with polypropylene rope to trees or bridge structures.

Dye detectors were changed at regular intervals, and collected detectors were stored on ice and transferred to a refrigerator prior to testing at the lab. After the test ended, all charcoal packets were brought to the lab and rinsed thoroughly to remove any sediment or algae that might interfere with analysis. Approximately two tablespoons of charcoal from each packet was collected and placed in individual, labeled, disposable plastic cups. The remaining charcoal was placed on ice to be used as a back-up if there was lab or sample error asso-

Figure 7. Charcoal Sample Collection Methods. A. Monitoring well sampling technique. B. Monitoring well charcoal packet design. C. Quarry and Gibsobburg well charcoal packet design.

ciated with the readings from the first set of samples. A 10ml solution of 5% potassium hydroxide in 70% isopropyl alcohol was added to each cup to elute the dye. After one hour, any visible dye coloration was noted and the elutant was decanted into individual cuvette containers to be read in the fluorometer.

A combination of methods was used to estimate quantities of dye needed for each trace, end point dye concentrations, and optimum sampling frequency at each receptor site. U.S. EPA's Environmental Hydrologic Tracer Design (EHTD) program had been used to successfully determine dye trace concentration curves at receptor sites for past dye traces (Ohio EPA 2009), but the program was not as helpful for this investigation due to program limitations. Since springs were not apparent at this study area, Ohio EPA used the discharge from public water system wells as a substitute for the calculations. Determining what an appropriate cross-section area to use (easy to determine for springs) was more difficult, and the program output was highly sensitive to this parameter. Depending on what value was selected, predicted arrival times ranged from hours to years. Perhaps in the future the EHDT program can be calibrated to similar well-to-well dye traces and better guidance on parameter selection can be developed. Since there was a high level of uncertainty in the EHTD program results, the dye injection volume for the first trace was based on a worst case scenario of 100 percent of the injected dye entering the Village of Gibsonburg's clear well. The Village did not want a visibly detectable quantity of dye in their water system, and basing the injection volume on the worst case mixing scenario ensured a visible detection was not possible. Anticipated arrival times were based in part on the earliest possible arrival time as predicted by the EHTD model. Water samples were collected at frequent intervals, with a plan to decrease sampling frequency after a set period of time if dye was not detected. Since precipitation can affect travel times, data from the nearest weather station located in Fremont was collected and analyzed for a week prior to dye injection and for the entire time samples were collected following dye injection.

Quality Assurance

Water samples were taken from sampling locations prior to injecting the dye, and were tested for the presence of background levels of dye using the fluorometer. In addition, dye detectors were placed at the sampling location and then collected prior to injecting the dye. Dye detectors were analyzed for the presence of fluorescein prior to injecting the dye, to ensure the detectors were operating properly, were not contaminated with dye, and there was little to no background dye present in the aquifer. Grab samples collected at ground water sampling sites prior to dye injection had fluorescein concentrations that ranged from 0.21 – 0.31 ppb. The fluorometer was calibrated using prepared standards prior to reading each set of samples (at least daily). Field measurements were always confirmed with measurements taken in the lab to reduce any potential error that could be attributed to a failing power source (rechargeable batteries used in the field could give marginally lower readings if they were low on power).

To avoid cross-contamination, the individual responsible for handling and injecting dye did not collect any samples on the day dye was injected. Collected samples were placed in coolers and

wrapped in evidence tape to ensure tampering did not occur with the samples prior to analysis. In all cases, the Quality Assurance and Quality Control procedures outlined in Appendix B of U.S. EPA's "Guidelines for Wellhead and Springhead Protection Area Delineation in Carbonate Rocks" were followed (1996).

First Dye Trace

For the first trace, 50 ml of a 41.75% fluorescein dye solution was injected into Ohio EPA monitoring well 3 on March 24, 2009 (See Figure 8). The monitoring well is screened from 20 to 30 feet below ground surface and bedrock is encountered at a depth of seven feet. The depth to water was 4.3 feet below ground surface immediately preceding dye injection. Well construction information for this and all other monitoring and public water system wells is depicted in Table 1. Charcoal dye detectors and water samples were collected at four surface water receptor sites and six ground water receptor sites.

Figure 8. Injecting 50ml of Fluorescein Dye into Monitoring Well 2.

One hour prior to dye injection the Village's pumping schedule was varied from normal, as follows: well 2, the water supply well located closest to the injection site, was pumped continuously for 24 hours and then pumped 15 minutes out of every hour thereafter and the remaining public water supply wells were pumped at their normal rate of 15 minutes out of every hour. On April 2nd, the Village resumed its normal pumping schedule, which is all wells pumping 15 minutes out of every hour, except for well 2, which pumps 15 minutes every two hours. Table 2 lists the daily total pumping rates for each well for the entire month of March. The pumping schedule was modified in an effort to increase the likelihood of observing dye in the wells located closest to the injection site.

Samples were collected every 15 minutes at Gibsonburg's well 2 for six hours and then collected hourly until March 27th. Hourly samples were also collected at Gibsonburg's wells 3 and 4 until March 27th. Gibsonburg's well 2 was sampled every 1.5 hours and wells 3 and 4 were sampled every three hours until April 2nd and then sampled at a reduced rate until April 29th. Charcoal packets were changed daily at Gibsonburg's wells 2, 3, and 4, Ohio EPA's monitoring wells 2 and 4, and a local inactive dolomite quarry until March 27th and then changed at a less frequent interval until April 29th. Water samples were also collected periodically at the monitoring wells and quarry (See Figure 9).

Table 2. March Pumping Rates for Gibsonburg's Wells.

Date	Pump Rate (gallons/minute)					
March	**Well 2**	**Well 3**	**Well 4**	**Well 5**	**Well 6**	**Well 7**
1	10000	52100	34100	17900	29900	75000
2	19600	95600	64700	33600	53900	134000
3	19800	100200	68000	35100	63400	141000
4	19600	97000	65300	34000	57500	137000
5	29500	96100	64700	33200	58800	134000
6	19800	98600	66500	35000	61800	140000
7	19000	96200	64600	33400	59000	135000
8	8600	48000	31000	16900	29200	68000
9	17500	88400	59200	31200	54100	126000
10	19500	98900	66600	34700	61100	139000
11	19300	94200	62400	32800	57600	132000
12	19600	98200	66800	35300	62100	141000
13	17700	92900	62300	32800	57300	132000
14	18900	93400	62400	32700	57900	132000
15	10800	53300	34300	18700	32900	76000
16	19100	98800	66200	34500	58300	140000
17	19200	93700	63500	32900	46500	132000
18	20000	99200	66200	34400	61200	139000
19	18300	95400	63800	33500	56700	135000
20	19500	100600	68500	35200	59100	142000
21	19500	93000	62400	32300	57900	130000
22	10400	53300	34400	18500	33100	76000
23	28200	99600	65400	34600	60800	138000
24	62200	97100	62300	33600	60000	135000
25	47200	108500	72500	37400	64300	152000
26	47200	109000	72600	37200	65100	148000
27	41800	95100	63600	33400	59600	134000
28	40300	93200	61600	31300	55500	126000
29	20900	50000	32000	17500	30500	71000
30	46800	107300	71400	36900	66300	148000
31	44800	101800	68100	33100	60900	136000

Figure 9. Collected Samples are Prepared for Analysis in the Laboratory.

Second Dye Trace

For the second trace, the volume of injected dye was increased to 500 ml, the public water system's pumping schedule was modified, and additional locations were monitored for dye. For this trace, Gibsonburg's wells 3, 4, 5, 6, and 7 were all pumped at their normal schedule of 15 minutes for every hour, but well 2 was not pumped for the first four days of the test (See Table 3). This pumping modification was made in part to help determine if flow was limited to main fractures between the injection site and Gibsonburg's well 2 or if ground water flow was more interconnected and distributed in nature. Dye was injected on July 21, 2009. Grab samples were collected hourly at Gibsonburg's wells 3-7 and at the quarry until July 24th and then once every three hours at all of Gibsonburg's wells and the quarry until July 27th. Additional sampling occurred at a reduced sampling rate until August 4th. Water samples were also collected at monitoring wells 2 and 4. As a back-up, charcoal packets were placed and changed at regular intervals at all sites.

RESULTS

First Dye Trace

Water samples collected from the first dye test showed slightly elevated fluorescein concentrations (approximately four times background levels) at four sites: Ohio EPA monitoring well 2 and 4, Gibsonburg's well 2, and at the quarry. A water sample taken at Ohio EPA monitoring well 2 four and one half hours after injection had a fluorescein concentration of 2.2 ppb and represents the fastest flow path from injection site to receptor site (3,500 feet/day). Monitoring well 2 is screened from 96 to 106 feet below ground surface and is located approximately 650 feet away from the injection site. The elevated fluorescein was not, however, corroborated by elevated levels in the charcoal data. The highest observed concentration of fluorescein in a public water system well water sample was 1.1 ppb and was collected 24 hours after dye injection at Gibsonburg's well 2. A cross section showing the relative position of Gibsonburg well 2, Ohio EPA monitoring well 2, the injection location, and the quarry is depicted in Figure 10.

Four sites had elevated fluorescein in the charcoal samples (See Figure 11). Dye detections occurred within 24 hours at Gibsonburg's wells 2 and 3, which are located approximately 900 and 1100 feet from the injection site and at Ohio EPA monitoring well 4 and the

Table 3. July Pumping Rates for Gibsonburg's Wells.

Date	Pump Rate (gallons/minute)					
July	**Well 2**	**Well 3**	**Well 4**	**Well 5**	**Well 6**	**Well 7**
1	23400	117000	80700	39600	74600	152000
2	23700	113300	78300	38000	71700	147000
3	22900	118600	83000	41000	77100	157000
4	22800	102800	70400	35300	64900	136000
5	15800	76400	50200	26200	43400	104000
6	20000	97800	69000	33800	59200	126000
7	24100	120300	83600	39900	59000	153000
8	25400	118000	81700	39900	75600	153000
9	26900	127500	89100	42200	80800	163000
10	25700	118900	83400	40600	77100	155000
11	23100	116700	81200	39400	74600	152000
12	13700	65600	43600	23100	43100	90000
13	22900	113600	78800	38600	73200	149000
14	24100	118600	83600	40000	53800	155000
15	24200	113700	79700	38400	73900	149000
16	24600	127400	89900	42700	82700	165000
17	27900	128100	90200	42300	83200	166000
18	27800	130700	92300	42500	84700	169000
19	16000	72100	48100	24600	45900	96000
20	24600	119500	83900	40000	77400	156000
21	22600	133000	94800	43000	86800	171000
22	0	134800	97000	43500	88200	173000
23	0	129900	92300	41300	83200	165000
24	0	123800	88900	40800	83000	162000
25	10000	133700	95300	43200	87300	171000
26	15000	71900	48200	23000	44700	94000
27	27900	128200	90100	42000	84800	168000
28	25500	122400	85900	39400	78400	156000
29	23900	112300	79100	38400	75400	149000
30	24500	111800	77300	37400	71100	147000
31	23100	108500	76300	34500	69000	140000

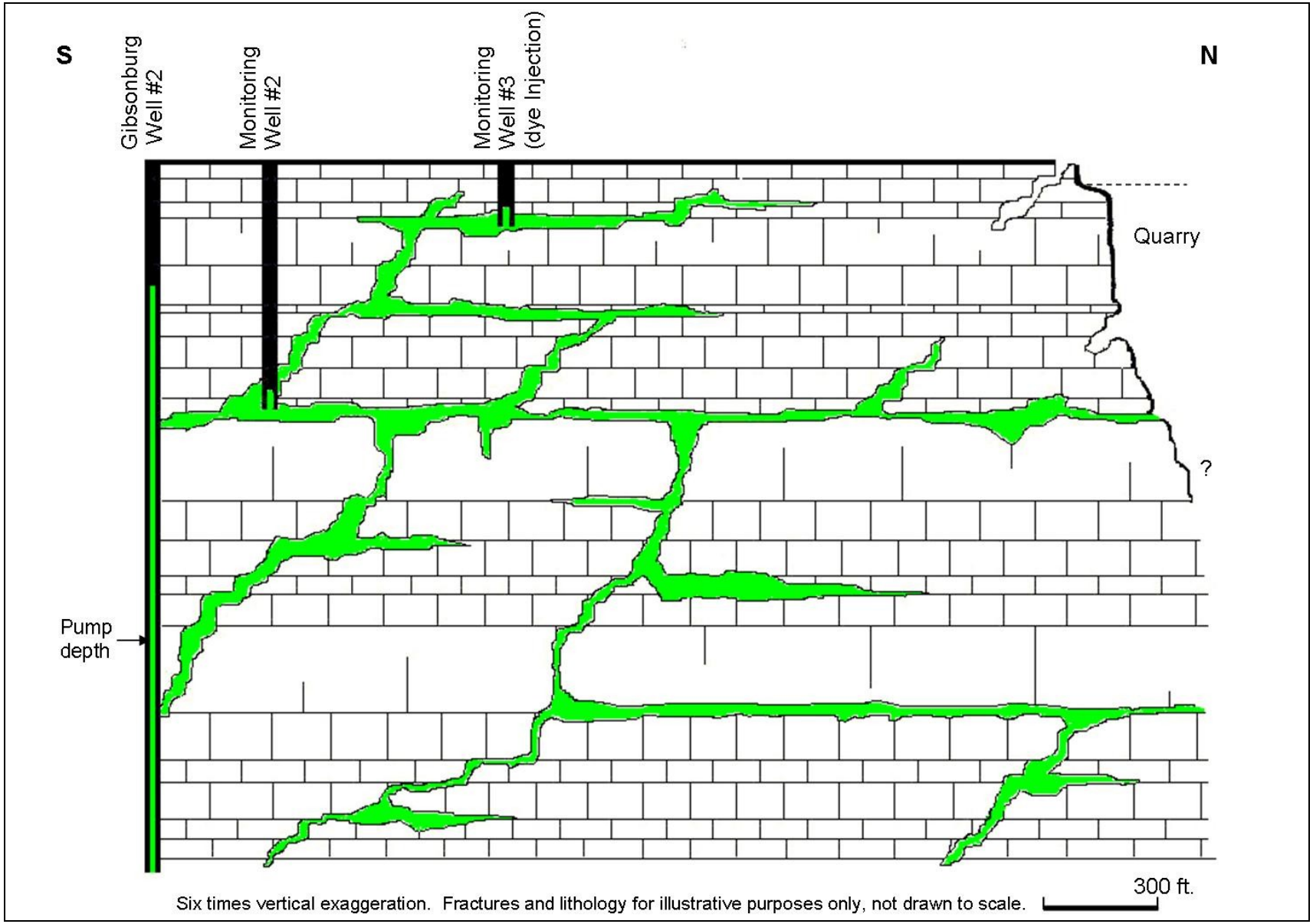

Figure 10. Geologic Cross-Section of Gibsonburg, Ohio.

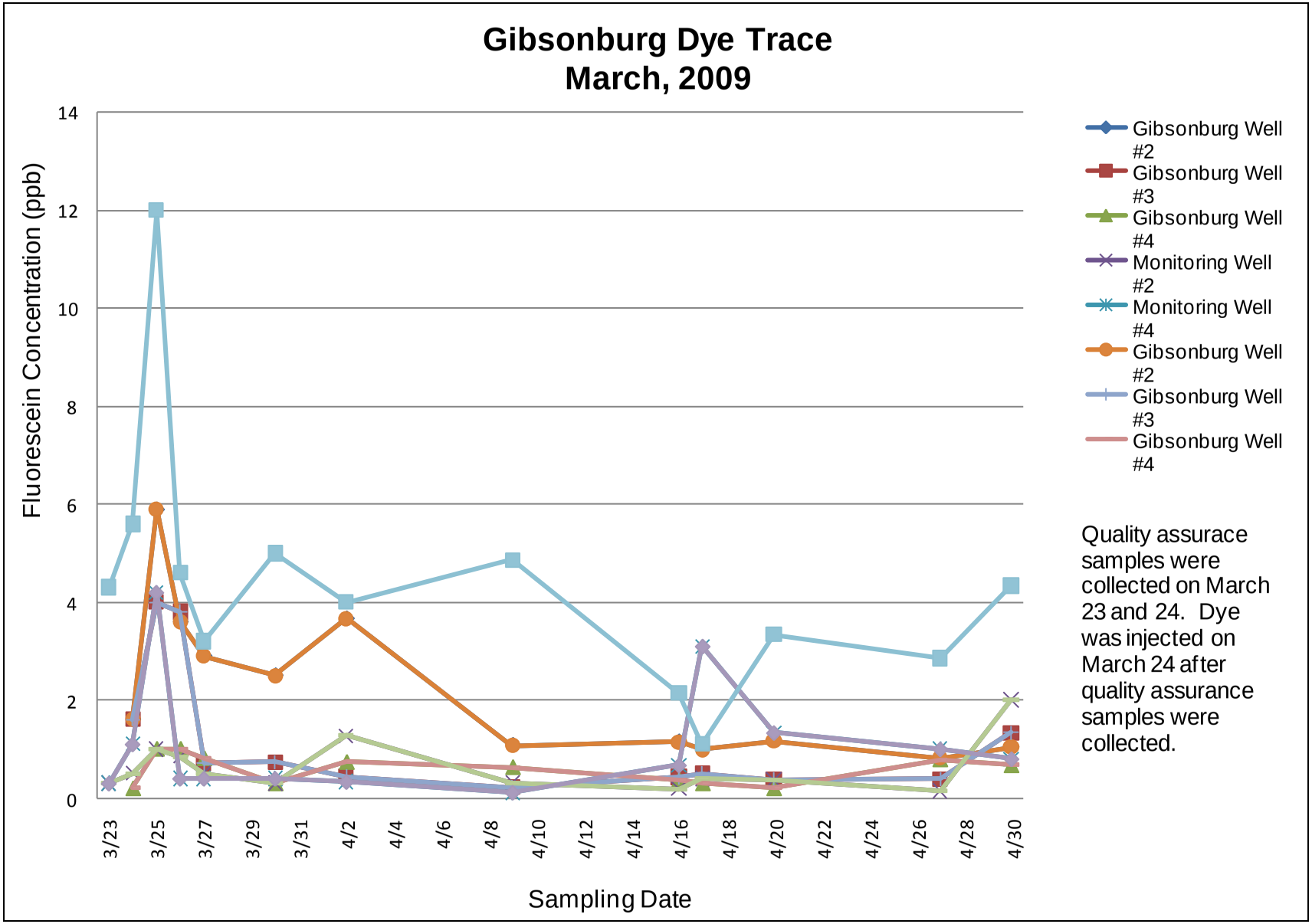

Figure 11. Fluorescein Concentrations Measured in Eluted Charcoal Samples from the March-April Dye Trace.

quarry. Since charcoal packets accumulate dye over time the fluorescein concentrations were higher in the charcoal packets and presented more obvious dye spikes, with a maximum concentration of 12.0 ppb. Unfortunately, these results are qualitative and cannot be used to precisely pinpoint peak arrival time at any of the locations. In order to compare data from charcoal packets that had a longer placement with those with a shorter placement all results were divided by the total number of days the charcoal packets were placed at a sampling location. This analysis assumes that fluorescein adsorption is consistent over time, which may not be accurate and introduces potential error in the results. Results from the charcoal packets placed at surface water sampling sites were inconclusive, since background levels of fluorescein were greater and highly variable at the surface water locations and the small amount of dye injected was not detectable above background levels. Since the sampled surface water was consistently turbid, the high background fluorescein levels were probably not indicative of fluorescein but other substances that could have accumulated on the charcoal and given a false positive for fluorescein (USEPA, 1997).

Precipitation did not appear to have an influence over the results of the first dye trace. Less than 0.13 inches of rain fell the entire week preceding dye injection and a total of less than a quarter inch of rain fell in the week following dye injection (See Figure 12). A more significant single rain event of 0.55 inches occurred 13 days after injection, but there was no corresponding secondary peak in fluorescein associated with that rain event.

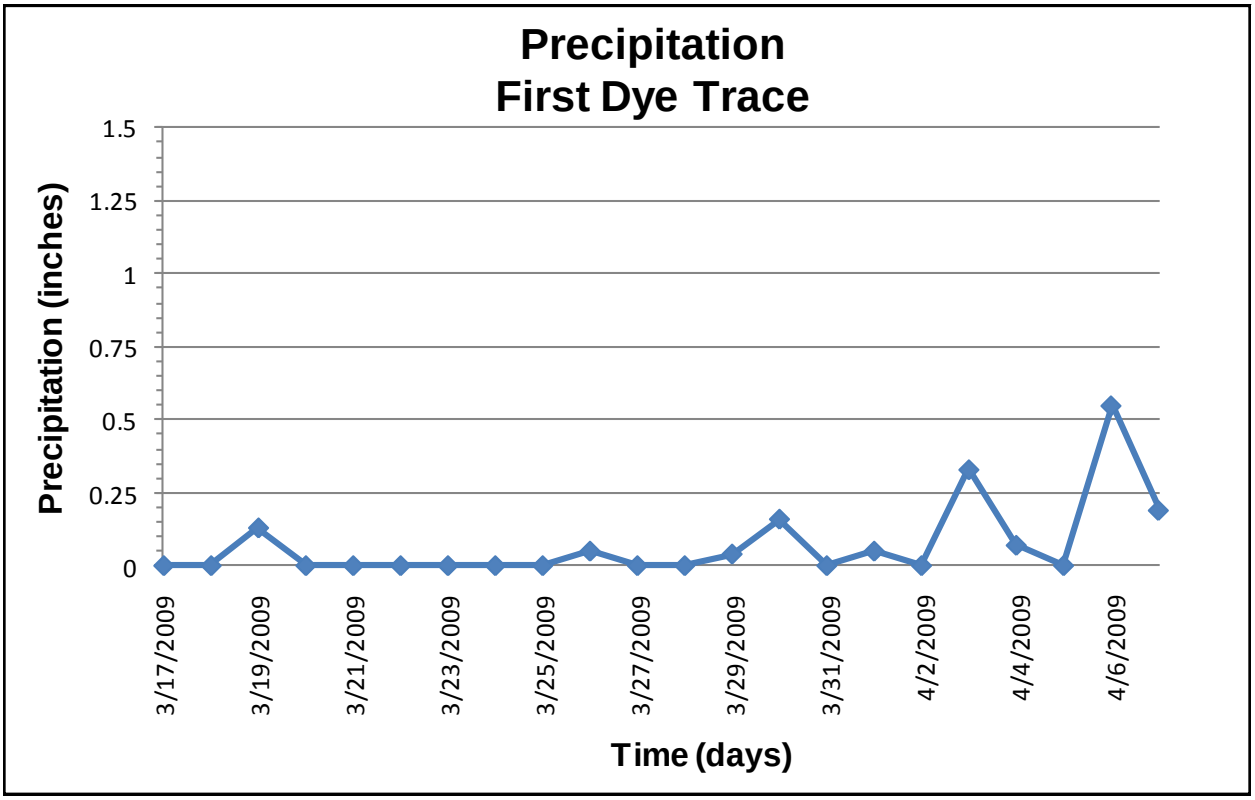

Figure 12. Precipitation Preceding and During the March-April Dye Trace. Data from the Fremont Weather Station (Station 332974).

Since the measured fluorescein levels were only slightly above background levels in the water samples, there were some inconsistencies between the water sample data and charcoal data for monitoring well 2, and the new wellfield was not sampled, Ohio EPA decided to conduct a second dye trace using a higher volume of dye. The purpose of the second trace was to attempt to confirm the fast flow rates measured during the first trace and gather additional data about the new wellfield and the nature of ground water flow in the region. The second trace would also collect more background quality assurance samples to better quantify any natural fluctuations in fluorescein levels that might occur at the sampling sites.

Second Dye Trace

Results from the second trace had clear dye detections up to 20 times background levels observed in water samples from Gibsonburg's well 3, 6, 7, and the quarry (See Figures 13 and 14). Dye was first detected at Gibsonburg's well 7, 6.5 hours after injection, with a flow rate of 8,600 feet/day. This represents the fastest flow rates under a stressed aquifer condition. Dye was detected downgradient from the injection site at the quarry 8.5 hours after injection, representing a more ambient flow rate of 4,500 feet/day (although this rate could have been repressed due to the influence of the pumping wells). Please note: no samples were collected from the quarry 25-29 hours after injection and 34 -46 hours after injection. This data gap was due to problems with the auto-sampler during this time period. Since dye was elevated in the quarry sample taken 47 hours after injection and even higher concentrations of dye were measured in Gibsonburg's wells 3 and 7 during hours 41-45, a higher dye concentration spike for the quarry may have been missed due to the sampling error. In addition, samples were not collected for Gibsonburg well 3 from 24 to 27 hours after injection due to auto-sampler error. Since this was the time period when dye concentration spikes were observed in Gibsonburg's wells 6, 7, and the quarry, a dye spike in well 3 may have also been missed due to sampling error.

The fluorescein dye concentration curves depicted in Figures 13-14 are not smooth, as is typically seen. This may be due to the cyclical pumping of the public water system wells. When the wells are pumping they draw dye into them, but during periods when the wells do not pump dye follows a more ambient flow path to the north-northeast. This explains how dye could be detected in both the public water supply wells and quarry, even though they lie in opposite directions from the injection location. The multiple spikes may also be partially influenced by a major precipitation event that occurred on July 23 and a second event that occurred on July 30 (See Figure 15).

Dye concentrations in Gibsonburg's wells 2, 4, and 5 never exceeded 0.45 ppb. The lack of a dye spike in Gibsonburg well 2 was expected, since the well was not pumped for the first four days of the test and dye was detected at the other sites within this initial period. Dye was not detected in well 4 during either dye trace, and this may be due to its greater distance to the injection site or it may not be aligned with more major fractures that connect the other positive receptor sites with the injection location. Gibsonburg's well 5 is located closer to the injection site than Gibsonburg's wells 6 and 7 (which did detect dye), but Gib-

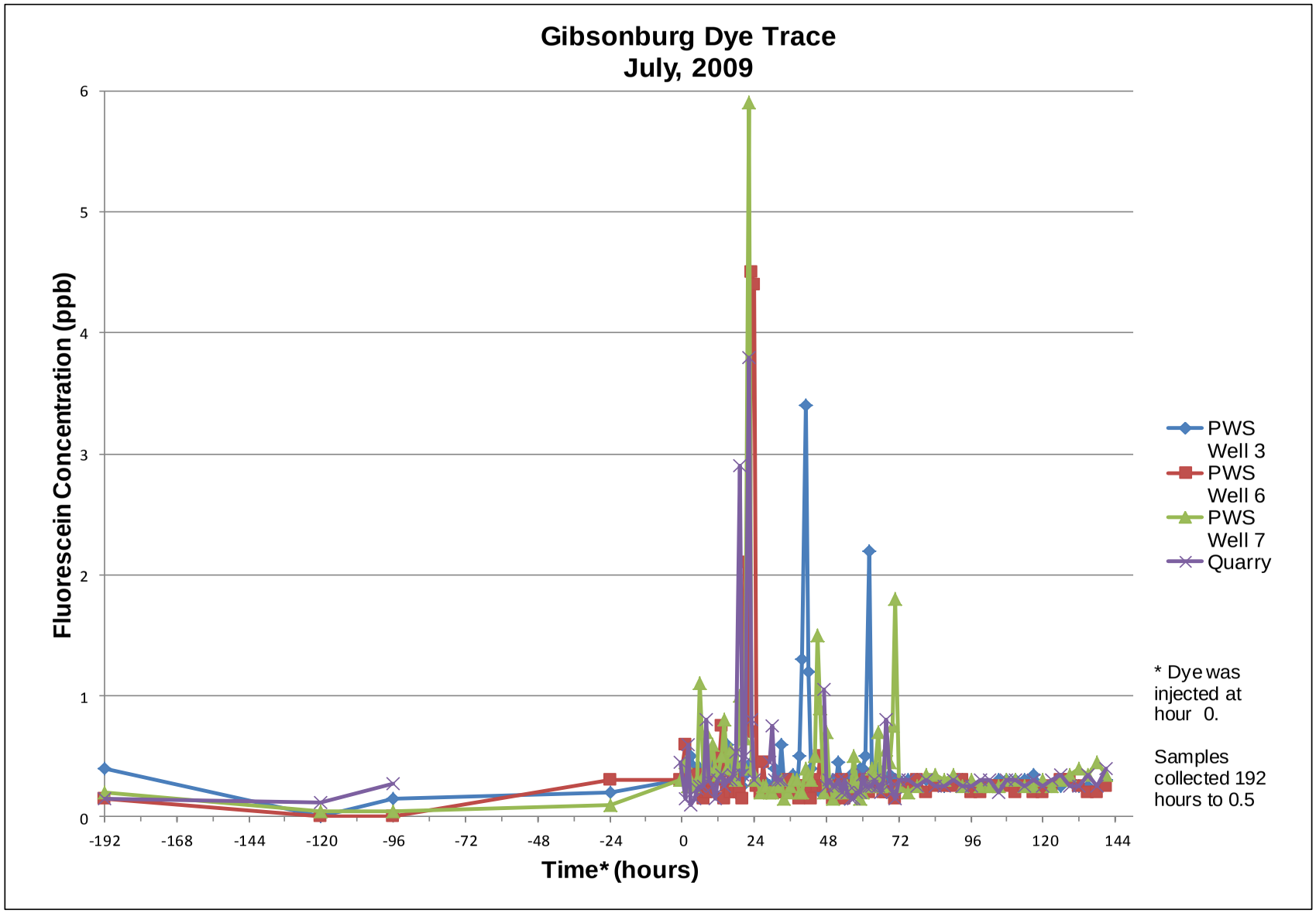

Figure 13. Fluorescein Concentrations in Water Samples Collected During the July Dye Trace.

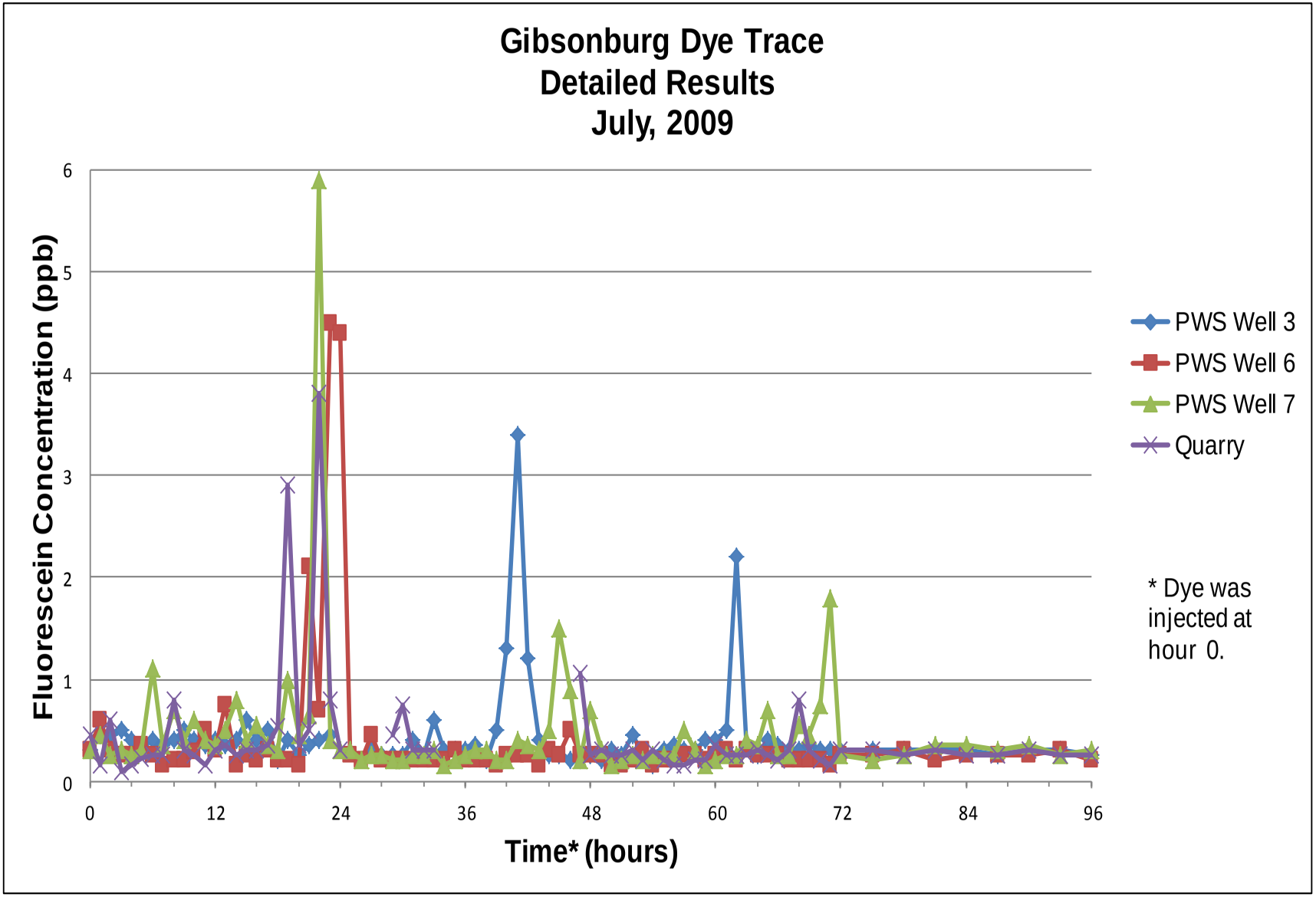

Figure 14. Detailed View of Peak Fluorescein Concentrations in Water Samples Collected During the July Dye Trace.

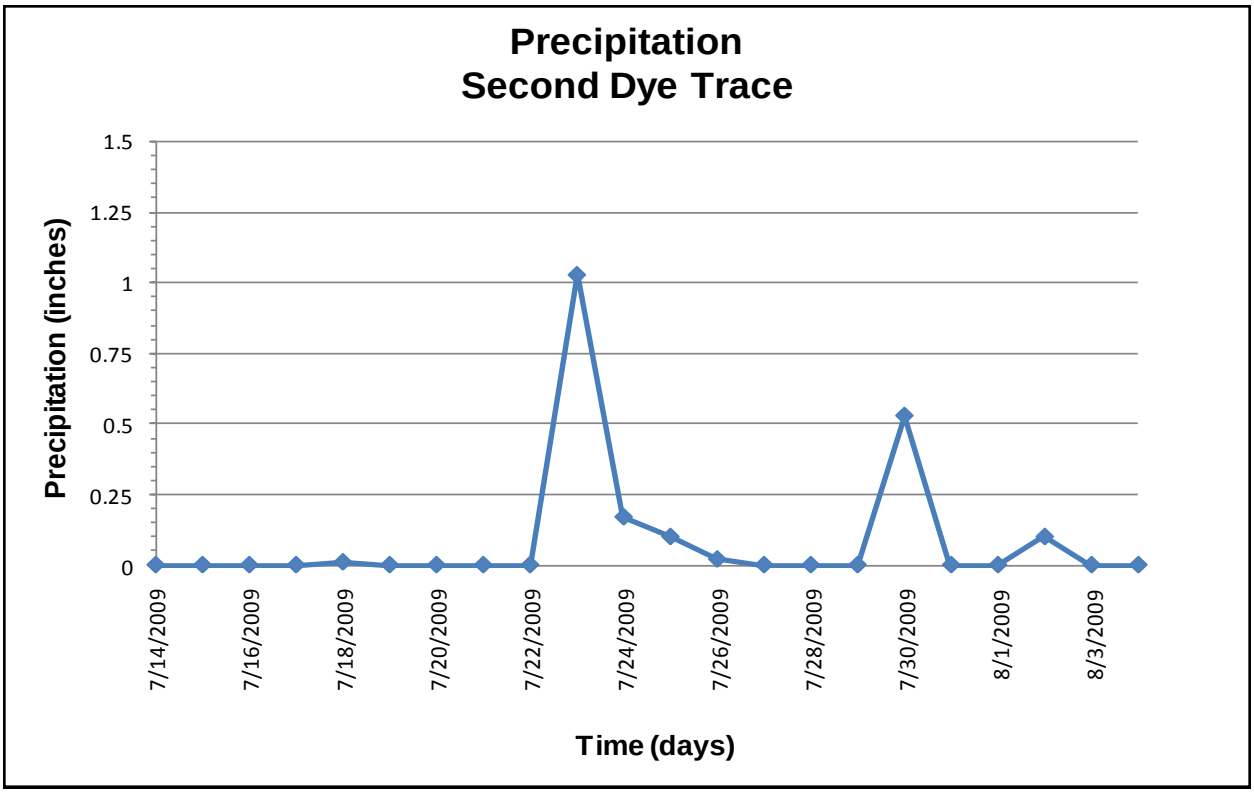

Figure 15. Precipitation Preceding and During the July-August Dye Trace. Data from the Fremont Weather Station (Station 332974).

sonburg's well 5 pumps much less than wells 6 and 7 (75 gpm versus 525 gpm for Well 7) so that may be the reason why dye was not detected. It was not possible to set up an auto-sampler at either monitoring well, so the only data available was from grab samples taken prior to placement of the charcoal dye detectors. Data from Ohio EPA monitoring well 4 is inconclusive, since background charcoal levels were high. This could be due to remnant dye in the well leftover from the first trace or the fact that the well appeared very turbid when the background samples were collected and the well may have been influenced by surface water infiltration. Water samples from monitoring well 2 were not significantly greater than background levels, but this is expected since Gibsonburg's well 2 was not pumped for the first four days of the trace and therefore there was less of a force to pull dye up-gradient towards monitoring well 2.

CONCLUSIONS

Tracer test results from the tests initiated on March 24 and July 21, 2009 clearly indicate fast ground water flow rates of up to 8,600 feet per day to public water supply wells and 4,500 feet per day ambient flow downgradient towards a quarry. These flow rates were more rapid than anticipated for a relatively flat-lying fine-grained dolomite aquifer with a high water table. The presence of dye at multiple, widely spaced, receptor sites indicates that the ground water flow in this area is complex, and at least some bedding planes and fractures are inter-

connected. The fast ground water flow rates measured in this investigation are similar to rates measured in areas with more pronounced surface topography and surficial karst features and caves. This study suggests that rapid ground water flow rates, indicative of karst aquifers, are possible even in carbonate aquifers that lack well-developed surficial karst features. Traditional porous media ground water flow models would not be appropriate for delineating drinking water source protection areas in this region.

These were the first dye traces conducted by Ohio EPA where an artificial injection site and public water system well and quarry receptor sites were used for a successful dye trace. Typically, dye is injected into natural features, such as a sinkhole or swallet hole (sinkhole within a stream) and it is traced to natural receptor springs. In this investigation, a shallow monitoring well was used as an artificial injection site and deep municipal public water system wells, monitoring wells and quarries were successful artificial receptor sites. This study confirms the feasibility of using artificial injection and receptor sites and expands the usefulness of dye traces for contaminant transport and other hydrogeologic investigations in Ohio where natural karst features are lacking. Results from this study also demonstrate that transport is not restricted to the uppermost portions of the karst aquifer, and contaminants can quickly reach significant depths under various pumping scenarios.

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