TEMPORAL VARIATION OF SEDIMENT DISTRIBUTION IN A KARST AQUIFER, EASTON, PENNSYLVANIA

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by
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ABSTRACT

I studied the amount and type of sediment transport in a karst system as a function of storm events and seasonality. My research area is a karst groundwater system in the vicinity of the Bushkill Creek, north of the City of Easton, Northampton County, Pennsylvania. The karst system developed within the Ordovician Epler Limestone and Rickenbach Dolomite. Groundwater samples were collected from two karst springs identified along the eastern bank of the Bushkill, and a well installed in the Epler Formation, approximately 2,000 feet east of the Bushkill in a local recharge zone. Samples were also collected from a non-karst spring in the red shale of the Triassic Stockton Formation approximately 40 miles south of Easton in the Town of Buckingham, Bucks County, Pennsylvania. Biweekly samples were analyzed for particle size and water chemistry and selected samples for clay mineralogy. In addition, water level was measured in the monitoring well and Spring No. 1. An increased amount of sediment was transported in the monitoring well (approximately 200 to 800 mg/L) during the autumn and early fall compared to a low of 0 mg/L during the spring and summer. The spring discharged a low amount of sediment (a maximum of 9 mg/L) during the autumn of 2000 and three times the amount during the spring and summer. One storm monitored in March, 2000, monitored at the spring only, showed that the sediment load reached the maximum discharge of sediment (13 mg/L) subsequent to the storm peak. Correlation between sediment yield and water level in Spring No. 1 and the monitoring well show that the overall sediment load increased during periods of low precipitation. The cumulative effect of karst systems flushed during the spring and summer may be to decrease sediment loading to discharge points, while water chemistry varies with individual precipitation events. The aqueous chemistry of the system shows dilution during wet periods and enriching of ions during dry periods. Storm chemistry shows that both dilution and flushing does occur in karst systems because ion concentration decreased over the course of a storm whereas the sediment yield increased. Sediment transport in karst aquifers varies because of how precipitation infiltrates the complex diffuse-conduit systems of karst.

ACKNOWLEDGMENTS

Much appreciation is deserved to my thesis advisor, Dr. Laura Toran, for all of her patience, insight, intelligence and comedic break during the bone-chilling dye trace in January 2000, and my two years at Temple University. A big thanks is extended to everyone at American Resource Consultants, Inc. (ARC) for their support. Thank you Dr. Mary Roth and Dr. Jon Nyquist for providing the Lafayette College field site. Dianna Crilley and Dr. Grandstaff, thanks for all of your help with the Dionex; and Dr. Dennis Terry, Jr., thank you for the XRD assistance. The Prout family deserves a thank you for your support, as well as my insightful, loving fiance - Kate Faia. A special thanks has to be extended to my father for allowing me to gain valuable practical knowledge in the environmental consulting field while completing this thesis research.

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OVERVIEW

Purpose

I evaluated the transport of sediment in a karst system over time. Specifically, I tested the hypothesis that the amount of sediment transported in a karst aquifer increases during storm events and varies seasonally. Both storage and mobilization of sediment occurs but factors (*e.g.* total rain, cumulative rain, water table elevation, and transport velocity) that influence transport can change abruptly in karst. Transport variability during storms and seasonal changes may influence the amount of natural and anthropogenic contaminants that absorb onto suspended sediments in a karst aquifer, which could similarly control microbial and viral transport in karst groundwater systems.

Sediment is mobile in karst aquifers. Large pore diameters and rapid flow velocities result in turbulent flow and subsequent transport of variable particle sizes. Mobile sediment may act as a mechanism for contaminant transport, particularly for poorly soluble compounds, including metals and hydrocarbons (Mahler, 1997). In addition, microbial contamination of groundwater results in numerous disease outbreaks each year. The transport of sediment and microbes is potentially similar; as a result this research has implications for tracing microbial and viral movement in karst systems. Future work involving the transport of microbes, viruses and antibiotics could be performed in conjunction with sediment transport to fully understand transport of organic and inorganic materials in groundwater.

Karst aquifers are an important source of potable water worldwide, and are probably the most vulnerable to groundwater contamination. Shallow karst aquifers receive either distributed recharge from percolation through the soil, or concentrated recharge from surface runoff that flows directly into the aquifer at stream sinks and sinkhole drains. The velocity and concentration of a contaminant in shallow karst aquifers depends on whether the system receives primarily diffuse or concentrated recharge. Karst springs and water wells, if supplied entirely by distributed recharge through thick regolith, are more likely to be good sources of potable water. However, karst springs and water wells in shallow areas can receive concentrated recharge from nearby areas where sources of contamination are present (Crawford and Whallon, 1985).

Research Locations

My primary research area was a karst groundwater flow system, which included Lafayette College's Metzgar Athletic Field, a region of the Bushkill Creek parallel with the athletic fields, and private agricultural land between the fields and creek. The research site is located in the Lehigh Valley, near the City of Easton and the Town of Tatamy, Northampton County, Pennsylvania, approximately 50 miles north of Philadelphia (Figure 1). An additional sample point in a fractured shale groundwater flow system was included late in the study. This sample point is a spring located on private property, approximately 25 miles south of Easton on Honey Hollow Road in Buckingham, Bucks County, Pennsylvania (Figure 2).

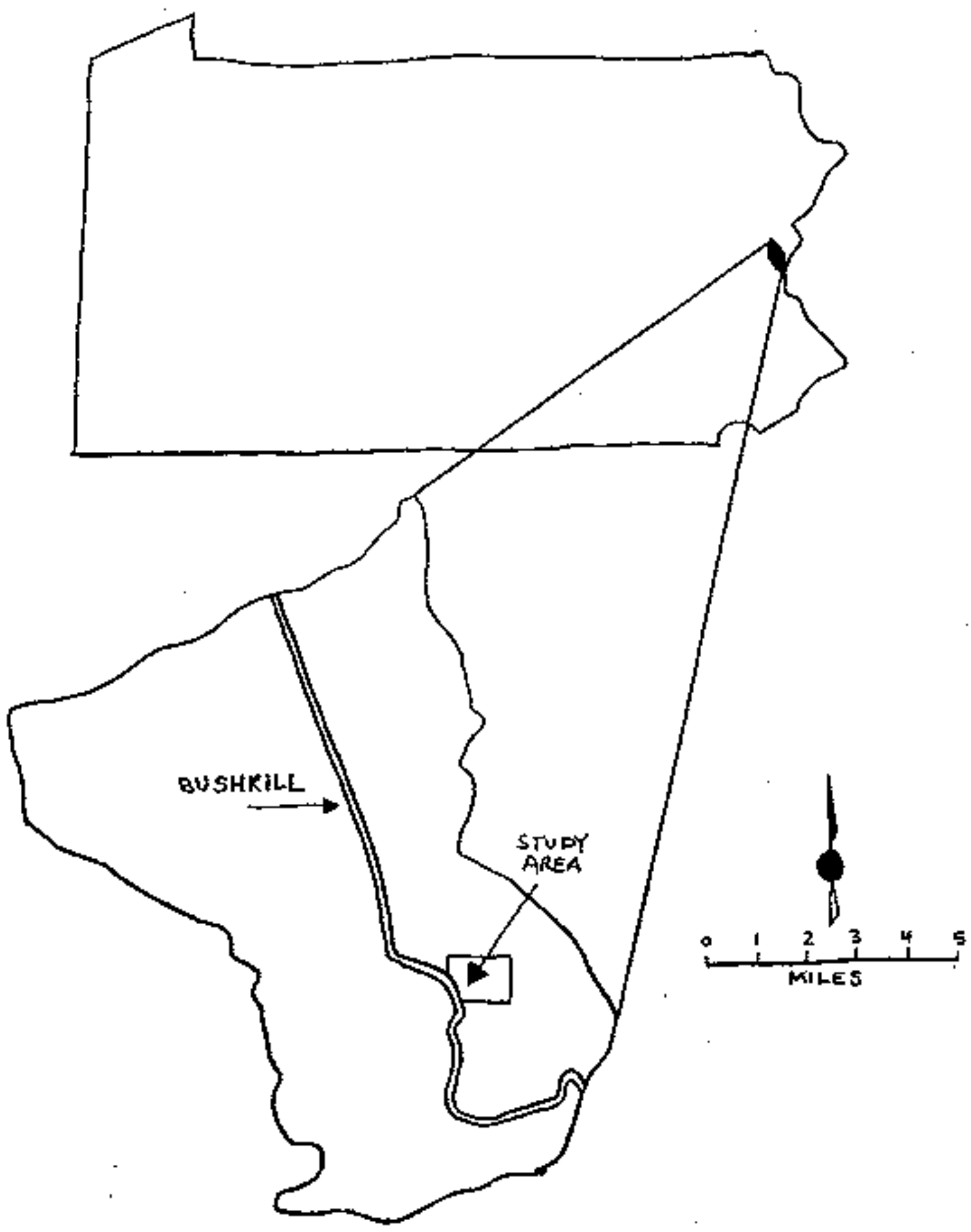

Figure 1 General Research Location Site in Pennsylvania (after Bushkill Creek - Joint Planning Commission Lehigh-Northampton Counties, 1992).

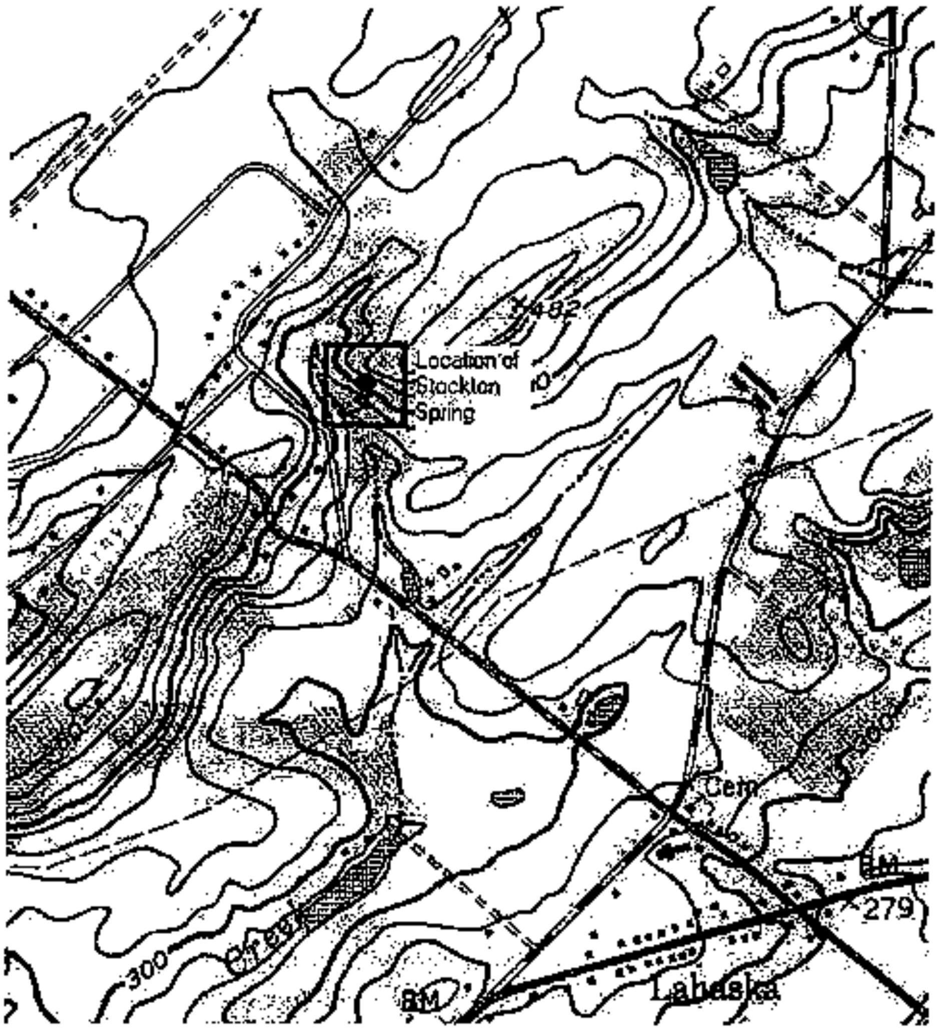

Figure 2 Location of Stockton Spring in Buckingham, PA; 1": 2,000' (from 7.5 Minute Buckingham, PA Topo Map – from USGS, 1983).

Bushkill Creek flows south, ultimately discharging to the Delaware River. Input to Bushkill Creek is primarily from groundwater flow. The groundwater flow system of the karst likely includes both diffuse and conduit flow. Geophysical mapping of subsurface karst voids (Jenkins, 1999; Maule, 2000) suggests that conduit flow does occur in the research area. In order to further study the area, a 65' PVC cased monitoring well (MW-1) was drilled along strike with several boreholes that intersect cavities in the Metzgar Athletic field. The well was installed in the summer of 1999. The monitoring well intersects a void within the Epler Formation approximately 54.3 to 58 feet below the ground surface (see Appendix A for the borehole log).

Physical Characteristics and Development of the Study Areas

Bushkill Creek is a tributary of the Delaware River. The creek has a drainage area of approximately 80 square miles and consists of three tributaries: 1) East Branch Bushkill Creek, 2) Little Bushkill Creek, and 3) Schoeneck Creek (Joint Planning Commission Lehigh-Northampton Counties [JPCLNC], 1992).

The watershed basin consists of three lithologies: sandstone, shale and carbonate. The headwaters of Bushkill Creek originate from the Silurian Tuscarora Sandstone located in the Blue Ridge Mountains. The shale is from the Ordovician Martinsburg Shale. In the Town of Stockertown, the creek encounters Lower Ordovician Jacksonburg Limestone. A Martinsburg Shale and Epler Limestone carbonate boundary extends east and west beyond Stockertown. This line is approximately the northern extent of Forks Township and Upper Nazareth Township. Shale underlies approximately 60% of the watershed area.

The topography of the basin changes between the shale and carbonate areas. In the shale areas, the stream banks and channel slope are steeper. Numerous small hills characterize this area. These data suggest that a majority of subsurface flow, both recharge and discharge occurs in the limestone region of the watershed (JPCLNC, 1992).

The United States Environmental Protection Agency (US EPA) and Pennsylvania Department of Environmental Protection (PA DEP, Chapter 16 – Fresh Water Regulations) have characterized the Bushkill Creek under two protected water categories: 1) cold water fishes (CWF), and 2) high quality waters (HQ). These categories protect cold-water aquatic life and excellent quality water characteristics respectively (JPCLNC, 1992).

The upper parts of the Bushkill watershed in Monroe County and Northampton County, approximately thirty miles north of the research area, are relatively free of human impacts other than agriculture. The downstream half of the basin, including the study area and south of the Town of Tatamy is undergoing rapid residential and commercial land use development. Historically, industrial facilities lined several miles of the stream in Easton, PA. Quarry discharge and treated wastewater from the town of Nazareth enters upstream at Schoeneck Creek, a tributary of the Bushkill. However, the creek has sufficiently recovered from historical pollution to become a competent trout stream. Detailed hydrologic modeling studies have been performed by The Pennsylvania State University on the watershed, and there is ongoing water quality monitoring by Lafayette College's Department of Geology (Lafayette Bushkill

Project 2000, web site), among other educational, private and government groups. The Lafayette College Bushkill project includes real-time analysis of the Bushkill including pH, conductivity, temperature and discharge at two points (in Easton and near the Tatamy bridge) in the creek.

My ancillary study area in Buckingham, PA is located in the Delaware River basin and watershed. The unnamed spring is in a Stockton Formation shale-hosted fracture protruding from a topographic break on a steep hill, that discharges to a small intermittent stream. The topography of the area and region consists of hills and gently undulating land.

Geology and Hydrogeology of Bushkill Creek Area

The strata of the Lehigh Valley represent a Lower Paleozoic carbonate shelf environment of Middle Cambrian to Lower Ordovician age that gave way to a deeper water foreland flysch facies, the Martinsburg Formation, by Middle Ordovician times. Strata in the Lehigh Valley were subjected to intense deformation during the Late Ordovician Taconic Orogeny and the Pennsylvanian Alleghenian Orogeny. The area is cut by a series of faults ranging in age from lower Paleozoic to Triassic. The strata have been exposed at the surface since the Mesozoic. Materials deposited in the valley consist of Pleistocene glacial drift, alluvial gravels, and thick strata of colluvial material shed off the uplands that border the valley both on the north and south (Myers and Perlow, 1984).

Geologic units of the Bushkill Creek study area consist of the Lower Ordovician Beekmantown Group (Figure 3). The Beekmantown Group includes the Epler Formation and Rickenbach Dolomite. The Epler Formation is an interbedded very fine grained to cryptogranular, light to medium-gray limestone and fine to medium grained, light to dark, medium gray dolomite. Nodular and bedded chert is common in this formation, which is approximately 800 feet thick and has a prominent chert rich zone near the base. The Rickenbach Dolomite is a fine to coarse grained, light medium to medium dark gray dolomite. Sedimentary breccia and bedded, nodular chert are common. The Rickenbach Dolomite is approximately 650 feet thick (Drake, 1967). The Beekmantown Group strikes at 60° and dips consistently between 42° and 47° to the southeast. In the study area, Jenkins (1999) identified four distinct faults dipping at 45° in the chert-rich units of the Beekmantown Group.

Karst features are common in Northampton County. Most common among karst features are sinkholes, which occur along the landscape of areas underlain by limestone. Historically, sinkhole activity throughout the Lehigh Valley was brought to the public's attention in 1854 when the southwest corner of 6th and Hamilton Streets in Allentown, PA dropped several feet. Historical recordings include such items as "basement of house cracks open, "porch is separated by house", "half of street disappears, disrupting traffic"! In the days dominated by farming, many events were not recorded because sinkholes became ideal refuse dumps for farmers and chemical companies; they were heard of only on occasion, such as when a farm animal was trapped (Lilly, 1973). Approximately four years ago, a leaking pipe in

Allentown caused a six story building to collapse. Sinkhole formation and collapse in areas underlain by carbonate rock in the Lehigh Valley continues to this day.

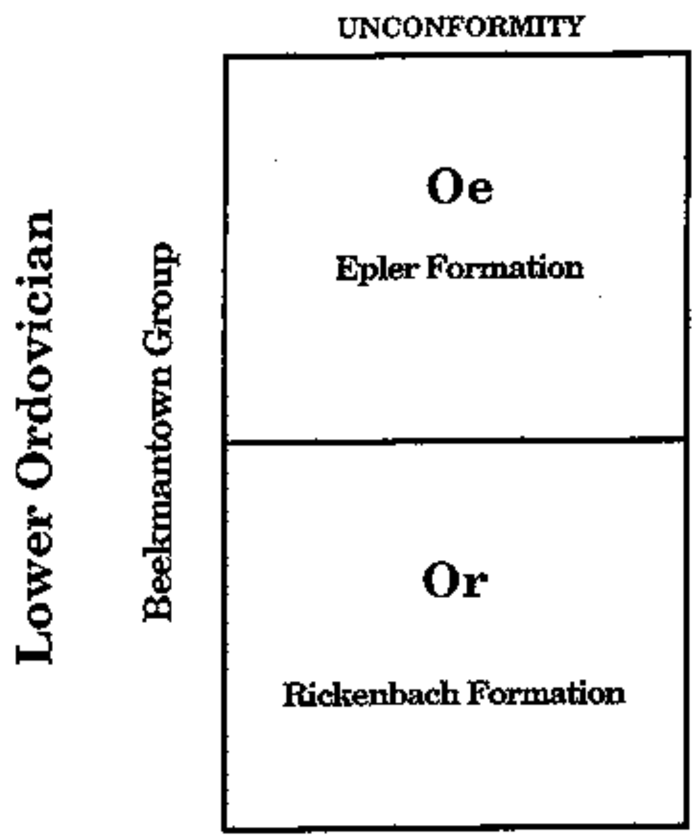

Figure 3 Geologic Column of Research Area.

Allentown caused a six story building to collapse. Sinkhole formation and collapse in areas underlain by carbonate rock in the Lehigh Valley continues to this day.

Figure 3 Geologic Column of Research Area.

Geology and Hydrogeology of the Buckingham Area

The spring in Buckingham, Pennsylvania is located within the Triassic Basin Gettysburg-Newark Lowland Section of Pennsylvania. This physiographic province is dominated by rolling lowlands, isolated hills and highlands. The local relief is low to moderate. The underlying rock type includes red and gray shale, siltstone, sandstone and conglomerate, as well as diabase. The geologic structure of this area includes half-grabens, and monoclinical, dominantly northwest-dipping beds. Geologic contacts include Paleozoic and Precambrian strata of South Mountain, Great Valley, the Reading Prong and the Piedmont. The origin of the strata are attributed to fluvial erosion of moderately resistant and nonresistant beds and minor periglacial mass wasting (Pennsylvania Department of Conservation and Natural Resources, 1996).

The Stockton Formation, underlying this sampling point, is a section of the Late Triassic part of the Newark Supergroup exposed along the Delaware Valley and consists of as much as 20,000 feet of nonmarine sedimentary rocks and an associated diabase sill. In the northeast United States, the Newark Supergroup consists of a lower, locally conglomeratic Stockton Arkose (6,000 ft), grading upward into reddish-brown Brunswick Mudstone. In the central part of the basin, the predominant Stockton and Brunswick Formations are separated by, and interfinger with, the dark gray to reddish-brown Lockatong Formation (Van Houten, 1969).

The Stockton Formation consists primarily of light gray to buff, coarse-grained, arkosic sandstone; and includes red to purplish-red sandstone, shale and siltstone.

The maximum thickness is approximately 3,300 feet. In addition, the Stockton Formation includes a large network of fractures and joints. The fracture and joints are moderately developed, very closely spaced and vertical. The Stockton Formation is only slightly resistant to weathering. Weathering produces small, pencil like, platy fragments. Groundwater primary porosity occurs in the weathered part of the rock; joint and bedding-plane openings provide a secondary porosity in unweathered rock.

Geophysical and Borehole Camera Investigations

Geophysical mapping of the subsurface near the monitoring well was performed to obtain an understanding of the local karst geomorphology. Recent studies have used geophysical techniques to locate karst features such as sinkholes and caverns and to identify large-scale groundwater flow conduits (Jenkins, 1999; Maule, 2000). The Sting™ earth resistivity meter, in conjunction with the Swift electrode system, and gravity techniques, were used to map selected areas in Metzgar Field and the private farm fields closer to Bushkill Creek. The Sting™ system uses a meter to record changes in subsurface earth material resistivity along an electrode cable. Different configurations of the electrode cable provide an efficient method to rapidly obtain measurements. Different geophysical array types are compatible with the Sting/Swift™ instrumentation package, thus providing a comparison of techniques.

The geophysical investigations performed in the study area included a pair of sting lines run parallel and perpendicular to strike. Neither line alone provided sufficient evidence of voids or mature karst conduits. The drastically different nature of the two lines provided evidence that three-dimensional variation, or a karst conduit network may exist. The geophysical data showed the voids, but the comparison of perpendicular lines provided stronger indication of a karst network.

In the autumn of 1999, Temple University and Lafayette College personnel performed a borehole camera investigation in the Metzgar Fields to gather information on the general dimensions of solution enhanced groundwater conduits in the study area. Three boreholes were used in this study. Each of the borehole investigations revealed well developed conduit fractures. Figure 4 is a captured video frame of a fracture / conduit in a Metzgar Field borehole obtained by SearchCAM® 2000 equipment (Maule, 2000).

I obtained comparative data from American Resource Consultants, Inc. (ARC), an environmental engineering company in Doylestown, PA. A geophysical investigation of the Epler and Ontalaunee Formations (interbedded limestone and dolomite) in Allentown, PA included downhole camera studies of a 175 ft well (American Resource Consultants, Inc., unpublished data). Numerous solution enhanced fractures, approximately 5 inches wide and about 10 to 12 inches in height, were observed at the level of the water table (50 feet below the ground surface).

Only a few karst fractures and conduits were identified below 70 feet. These fractures and conduits were not very large when compared to the conduits at the approximate water table level or at the Metzgar Athletic Fields. These optical investigations further supported the geophysical identification of solution-enhanced karst groundwater flow conduits in the study area.

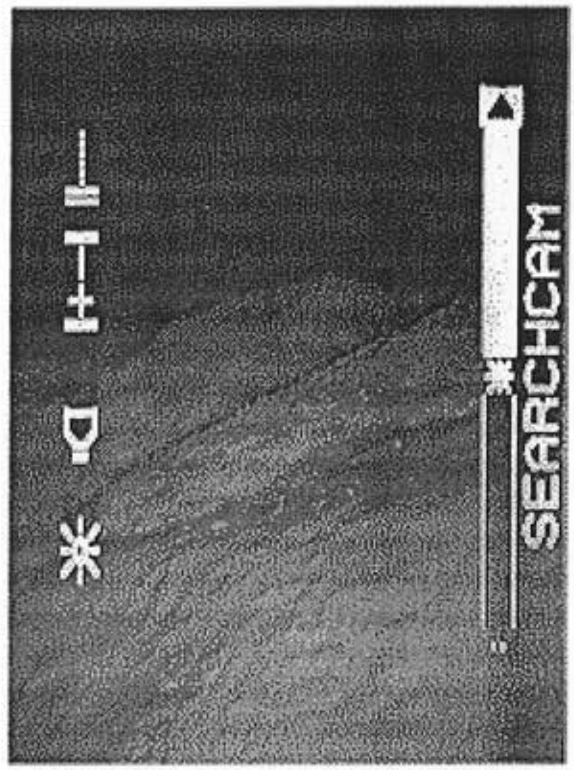

Figure 4 – Captured Video Frame of a Karst Conduit Underlying Metzgar Athletic Fields. The camera did not have scale or size determination. The symbols represent the direction to which the camera is looking (Maule, 2000).

CHAPTER 2

KARST AND KARST FLOW SYSTEMS

Karst is a type of terrane, commonly formed on carbonate rock (both limestone and dolomite), where an underground drainage system is formed by dissolution. This process is described in the equation:

$$CaCO_3 + H_2O = Ca^{+2} + 2HCO_3^-$$

Limestone solubility is primarily influenced by the addition or loss of CO_2 gas to pore water. Calcium carbonate solubility is also influenced by changes in temperature, pressure, biological activity, pH and the mixing of different water compositions. Solubility increases with the partial pressure of CO_2. Temperature and pH plays a critical role in the development of karst terranes. Larger amounts of CO_2 are dissolved in colder and more acidic waters. Biological activity plays a part in the structure of karst environments. The organic acids of plants, including algae, can generate pits, holes, and pinnacles in carbonates (White, 1988a). Most large solution conduits and caves are formed just at or below the water table, where there is both water and CO_2 gas exposure. Each of the factors contributing to the development of karst is further enhanced by a humid climate.

The movement of groundwater in karst environments is controlled by enlarged, carbonate conduits, rather than the intergranular pore spaces through which water normally moves in other aquifers (Figure 5). These solution-enhanced large conduits are marked by both laminar and turbulent flow, which discharges at springs and seeps. In karst flow, initially small planar openings such as bedding planes, faults and joints are enlarged by solution, especially along intersections.

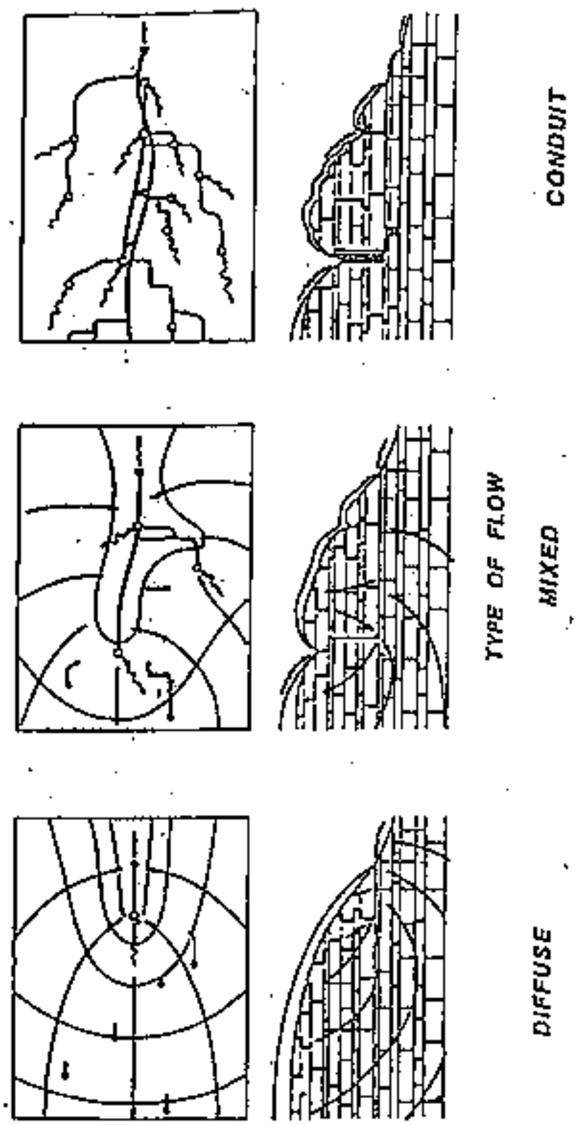

Figure 5 Schematic Exhibiting the Development of Karst (from Crawford and Whallon, 1985). More extensive karst networks lead to conduit flow, less extensive have diffuse flow in the matrix.

Approximately 20% of the United States is underlain by limestone or dolomite; limestone and dolomite constitute approximately 15% by weight of the total sedimentary rock mass. Exposed rock can develop shallow and deep pits formed by rain and guano. These vertical openings are also commonly referred to as solution pipes and notches. As surface drainage is diverted underground, streams disappear and are replaced by sinkholes (Quinlan, 1990).

Another common type of karstic landform are karst windows, depressions with a stream flowing across its floor, such as an unroofed area of a cave. Karst windows are also believed to be deep sinkholes in which major subsurface flow or surface streamflow is occurring (EPA, 1988).

This final introductory section about karst geomorphology will present the current theories of karst cavern development. The theories try to answer the question of how caves and conduits form hundreds to thousands of feet below karst environments. One theory of karst development is the *water table, or shallow phreatic hypothesis*. The fundamental principle behind this theory is that the maximum dissolution of rock takes place within the phreatic zone or zone of water table fluctuation. In addition, it has been suggested that water has a variety of paths along which it can flow toward a discharge area (springs), but most of the water volume moves along the shortest path, which is along the water table (Crawford & Associates, 1999).

A second theory is referred to as the *deep phreatic* theory. This theory is based upon the evidence that cave initiation and most cavern enlargement occur at random depths below the water table, often in the deep phreatic zone. The caves are enlarged by the dissolving effects of slowly moving phreatic water. A second cycle of deep cavern development may occur during stream incision and subsequent lowering of base level, thus draining the caves of groundwater and permitting vadose zone water and air to enter the cave. During the second cycle, surface streams may then enter an existing cavern system from above via sinkholes and alter cave passages by dissolution (Reeder, 1988).

Karst groundwater flow is complex because it can occur as either diffuse or convergent pathways. Groundwater flow in a mature karst aquifer usually occurs in major conduits. This may not occur during times of flood, where the shallow karst network (epikarst) or other conduits may receive flow, or if the hydraulic gradient alters "normal" flow regimes or velocity patterns. Contaminant plumes in karst groundwater will not gradually spread (as in a diffuse flow system) but preferentially flow towards a system of springs or caves downstream (Domenico and Schwartz, 1998). Groundwater flow in carbonate systems is faster than that of other aquifers. Velocities of 7,500 feet / hour have been observed, while a range of 30 to 1,500 feet / hour is common at similar points (Quinlan, 1990). I believe that these unique flow and discharge patterns likely play integral roles in transport of sediment and contaminants in karst groundwater.

CHAPTER 3
KARST DYE TRACER TESTING

Introduction to Dye Tracing

Tracers are used to find the direction and rate of movement of subsurface water in karst regions. Most common methods involve injecting an artificial tracer into the flow system at a sinkhole or well, and detecting the occurrence of the tracer by sampling all possible points of resurgence. These techniques are divided into five categories: 1) dyes, 2) inorganic and organic chemicals and electrolytes, 3) mechanical, 4) radioactive isotopes and 5) dyed spores. The choice of a tracing technique depends on many factors, including environmental conditions at a test area that may have an adverse effect on a particular technique, laws and regulations that may restrict or prohibit the use of certain techniques in an area, and cost of a tracer study (Aley, 1972). A brief discussion of these techniques, as well as the narrative of a tracer test performed at the Metzgar Athletic Fields is discussed below.

The use of dyes as tracers involves injecting the dye into the flow system and detecting its occurrence by visual observation, fluorescence measurement, or detecting the presence of the dye in an absorbent material that is placed at sampling points. The main advantage of dye tracers is that they are fairly simple to use, can often be detected directly by eye or an ultraviolet light source, and can be detected in small concentrations with use of absorbent materials such as charcoal, or with a spectrofluorometer. The primary fluorescent dyes used in groundwater tracing include: rhodamine WT (CI Acid Red 388), fluorescein (CI Acid Yellow 73), optical brighteners and Direct Yellow 96. The corresponding numbers represent the wavelength of the fluorescent dye in micrograms per liter. Rhodamine dye is water soluble, detectable to 0.01 μm/L, non-carcinogenic, inexpensive, and reasonably stable in natural waters. Using multiple wavelengths is advantageous in karst dye tracing. The average time the dye arrives at a monitoring point aids in estimating the residence time and velocity of karst groundwaters (Aley, 1972).

Chemical and electrolytic tracers involve injecting non-fluorescent chemicals (such as NaCl) into the flow system, and analyzing grab or time composite grab samples, or continuously monitoring the conductivity of the water at the sampling points (www.dyetracing.com, 2000).

The oldest techniques used for subsurface tracing, dating back several centuries, are wood blocks or other floating objects. More recently, polypropylene floats have been used, although polyethylene powder, which works under the same principle as floats, does not pass through water filled passages (Aley, 1972).

Although the dyed-spore method is actually mechanical in the truest sense, it deserves special attention due to its significant applicability to subsurface tracing in karst regions. Dyed spores make excellent tracers in karst terrane because: 1) they are extremely small (30 microns in diameter) and can pass through very small openings, 2) they have a density close to that of water and will not readily settle out when flow is turbulent, 3) they are virtually indestructible and unaffected by water chemistry (www.dyetracing.com, 2000).

Field Tracer Test

On January 13, 2000, a fluorescent dye tracer test was performed at the Metzgar Athletic Field area to determine if hydrologic communication exists between the area of the subsurface borings, a monitoring well and the springs in the Bushkill Creek. Injection and sampling points were based upon the geophysical data obtained from previous research (Jenkins, 1999; Maule, 2000), the location of the installed cased borings and wells in Metzgar Field, and the identification of spring discharge locations along the Bushkill Creek in the spring and summer of 1999. The distance from the injection point (Metzgar Athletic Field) to the hypothetical discharge point (springs downstream from the springhouse and downgradient of the monitoring well) is approximately 2,000 feet.

John Diehl of the Pennsylvania Department of Environmental Protection (PA DEP), Dr. Mary Roth, P.E., Lafayette College, Dr. Laura Toran, Temple University and I conducted the tracer test. Lafayette College and Temple University undergraduate and graduate students also assisted.

During the summer and autumn of 1999, I performed field reconnaissance to determine possible discharge sampling locations for the dye trace test. It should be noted that during the summer of 1999, a significant drought occurred throughout eastern Pennsylvania. Drought conditions allowed for a more precise identification of spring locations along the dry stream banks. Field reconnaissance was completed along the eastern bank of the Bushkill Creek, beginning at the Stockertown bridge and ending approximately one mile south of the Tatamy Bridge. Three (3) distinct spring discharge areas are identified on Figure 6.

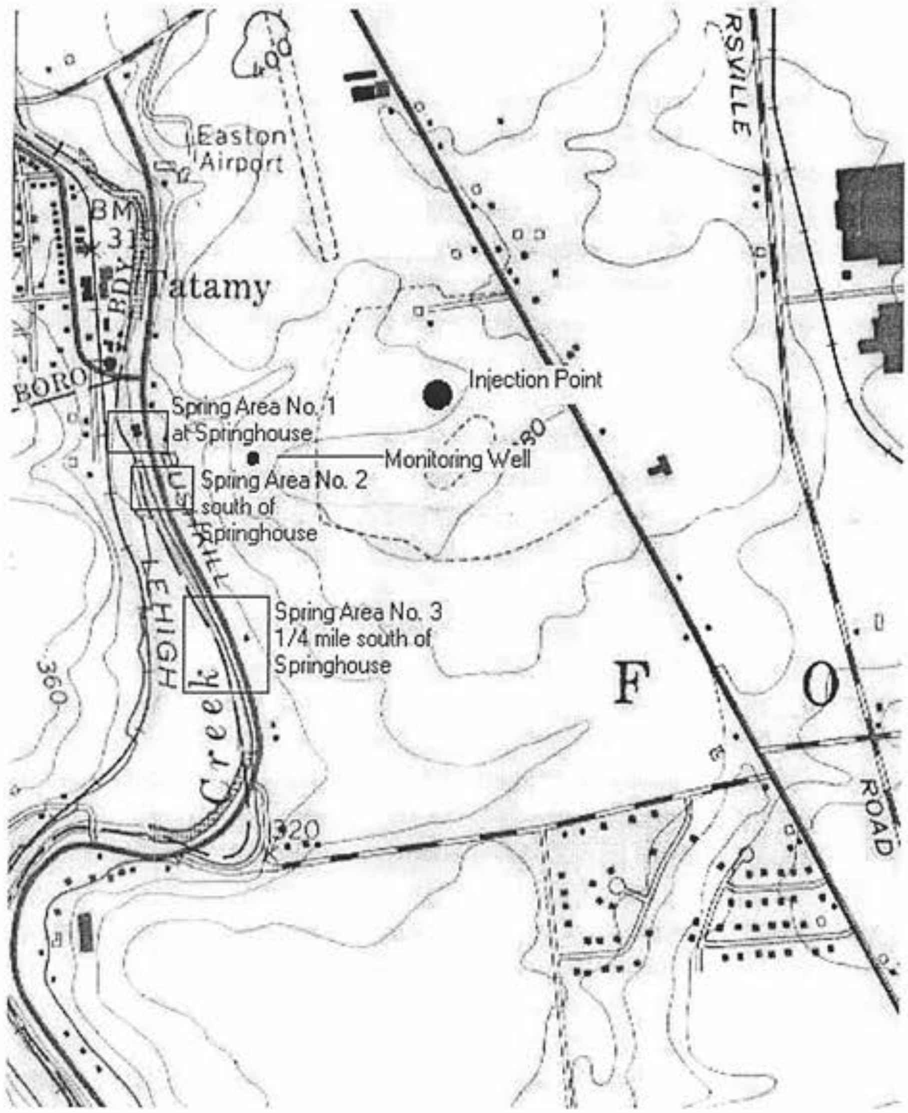

Figure 6 Spring Locations Identified in the Research Area, Injection and Monitoring Point(s); 1":2,000' (from 7.5 Minute Easton, PA Topo Map - USGS, 1983).

The spring (No. 1) located just downstream of the springhouse was monitored during the initial dye test as a potential discharge point because it is along strike of the injection point. This discharge point is an approximate one-foot wide by 1 ½ high solution-enhanced fracture along the creek bank. Approximate flow measurements were obtained from the spring prior to the tracer test using a 40 mL vial and stopwatch. The spring discharge flow was approximately 500 mL/minute. Based on the geophysical, geologic and topographical mapping of the area, the trend of groundwater flow is to the southwest, toward the Bushkill Creek.

Approximately one gallon of rhodamine dye was injected into an open borehole in Metzgar Field. Water was used to "lubricate" the flow system prior to injection to permit the dye to flow through the main conduit system, and not smaller fracture networks that could divert the tracer plume. A chaser was also used after the dye once injected to aid flow toward the discharge point. Approximately 600 gallons was injected ahead of the dye, and approximately 3,600 gallons used as a chaser. A garden hose provided the water for the pre and post-chaser. Hose flow was approximately five gallons per minute.

The water samples obtained from the downgradient well and the spring discharge area were collected and stored in 40 mL amber glass jars to minimize fluorescent degradation and absorption onto the collection vials. Prior to the dye trace, background samples were obtained from the well and discharge location to identify any background fluorescence in the groundwater and creek. No fluorescence was detected in the background samples. Figure 6 also illustrates the injection and sampling points.

The well was sampled using a two foot long, one-half inch wide disposable plastic bailer. The bailer was lowered beneath the water level using a 100 foot bailer line and reel. The bailer was raised to the ground surface and emptied into 40 mL vials. The water level was recorded every sampling period using a Solinst Water Level Meter and a time series profile of varying water level was generated.

Once the dye was injected, the well and discharge locations were sampled every 15 minutes. Over the course of the initial afternoon, the sampling interval was extended to every 30 minutes. During Thursday (13^{th}) night and early Friday (14^{th}) morning, the locations were sampled approximately every 30 minutes. An ISCO Autosampler was used to sample the discharge point location every 30 minutes from midnight Friday until approximately 7:00 am Friday. The well was sampled three times during the early morning. The well and discharge locations were sampled approximately every 30 to 45 minutes on Friday until approximately 4:00 pm. All of the samples were removed from the interior of the ISCO sampler (which protected again photodegradation) and transferred into 40 mL, amber glass vials to minimize fluorescent degradation of the dye. In addition, samples were stored in cool, dark coolers during transport to Lafayette College for analysis, and again for re-analysis at Temple University.

The water samples were analyzed using a JASCO Model 750 Spectrofluorometer and Lafayette College's Perkin Elmer Spectrofluorometer. The

Turner fluorometer was used in the field to determine initial traces of fluorescence. The Turner fluorometer noisy readings and did not allow adequate screening for laboratory samples. As a result, all samples were analyzed in the laboratory at Lafayette and Temple. During the course of the dye test, Lafayette College's Chemistry Department permitted the use of their spectrofluorometer. Samples were analyzed during the two days of the dye trace. When compared to background, the samples collected during the test did not reveal above background levels of fluoresence at 580 nanometers, the emission wavelength of rhodamine FWT.

After the two day monitoring period, charcoal packets were installed in the well and spring for continuous dye sampling. The charcoal packets were changed every day for one week after the dye test by Lafayette College students. Charcoal packets were installed below the water table in the well, and in the path of discharge at the spring location previously described, in order to maximize the amount of water passing through them. The charcoal packets were stored in plastic bags and kept cool and dark during transport and storage. Chemical removal of the Rhodamine dye from the charcoal packets was performed in accordance with the methodology described in the Water Tracers Cookbook (Aley and Fletcher, 1976). The resulting aliquot was then analyzed for fluorescence using a JASCO Spectrofluorometer at Temple University.

Field Tracer Results

Rhodamine dye was not detected during any phase of the January 13, 2000 tracer test. The possible reasons for non-detection include the following: 1) the use of an increased amount of post-injection chaser water increased the flow gradient and velocity and possibly flushed the tracer into a network of conduits that discharged into an unidentified locality, 2) the monitored discharge point is not the most concentrated, 3) the dye remained in the karst system isolated in epikarst, and 4) the tracer was intercepted by a flow system that discharged to the east toward the Delaware River. Our understanding of the underlying carbonate system and karst aquifer was limited to the geophysical surveys and installed borings and wells. Since I did not know the exact location of major conduits and the network of epikarst, if any, the destination of the tracer and the amount of water needed during the test precluded complete control of the tracer test.

CHAPTER 4

WATER CHEMISTRY

Karst Geochemistry

Groundwater in karst aquifers can move on a time scale faster than chemical reaction rates between the groundwater and the carbonate wall rock. Such waters, therefore, can be out of equilibrium with their environment. The extent to which they are out of equilibrium varies with the discharge and the arrangement of conduits. The discharge of carbonate groundwater through large springs exhibits rapid changes in both flow volume and chemistry. The variation in either discharge or chemistry with respect to specific recharge events (*i.e.* storms) can thus provide information on the behavior of the aquifer (White, 1988b).

The variation in water chemistry over different time scales and the analysis of karst groundwater geochemical data have been used to analyze the dynamic nature of karst groundwater and environments. I used an individual storm event and bi-weekly seasonal monitoring to determine changes in geochemistry of karst environments, and more importantly, to further understand the transport of sediments in karst systems.

Sample Locations

MW-1 and Spring No. 1 (Figure 6) located along the Bushkill Creek, downgradient of the Metzgar Athletic Field, were monitored for sediment and geochemical variability from January 2000 to January 2001. The spring discharging groundwater to the Bushkill Creek is approximately one foot wide and is even with the Bushkill creek bank.

Beginning in September, 2000, Spring No. 2 (located along the Bushkill Creek and approximately 30 feet from the initial spring; see Figure 6) and the Stockton Formation spring were monitored for sediment variability to determine if it is similar throughout karst groundwater systems, but different than that of fractured shale. During the first sampling event of January, 2001 (January 7, 2001), I discovered that the primary spring had collapsed. It appeared that rock and soil had fallen into the spring and impeded flow through the drainage conduit. For the final sampling event, the second spring was substituted for sediment and water chemistry measurements.

Temperature Monitoring of Storm Events

Karst tends to exhibit "flashy" geochemistry, which is attributed to the fast flow of groundwater in karst areas. The quick flow of water in karst is an important factor when considering chemical and sediment changes in karst groundwater. In order to determine an approximate residence time for flow within the karst aquifer, and to monitor the influence of storms on the spring temperature, a HOBO™ temperature logger was installed in the primary spring along Bushkill Creek.

The residence time of stormwater in a groundwater system is important information that allows qualitative assessment of diffuse versus conduit flow. The unique conduit flow of karst allows infiltrating water to move faster than in other porous media, and as a result has a shorter residence time. The transport of sediments and contaminants in a karst groundwater system is more likely during periods of intense rain and discharge.

The logger recorded temperature every fifteen (15) minutes. The precision of the instrument varies with temperature but is relatively accurate (± 0.6 degrees celsius) between –20 and 60 degrees celsius. The HOBO™ logger was removed from the spring area in early October because the spring stage decreased and the logger could no longer be submerged in water. In the late summer, one HOBO™ was lost (washed downstream) along with two months of data (summer only).

Aqueous Sample Analysis

Samples were collected both seasonally and during high flow rain events to determine water chemistry and sediment variability in the karst aquifer. Groundwater samples were collected from the monitoring well and spring discharge locations. Spring samples were collected with 40 mL glass vials and stored in quart-size amber glass jars. The well was sampled using a two-foot long, one-half inch wide disposable plastic bailer. The bailer was lowered beneath the water level using a 100' bailer line and reel. The bailer was raised to the ground surface and emptied into a quartz-size amber glass jar. The bailer used to sample MW-1 was cleaned subsequent to each sampling event with deionized water and Alconox biodegradable, non-toxic soap.

The monitoring well was not purged prior to sampling because purging could mobilize sediments not naturally suspended, dissolved or transported in the aquifer. In addition, the monitoring well was not purged because recharge in karst conduits commonly exceeds purge rates, which could potentially mobilize sediments natural to the groundwater system. These remobilized materials could potentially contaminate the sampling with sediment and chemical species that are not naturally transported in the karst groundwater system.

The standard field parameters (pH, total dissolved solids, temperature and conductivity) were measured using an Orion 250 portable meter (pH and temperature) Specific conductance and total dissolved solids were measured using Hanna Field Probes. The standard field parameters for the spring were analyzed *in-situ*, and for the well, immediately after collection of the well sample. The samples were kept cool (approximately 10° C) and dark during transportation and storage before laboratory analysis. The aqueous samples from the spring and well were analyzed for major cations, anions and alkalinity as $CaCO_3$. Alkalinity was measured with a Hach Digital Titrator® (Model 169001-01).

The major cation and anion concentrations for the well and spring were measured using a Dionex 500 Chromatograph. A water sample is injected *via* an injection valve into a carrier stream or eluent, which transports the solution through the chromatography column. The transport rate of the solution is maintained by a pump. As the mobile phase transports the sample through the column, ionic species compete for exchange sites on the analytical separator column. Separation of ions depends on their size and ionic charge. The first to separate are small monovalent ions. Fractions are registered in turn by an ion conductivity detector (ED 40, Electrochemical Detector – set to conductivity mode). Species are identified from their retention time, *i.e.* the elapsed time between the injection and detection. Method selection and the set of parameters for the analysis of the major ions was made through PeakNet[R] Windows software.

Seasonal Variation in Water Chemistry

The water chemistry data will be compared with the sediment (presented later), precipitation and other information to determine temporal changes of sediment transport and water chemistry in karst groundwater. The measurements include major cations and anions (sodium, potassium, magnesium, calcium, chloride, nitrate and sulfate), pH, alkalinity, specific conductivity, total dissolved solids, temperature for the spring and monitoring well, and a review of changes in the monitoring well's water level. Daily precipitation history (Figure 7) was compiled from the Allentown-Bethlehem Airport's precipitation data (http://www.nws.noaa.gov). Although this figure depicts daily precipitation, subsequent graphs depict both daily and weekly average of daily precipitation. Weekly rain was used to aid in interpretation of how the accumulation of rainwater and snowmelt affected the water chemistry and sediment transport in karst environments.

Seasonal sampling of the spring and well show a decrease in major cations and anions from January, 2000 to April, 2000 (see Figures 8 and 9). Calcium in the

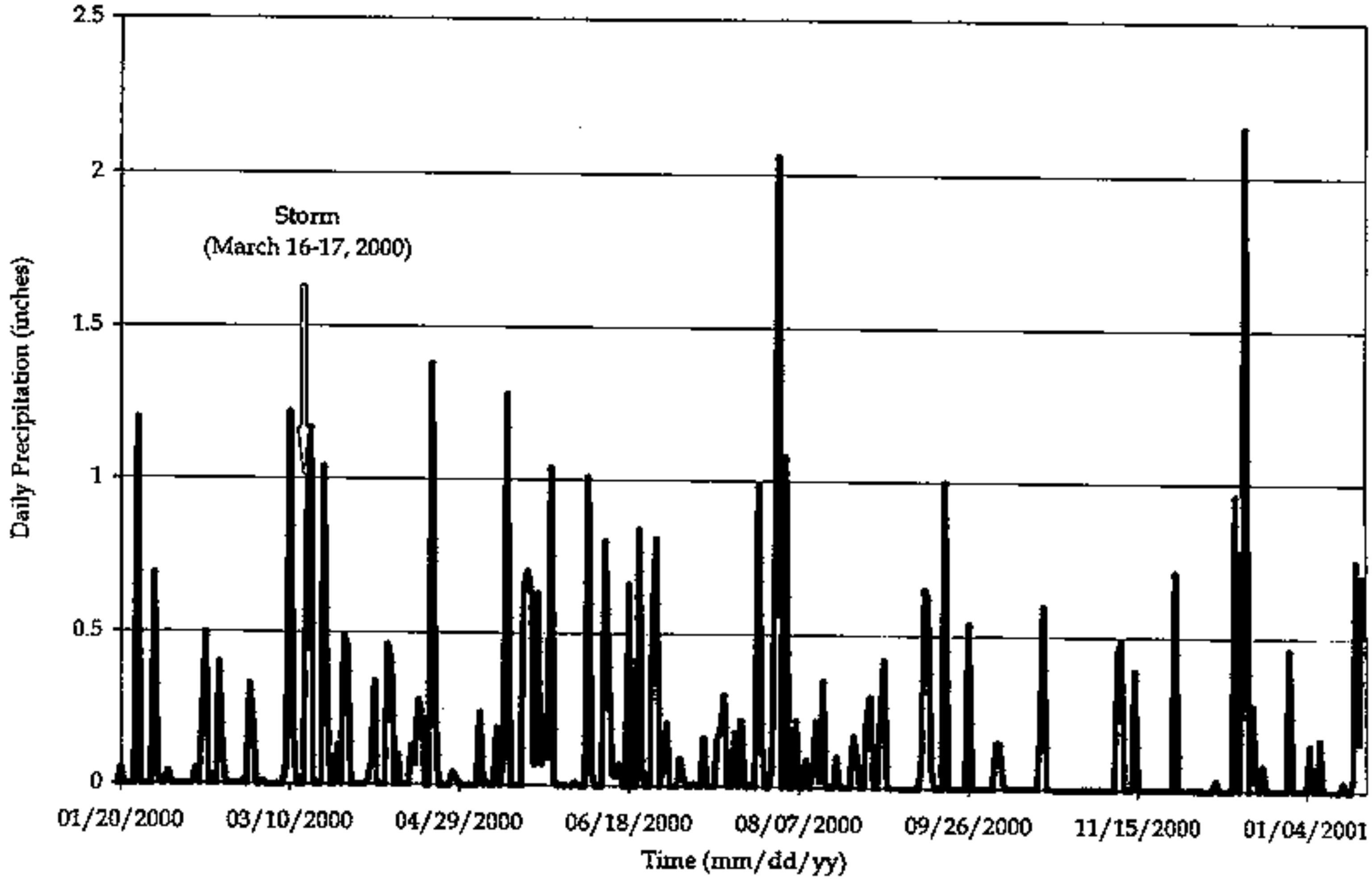

Figure 7 Allentown-Bethlehem Airport Daily Precipitation for the Research Period (1/21/00 - 1/21/00). There are more rain events in spring and summer than in the fall and winter.

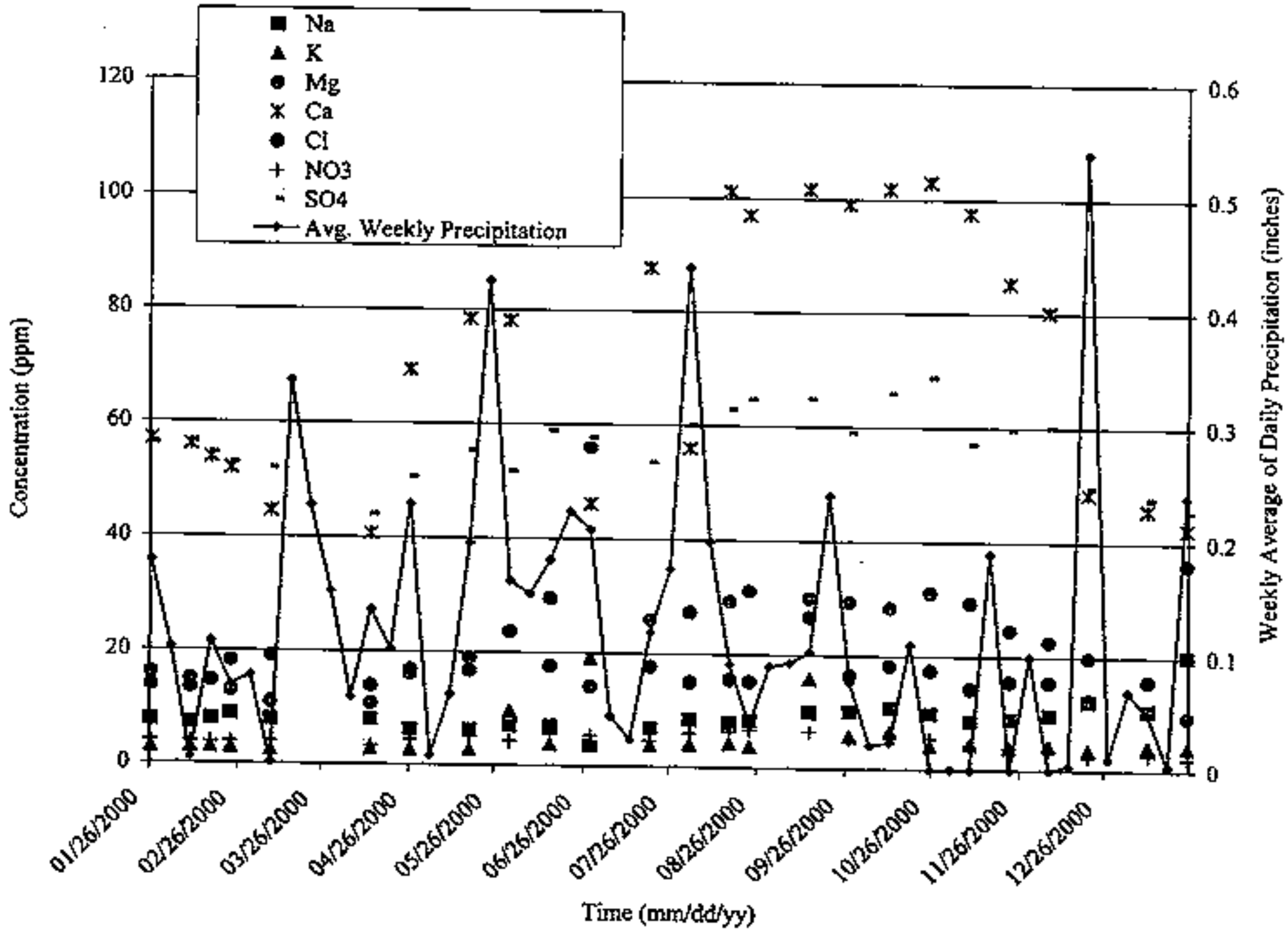

Figure 8 Variation in Water Chemistry in Spring No. 1 (Epler Formation) Over the Course of the Year. The concentration of the ions (in particular calcium) varies with storm events.

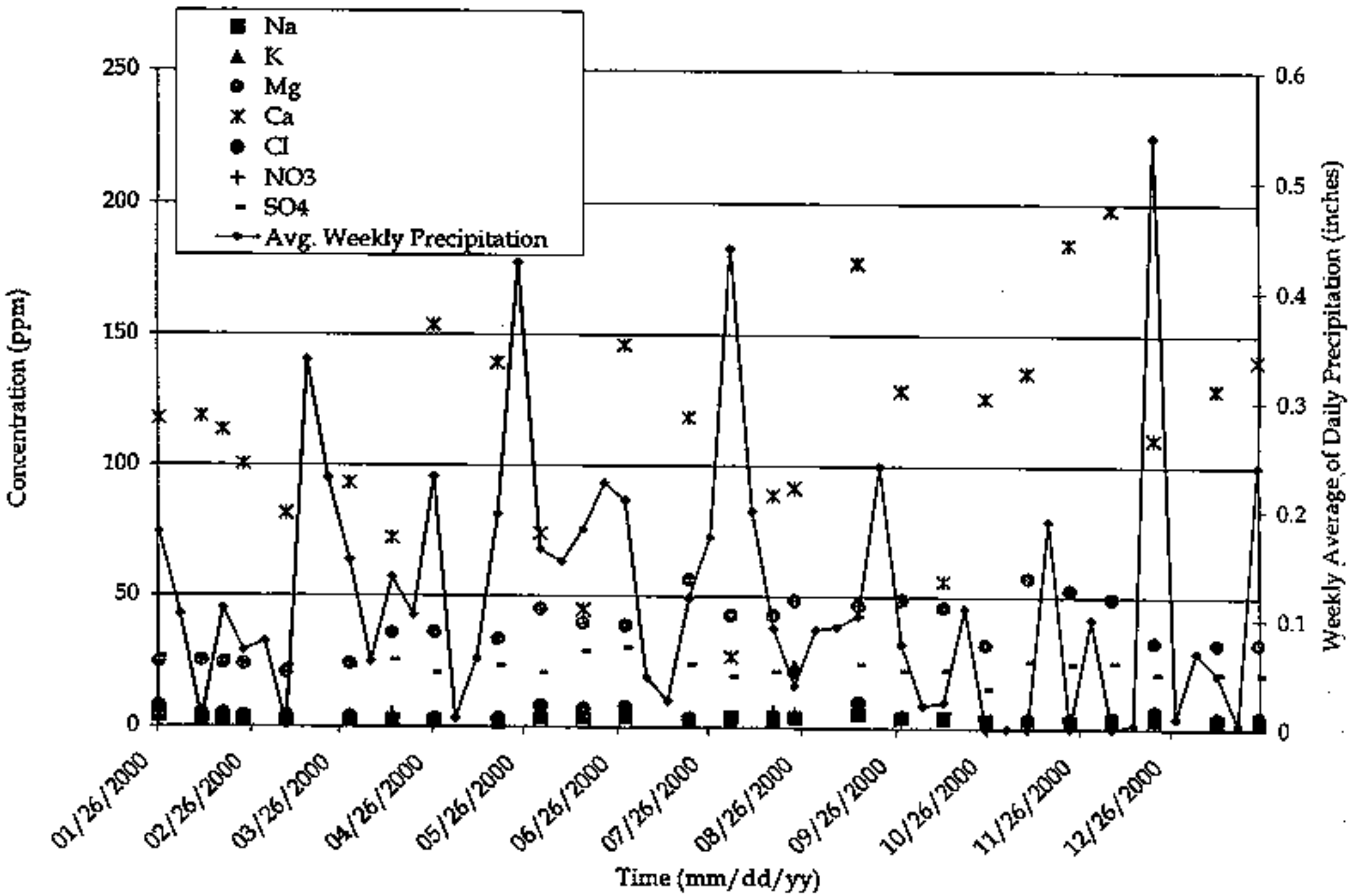

Figure 9 Variation in Water Chemistry in the Monitoring Well (Epler Formation) Over the Course of the Year. The concentration of the ions (in particular calcium) varies with storm events.

monitoring well decreased from 118 mg/L to 81.69 mg/L over the course of three months. Magnesium in the well decreased from 24.68 mg/L to 20.88 mg/L, and sulfate decreased from 26.72 mg/L to 22.41 mg/L. Calcium in the spring decreased from 56.96 mg/L to 40.63 mg/L, sulfate decreased from 56.33 mg/L to 44.06 mg/L, and magnesium decreased from 16.05 mg/L to 10.98 mg/L. The balance of the major ions in the monitoring well and spring share similar trends. In contrast, the concentration of sodium and chloride in the spring increased from 7.82 mg/L to 8.18 mg/L and 13.97 mg/L to 19.23 mg/L respectively during this period.

The geochemistry of the spring and well reveal a dynamic system from the beginning of April, 2000 to the beginning of 2001. In the monitoring well, calcium ranges from195 mg/L (the highest point in September, 2000) to 30 mg/L in July, 2000 (the lowest calcium concentration). In the spring, calcium ranges from 100 mg/L to 50 mg/L. Magnesium ranges from 57.33 mg/L on November 8, 2000 to 32.05 mg/L on October 25, 2000. The nature of the calcium and magnesium share similar trends with the other ions analyzed during the research period (Figures 8-9).

The depth to water in the monitoring well and spring stage was monitored bi-weekly to document the response of the groundwater system to recharge and storage before and after precipitation events (Figures 10 and 11). The highest water level recorded in the monitoring well was 50.38 feet below the ground surface (bgs) during the end of May, 2000. The lowest depth to water recorded in the monitoring well was

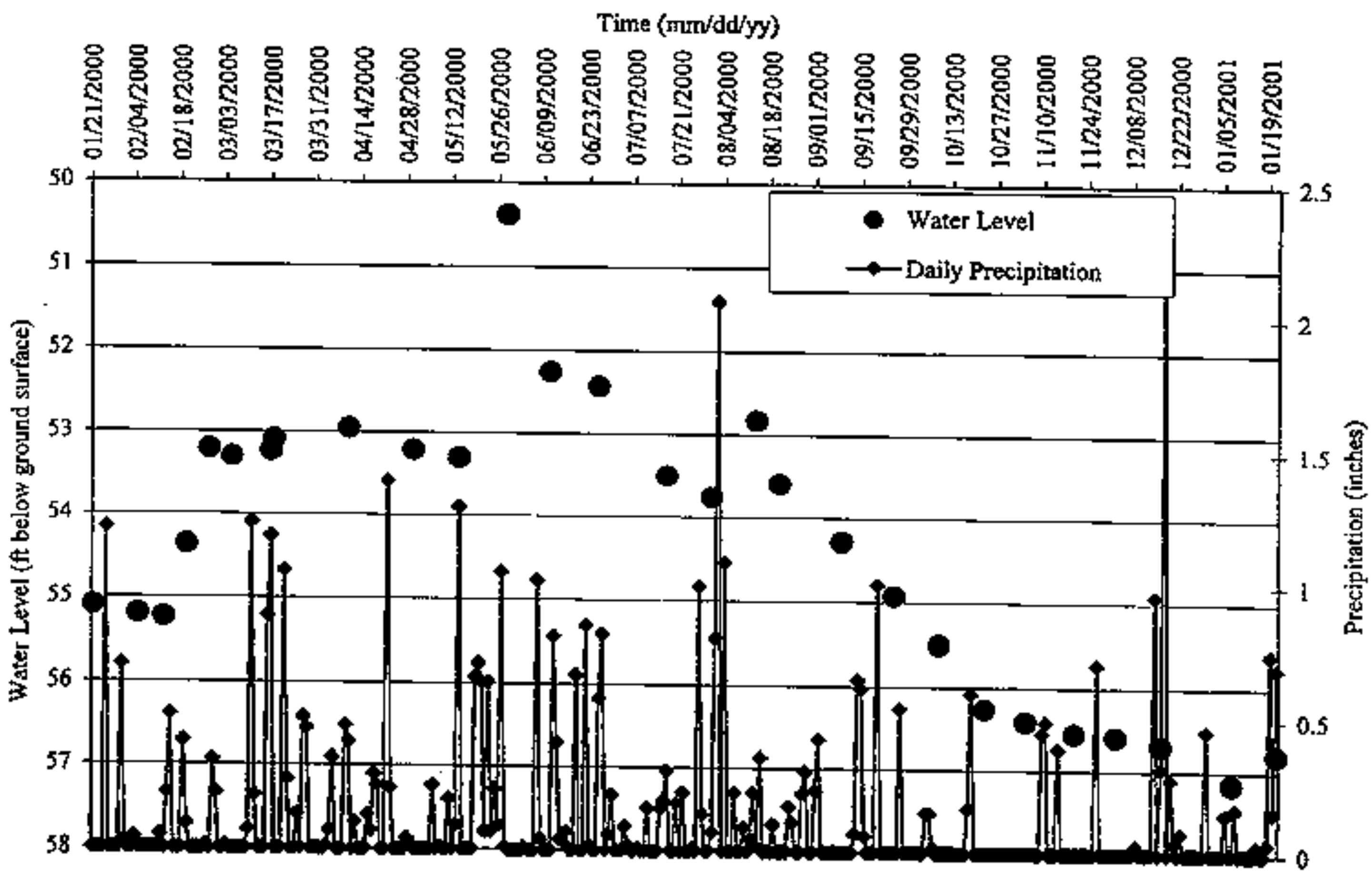

Figure 10 Variation in the Water Level of the Monitoring Well (Epler Formation) Over the Course of the Year. The water level reflects changes in the amount of groundwater in the karst network.

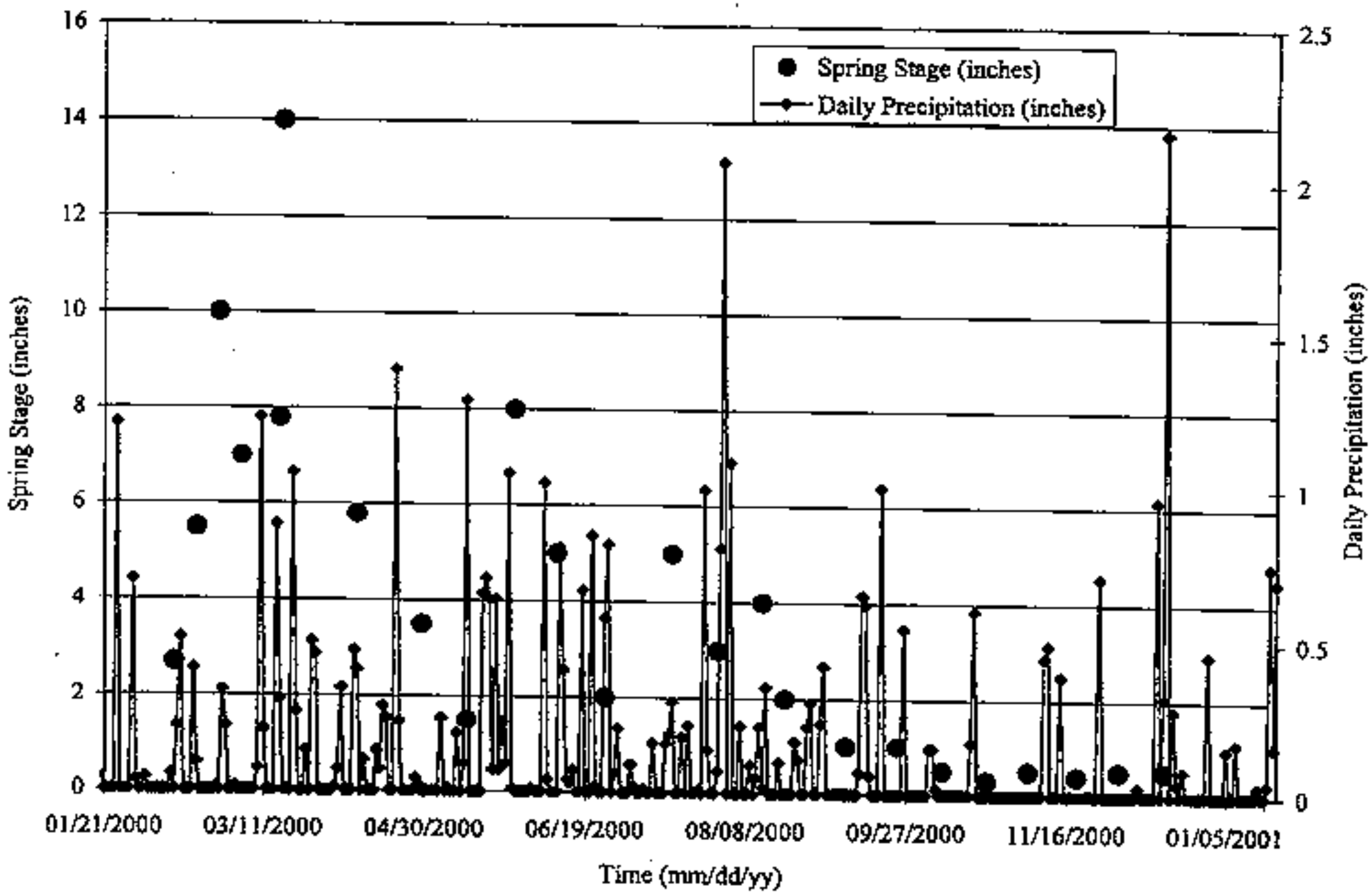

Figure 11 Spring Stage (#1, Epler Formation) and Daily Precipitation versus Time. The seasonal variation in stage height reflects seasonal variation in precipitation.

57.15 feet bgs on January 10, 2001. The most dramatic fluctuation occurred in May, 2000 when the water level increased three feet between sampling periods. During that period, the area was hit by a rainstorm (1.28" of precipitation). The highest water levels were measured during the wet spring and summer months, and the lowest in the autumn and winter of 2000. The water level recorded on December 20, 2000 was 56.7 feet bgs. On December 17, 2000, two inches of precipitation fell on the area. If the water level increased subsequent to the rain event, the reading on the 20th missed the rise, if any, in the monitoring well. The highest stage recorded in the spring was 14 inches on March 17, 2000, the lowest (0.3 inches) was recorded on October 22, 2000.

The water temperature in the spring and monitoring well increased and decreased over the course of research (Figure 12). The spring and well share a similar trend of warmer temperatures in the summer months. The well had cooler water than the spring by 2 degrees celsius until the beginning of March. The temperature in the well became warmer by 2 degrees celsius than the spring by March 8, 2000. The coldest temperature recorded was 1.7 C° in the well during October. The cause of this significant temperature drop is not known. The warmest well temperature recorded was 21.5 C° in July, 2000. This change is due to the temperature of infiltrating water entering the system. Recharging water, whether rainwater or surface water, is warmer in late spring, summer and autumn, and will result in warmer water entering the groundwater that ultimately discharges into the Bushkill Stream.

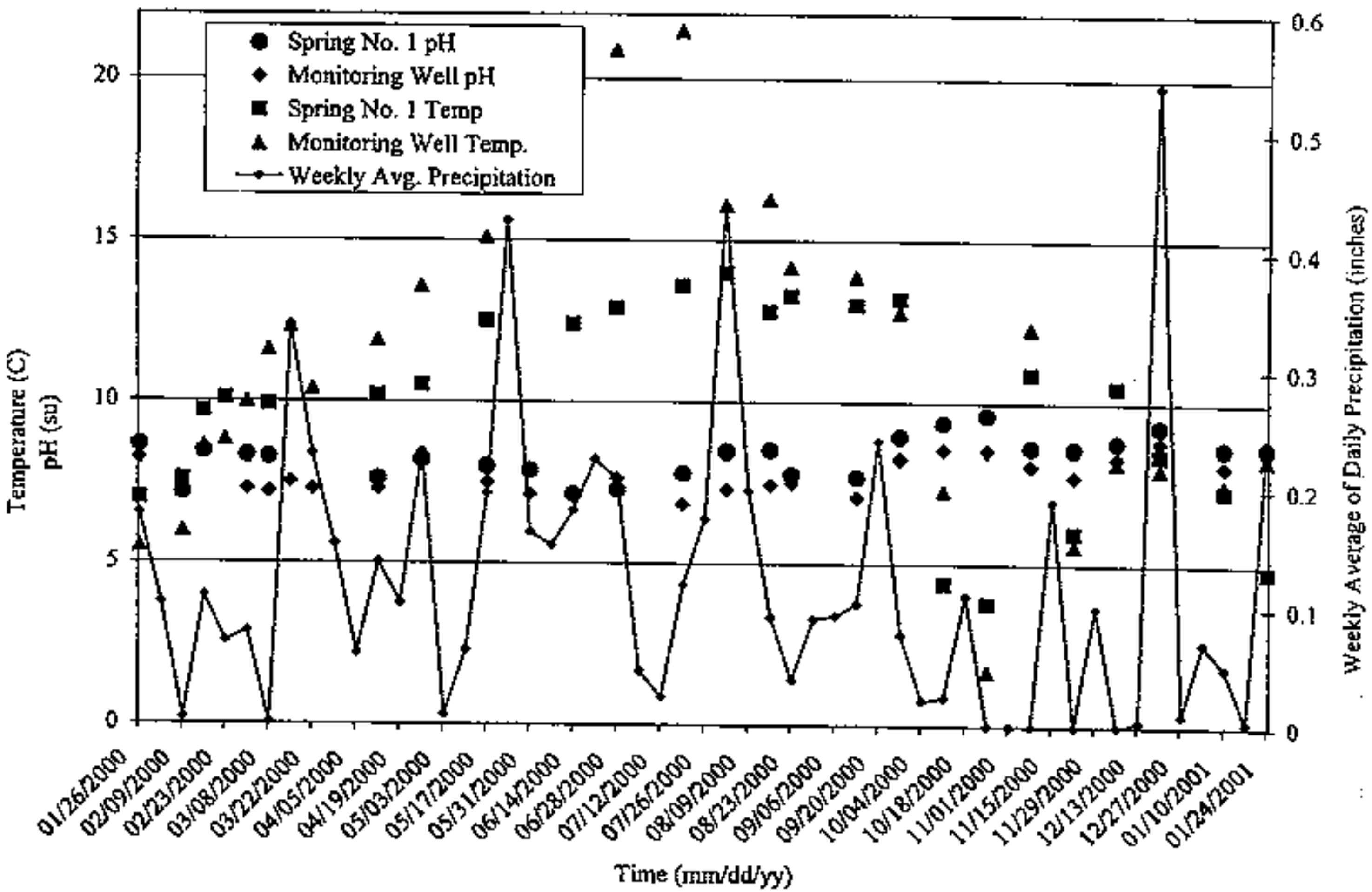

Figure 12 Variation in pH, Temperature and Weekly Average of Daily Precipitation in Spring No. 1 and the Monitoring Well (Epler Formation). Variability in these parameters reflect seasonal changes.

The pH of the spring and monitoring well varied between 7 and 9 standard units (Figure 12). The variation in pH is likely due to rainwater recharge into the flow system and subsequent carbonate dissolution, which increases the pH. The alkalinity of the spring and well also demonstrate the dynamic nature of the groundwater system throughout the year. In the monitoring well, alkalinity ranges from 548 mg/L (the highest point on December 6, 2000) to 241 mg/L on March 1, 2000. In the spring, alkalinity ranges from 298 mg/L (September 13, 2000) to 88 mg/L (June 28, 2000). The alkalinity in the spring and monitoring well share similar phases of increasing and decreasing values (Figure 13). An exception to this occurred in October – November, 2000. The spring appears to remain at a stable level of approximately 280 mg/L. This could be a function of karst water chemistry dynamics at the spring that cannot be fully explained in this study.

The specific conductivity also fluctuates due to seasonal changes (Figure 14). Recharge of the aquifer tends to dilute the ionic species in the water, therefore decreasing conductivity. Likewise, as recharge occurs in the conduits and into the karst system, the specific conductivity tends to decrease as dissolved materials are diffused. A specific example of this occurred after a rain event (0.11 inches) on October 18, 2000. The total dissolved solids (TDS) in the monitoring well prior to the storm was 429 ppm and decreased to 381 ppm after the storm. The specific conductivity decreased from 824 umhos to 769 umhos. TDS and specific conductivity values decreased similarly in the spring after the storm. The specific conductivity and TDS rose in the monitoring well two weeks later during sampling

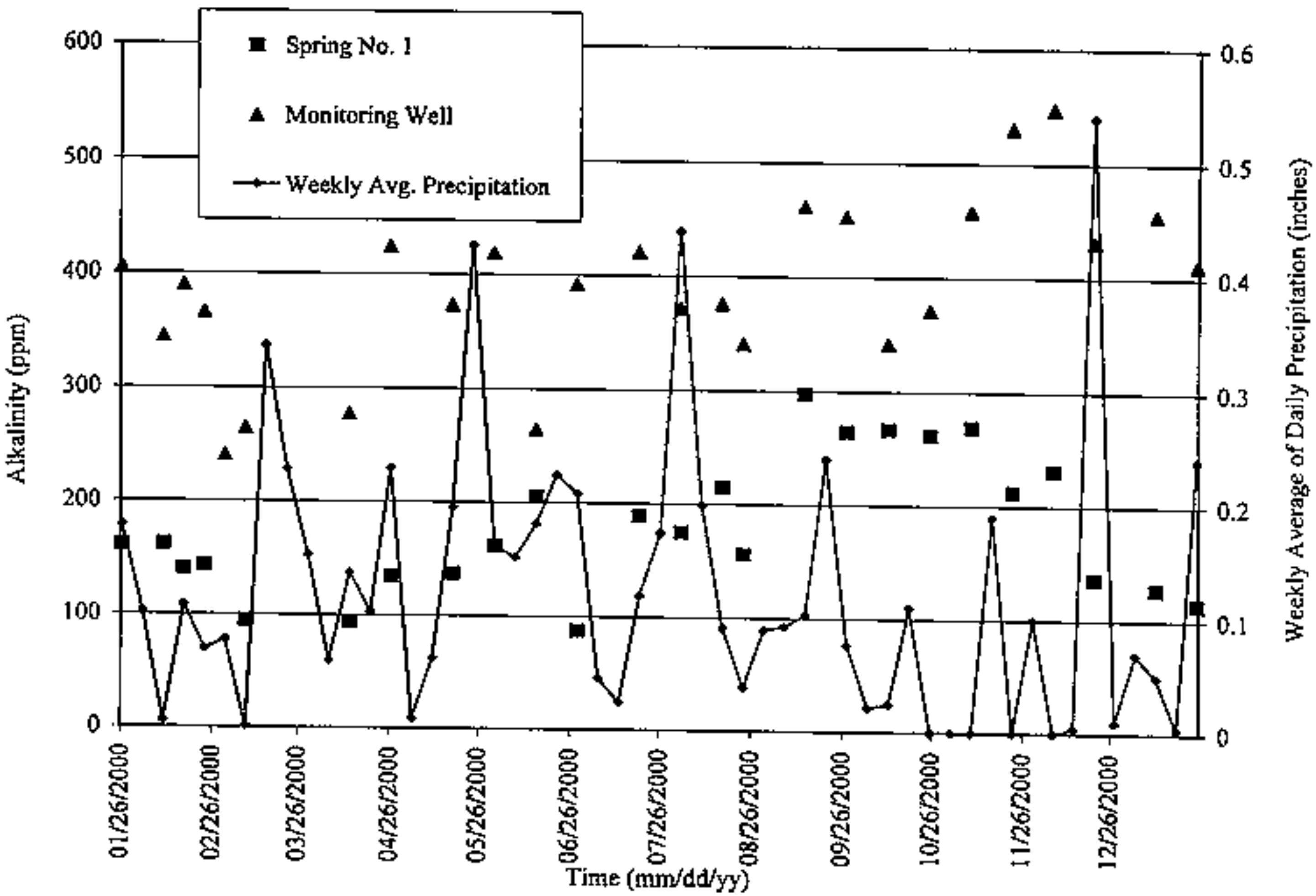

Figure 13 Variation in Alkalinity (as $CaCO_3$) in Spring No. 1 and the Monitoring Well (Epler Formation) Over the Course of the Year. The alkalinity increases when the average weekly precipitation decreases.

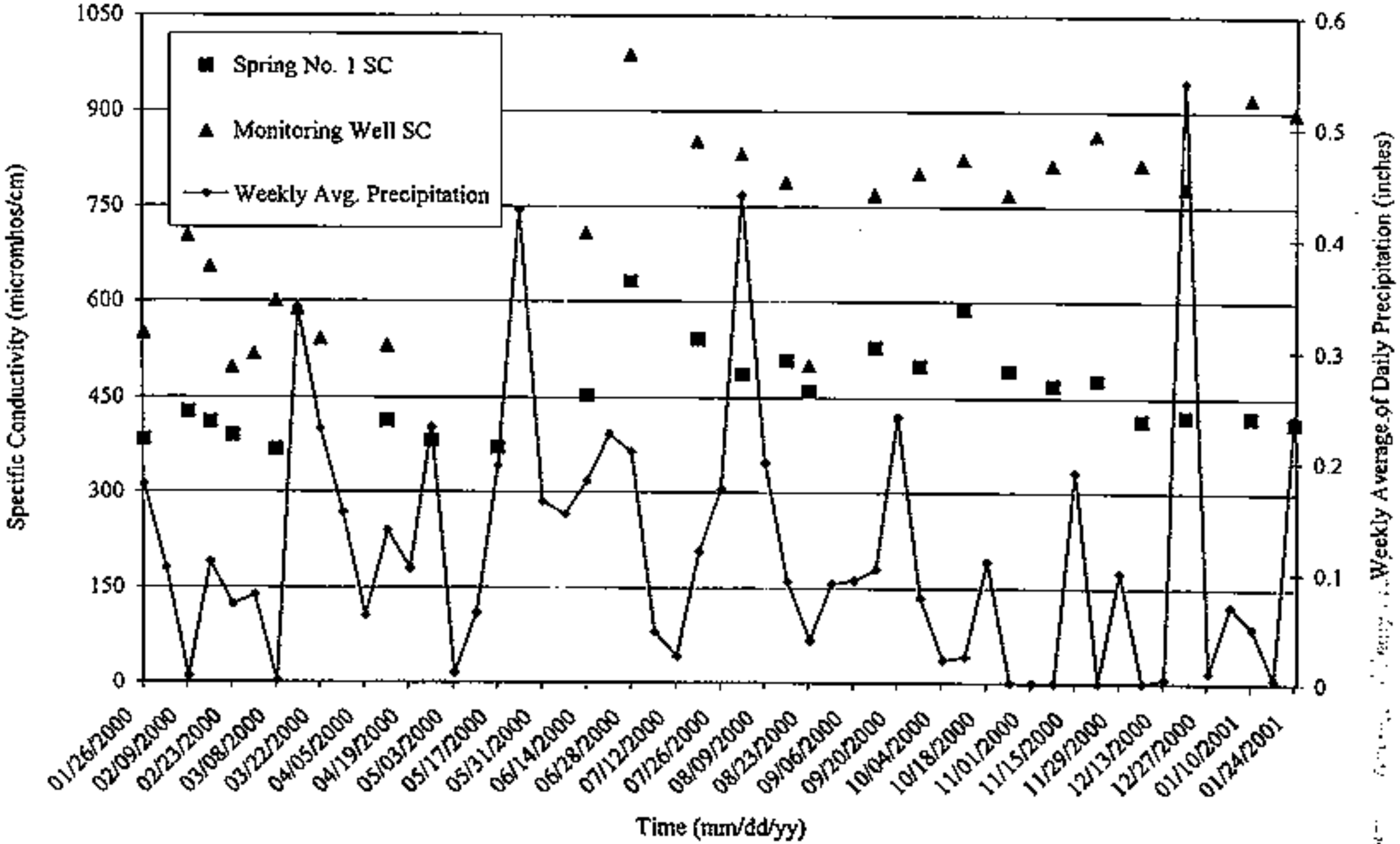

Figure 14 Variation in Specific Conductivity and Weekly Average of Daily Precipitation in Spring No. 1 and the Monitoring Well (Epler Formation). The similar trend for both varies with storm events.

(November 8, 2000). The specific conductivity and TDS increased from 769 to 815 umhos and 381 to 390 ppm respectively. The increase did not occur in the spring at this time, suggesting a time lag in recharge from the monitoring well to the spring. A counter-example to this occurred on November 15th and December 13th, 2000. The lack of decreasing values subsequent to precipitation events suggests that the rainwater had not yet reached the monitoring points or changes in the geochemistry precluded a natural expected decrease or increase in conductivity or TDS.

Variation in Water Chemistry During a Storm

The storm on March 16th – 17th, 2000 was monitored hourly and water chemistry trends analyzed every 3-6 hours (Figure 15). Sampling of the first storm occurred for a total of 24 hours, which included pre-storm, concurrent and post-storm samples. Sampling began approximately 3 hours before the storm and ended approximately 6-8 hours after the storm. The recovery to ambient water quality and discharge subsequent to the storm was not recorded.

The concentrations of major cations and anions in the spring decreased as recharge water entered the aquifer. The total precipitation during the storm was 1.17 inches. The zero hour on the time-series profile represents the beginning of rainfall. The maximum rainfall occurred in the fourth hour. The lowest geochemical concentrations were recorded during the 13th hour. Based upon this, the groundwater flow of the infiltrating water has a residence time of approximately 4 hours (from

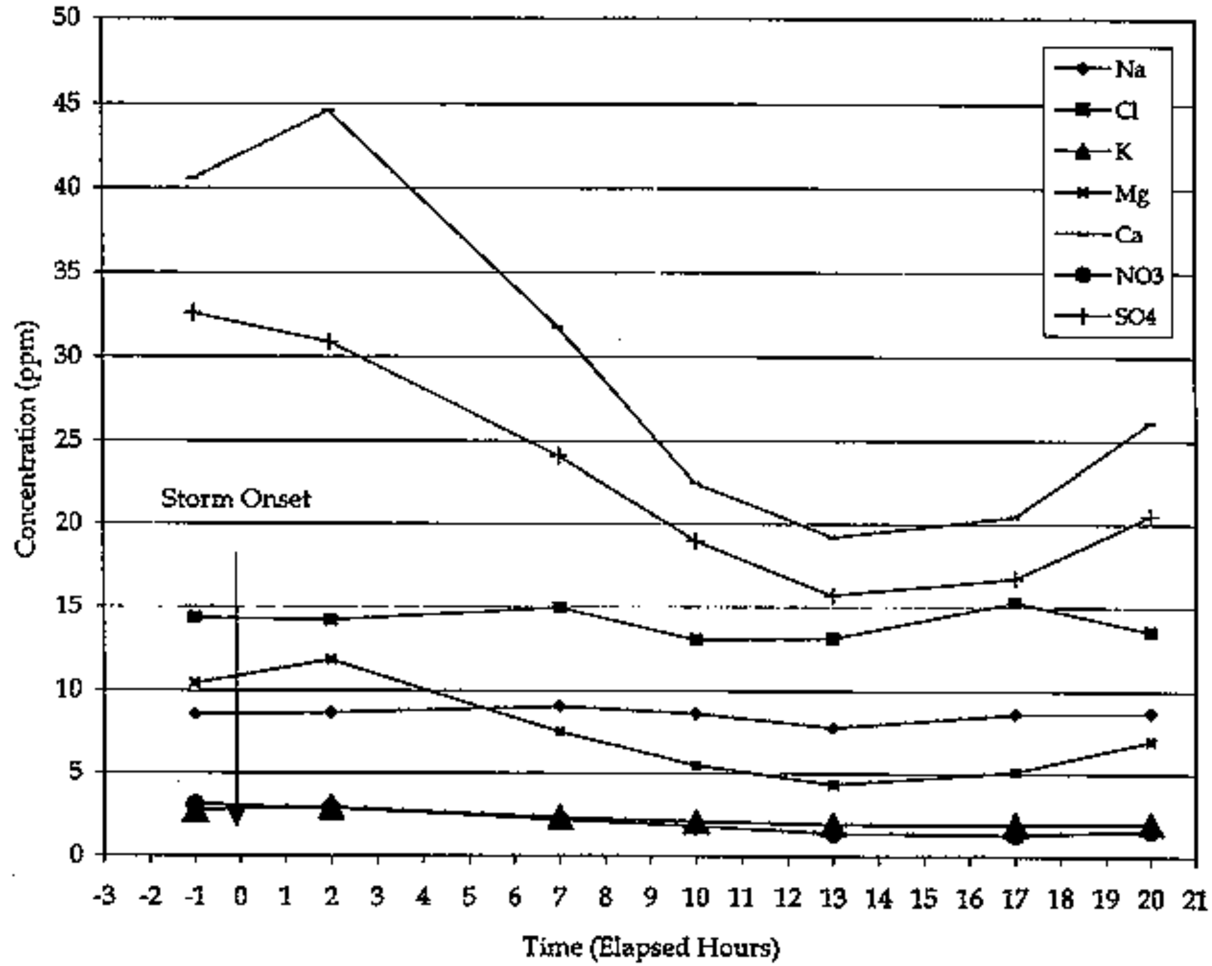

Figure 15 Variation in Water Chemistry Concentrations in Spring No. 1 During the Storm. Ions decrease with infiltrating stormwater to the lowest values during the 13th hour.

geochemical profile). The decrease in flow and a trend toward a return to natural, "ambient" conditions is evident in the water chemistry time-series profile. Calcium increased from 19.23 to 26.13 ppm from the 16th to the 20th hour. It is striking that Cl, Na, Mg, K and NO_3 retain relatively steady behavior during the storm. This is likely attributable to an influx of these ions during the storm pulse through the karst system.

The trends in chemical changes observed in the data collected during the storm were also reflected in the time-series profiles of pH and alkalinity (Figure 16). The water discharging from the spring prior to the storm exhibited a pH value of 8.04 standard units. As the storm progressed and stormwater infiltrated the karst system, the pH of the groundwater decreased to a value of 7.54 standard units (10th hour). The pH of the groundwater remained relatively low (7.5 standard units) subsequent to the storm. The recovery period of groundwater pH is longer than that of the major ionic species, which began to recover between the 13th and 20th hour. The highest alkalinity prior to the storm was 0.168 ppm. The alkalinity decreased to 0.052 ppm during the 10th hour and increased to 0.092 ppm by the 23rd hour. The recovery of groundwater alkalinity exhibited similar behavior to that of pH.

Analysis of the ionic concentrations discharged from the spring during the storm showed two distinct types of behavior. Each of the ions, except for chloride and sodium, exhibit a pattern of dilution in time-series profiles. When nitrate and

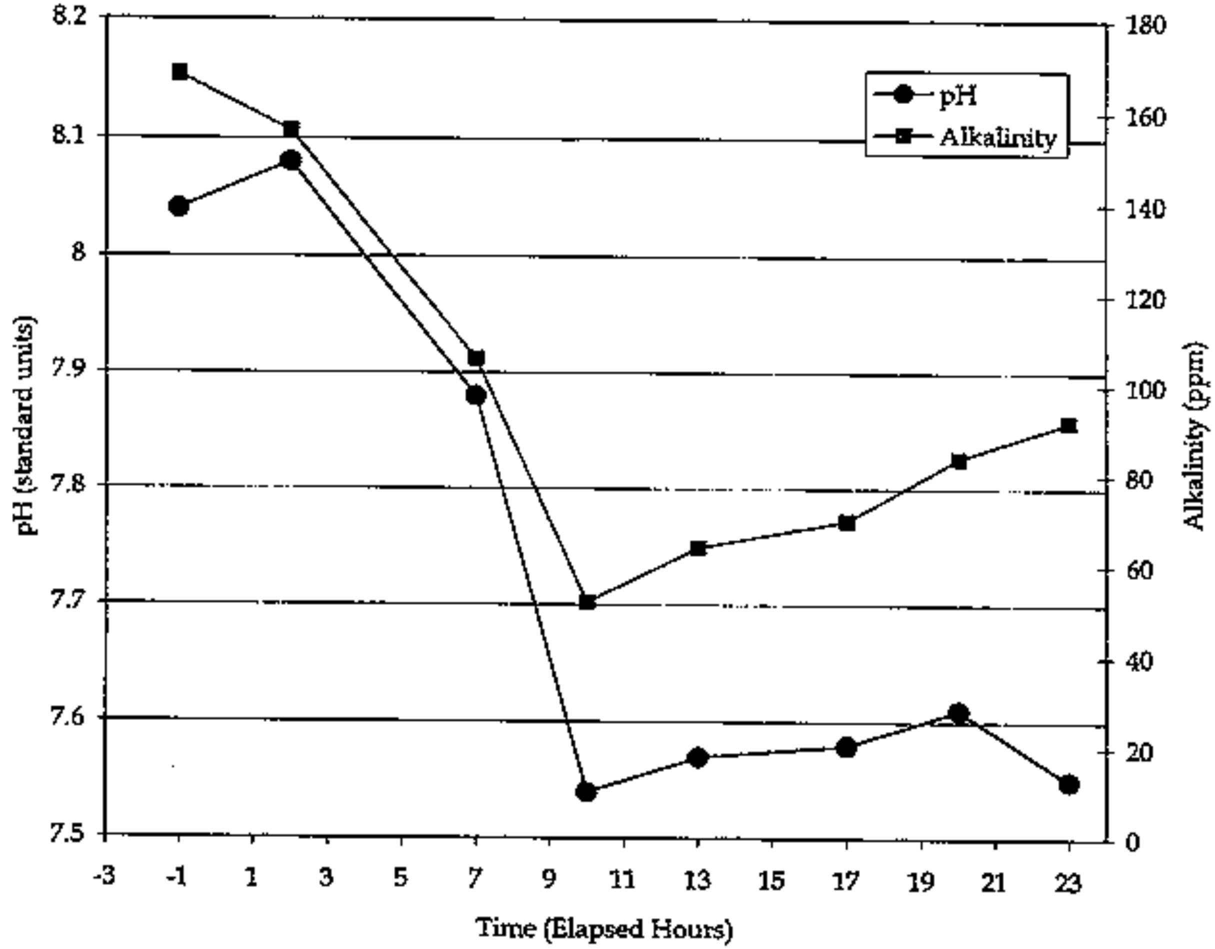

Figure 16 Variation in pH and Alkalinity (as CaCO3) in Spring No. 1 During the Storm. The pH and alkalinity decrease as stormwater infiltrates the karst system.

sulfate, calcium and magnesium, or magnesium (Figures 17 and 18) and potassium values are compared over the duration of the storm on the same profile, they plot on a mixing line of typical rainwater (Brittanica.com website, 2001) and the initial solution concentration (at hour -1). A dilution trend occurs during infiltration of storm water until the 14th hour when the solution concentrations rose during recovery. One exception to the dilution and recovery trend is hour 2, which has slightly higher instances of lower concentrations than hour -1.

Interpretation

The variability in calcium (the dominant cation), sulfate and magnesium can be attributed to the increase and decrease of infiltrating water into the karst groundwater system during the each season, as well as individual storms. The decreasing ionic concentrations in the beginning of the monitoring period can be associated with snowmelt and increased seasonal precipitation "flushing" the karst system. The low water chemistry concentrations in the well and spring throughout the spring and summer and into the late fall could be explained by the wet spring and summer and subsequent dilution of chemical species. The higher concentrations are probably attributable to dryer conditions and less water infiltrating into the system. The increase in sodium and chloride in the spring during the late winter / early spring is probably due to the influx of road salts into the local groundwater and stream network.

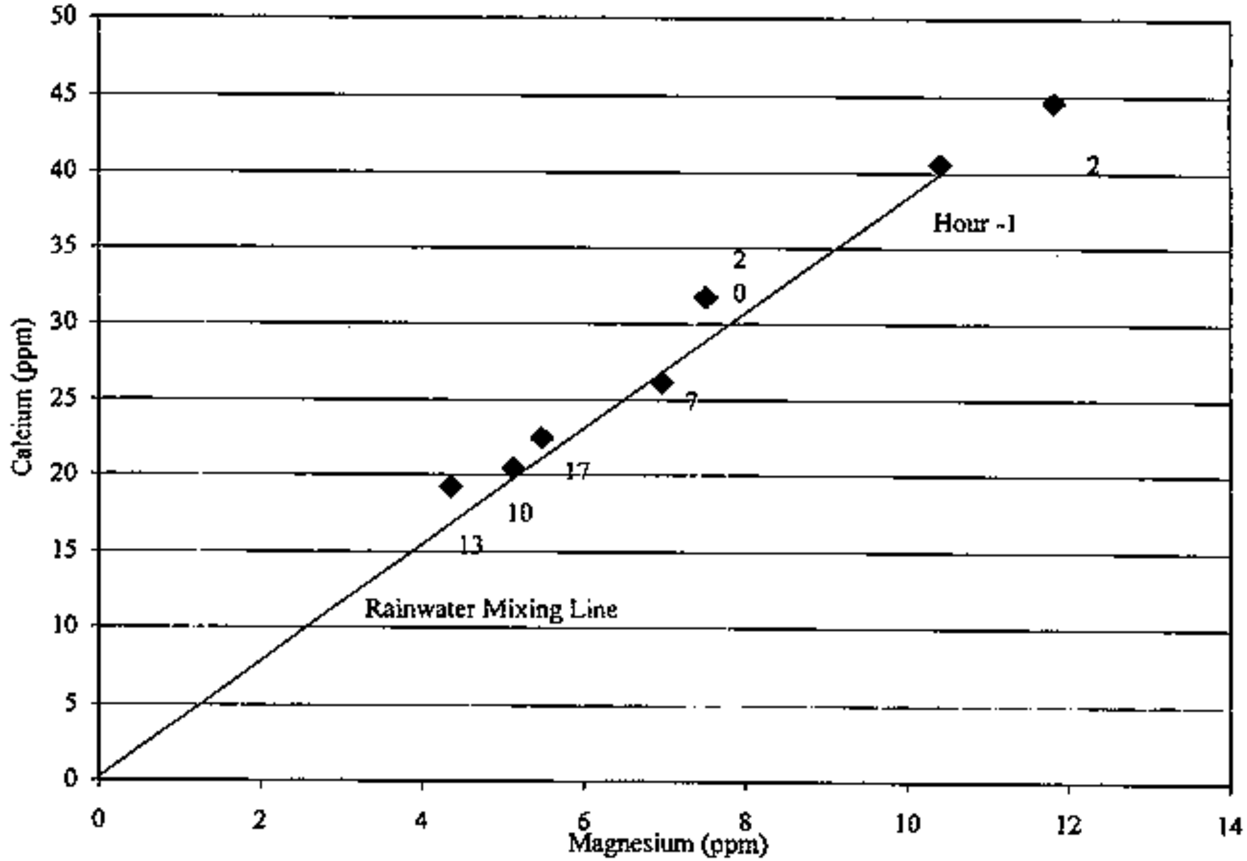

Figure 17 Correlation Between Calcium and Magnesium Concentrations During the Storm in Spring No. 1. The points on the rainwater mixing line show dilution (Hour -1 to 13) and recovery (Hours 17-20).

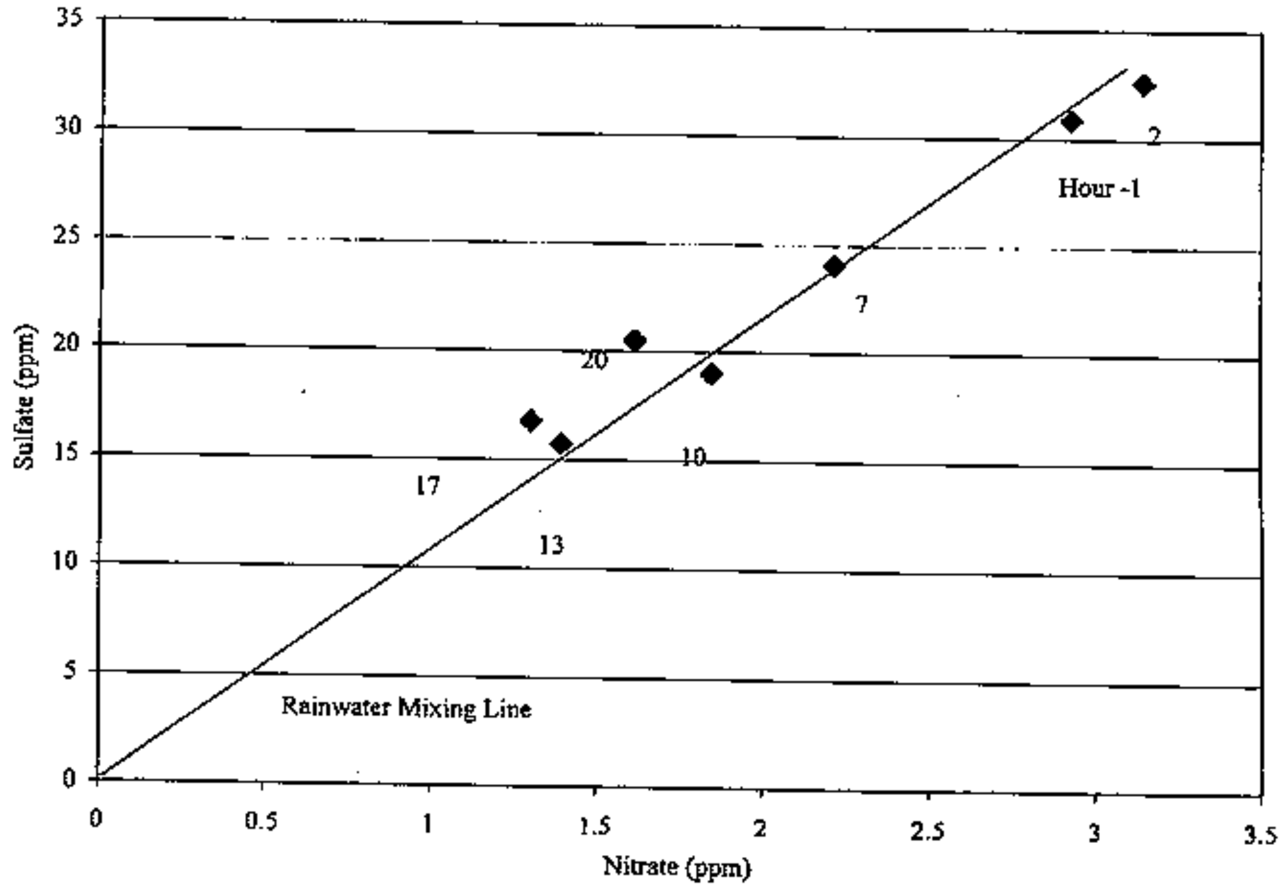

Figure 18 Correlation Between Nitrate and Sulfate Concentrations During the Storm in Spring No. 1. The points on the rainwater mixing line show dilution (Hour -1 to 13) and recovery (Hours 17-20).

Regression profiles of the spring stage and monitoring well water level versus the calcium concentration are provided in Figures 19 and 20. The R^2 values for the ions, specifically calcium, magnesium and sodium in the spring and well (all less than 0.1 except for calcium in the well [0.26]) show a very weak correlation between the water levels in the two monitoring points and the water chemistry. The measurements taken in the monitoring well and spring document the fluctuations in water levels due to precipitation events and recharge in karst groundwater networks. Although the correlation shows the effect of precipitation (represented by the water levels) on water chemistry, there are additional factors related to storm size, duration, and initial conditions involved as well.

Ternan (1972 as cited in Wicks, 1997) used hardness to determine the approximate residence time (t) of karst waters, in addition to the techniques discussed previously. Ternan's empirical equation relating hardness to residence time is:

$$t = 10^{(\log(CV-1.53) / (-0.524))}$$

CV is the coefficient of variation of hardness, expressed as a percent; it is the standard deviation divided by the mean. Hardness is calculated from calcium (Ca) and magnesium (Mg) concentrations; total hardness = 2.5(Ca) + 4.1(Mg) where Ca and Mg are in parts per million (mg/L). The CV value was 29% and suggests a conduit flow system in the area. This is further supported by the well installation and geophysical studies in the area. The calculated residence time for the karst system in this study is approximately 1.2 days.

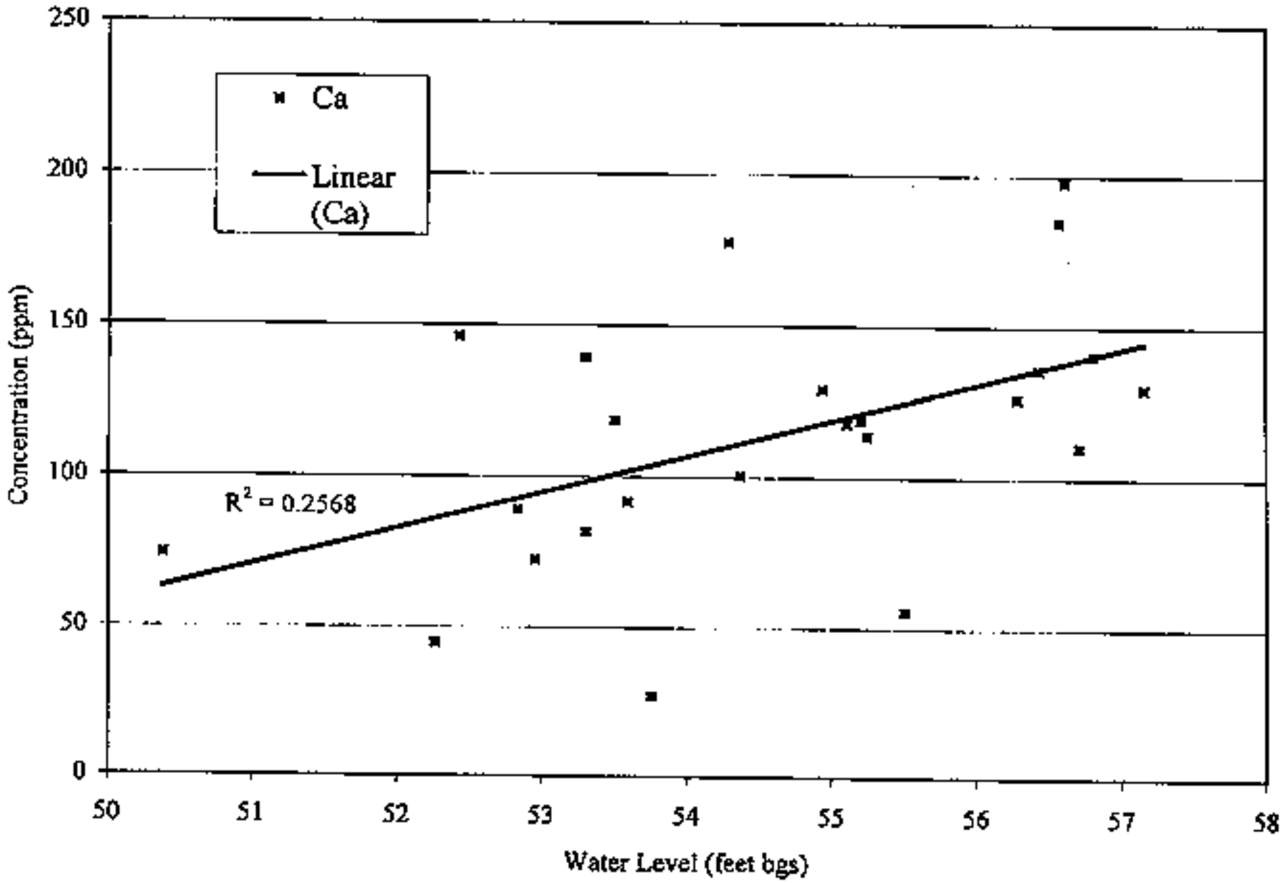

Figure 19 Correlation Between Water Level and Water Chemistry in the Monitoring Well (Epler Formation). The weak correlation suggests that these parameters are not related.

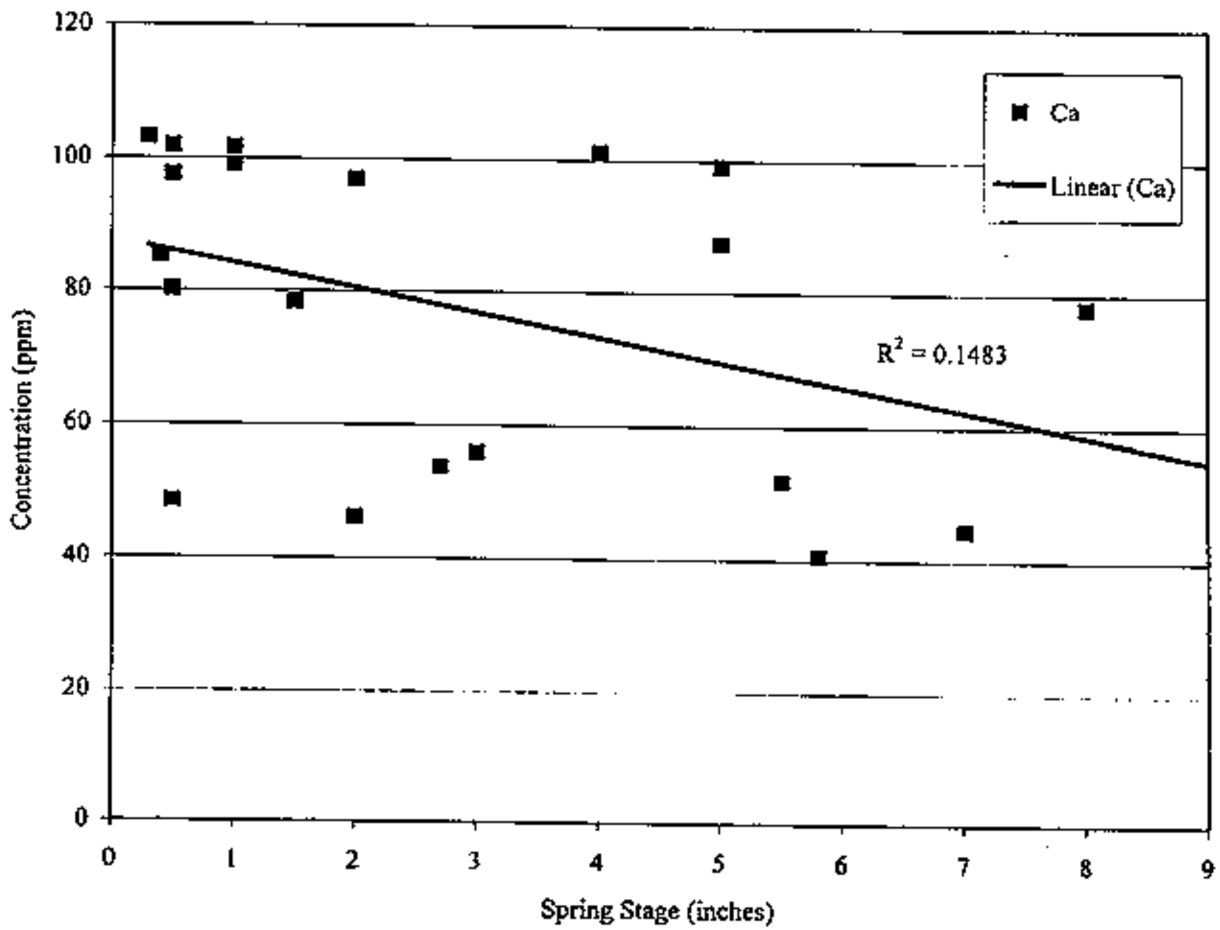

Figure 20 Correlation Between Water Stage and Water Chemistry in Spring No. 1 (Epler Formation). The weak correlation suggests that these parameters are not related.

A summary of residence time measurements support the conduit based karst groundwater system in the area. Conduit systems likely have high velocity and discharge and would discharge sediment during periods of high precipitation and infiltration. The CV calculations suggest that the residence time of groundwater in the area is 1.2 days. Calculations of the storm peaks in the HOBO™ data show that storms of a magnitude ranging from 0.81" to 1.28" vary in residence time (temperature peak to background temperature) from 27 to 37 hours, similar to the CV measurement. For example, the storm on June 6, 2000 (1.01") had a residence time of approximately 27 hours, and the storm on May 18, 2000 (0.05") had a residence time of approximately 14 hours. In addition, a storm on September 9, 1999 (1.43") had a residence time of approximately 29 hours and a storm on September 14, 2000 (0.62") had a residence time of 15 hours.

Further evidence that different storms have different amounts of flushing and dilution can be seen in the analysis of temperature spikes from storms. Storms were selected based upon a distinct temperature peak from seasonal temperature variation because throughout the study period numerous storms were subdued or hidden by diurnal or water temperature variations. An approximate velocity was calculated assuming the athletic fields as a general recharge area for groundwater (approximately 2,000 feet from Spring No. 1) as described:

Velocity = (Storm Onset – Start of Temperature Spike) / Recharge Distance

The velocity of groundwater during only two storms (May 13th and 18th, 2000) could be calculated because of missing data from the weather sites used during the research. The May 13th storm had an onset time of 18:00 hours and the temperature spike began at 21:00 hours, in addition 1.28" of rain fell during the storm. As a result the velocity of the groundwater was 1,333 ft/hr. The May 18th storm had an onset time of 17:00 hours and the temperature spike began at 18:00 hours, in addition 1.35" of rain fell during the storm. As a result, the velocity of the groundwater was 4,000 ft/hr. The rapid transport storm (May 18th) would be typical of those that mobilize sediments and dilute water chemistry. Storms such as May 13th occurred in a saturated system that would not mobilize sediments. Only dilution would occur during this storm. Neither storm would mobilize sediments if they were previously washed out, which appears to be the case during May.

As a result, small storms move rapidly through the conduit system. Large storms infiltrate both the conduit and matrix, and thus move more slowly through the system. The karst system can be referred to as a continuum in which the system varies from that of a conduit system to a diffuse system dependent on the size of a storm.

The geochemical modeling program PHREEQCI was used to determine saturation indices of minerals in the karst groundwater system. The PHREEQCI program is a Windows based version of PHREEQC (Parkhurst, 1995). The program simulates solution conditions (input data) based on dissolved species involved in reactions and the saturation indices for mineral phases. The saturation indices (SI) are an important variable, in that the velocity of the karst system can be described as rapid or slow, based on how close to saturation the solution is to respective minerals.

The monitoring well and Spring No. 1 saturation indices were calculated. A plot of SI (versus precipitation) for the monitoring well is included as Appendix C. The SI in the monitoring well varied from –0.36 to 1.69 (calcite), -0.51 to 1.54 (aragonite) and from –0.40 to 2.97 (dolomite). The SI in Spring No. 1 varied from -0.92 to 1.98 (calcite), -1.02 to 1.82 (aragonite) and from –2.02 to 3.48 (dolomite). The saturated and undersaturated conditions coincide with temporal changes in water chemistry and precipitation discussed in previous sections. The undersaturation of carbonate minerals occurs after wet periods when groundwater is diluted and moving rapidly. In contrast, saturation occurs during periods of low recharge.

The residence time, travel time and saturation indices, as well as the geophysical and water chemistry information, support a conduit based flow system, which is the key parameter in the dynamic nature of karst geochemistry and the sediment transport discussed in the next chapter. The similarity of residence times in the CV measurements (1.2 days) and the HOBO™ temperature data for different months of the year (approximately 30 hours) also suggest that the system is conduit based. The saturation indices show that the groundwater is saturated with carbonate minerals during periods of less infiltration of precipitation. The dryer intervals allow equilibrium between the carbonate rock and groundwater. The period of increased rain in the spring and summer in comparison to the fall and winter generate undersaturated mineral conditions in the PHREEQCI model. The changes in water chemistry, fast travel time, and residence time suggest periods of higher infiltration, less time for the groundwater system to equilibrate, and probably higher velocities that can flush the groundwater system.

CHAPTER 5
SEDIMENTS AND SEDIMENT VARIABILITY

Introduction to Sediment in Groundwater

The focus of this stage of research was to characterize sediment transport in a karst aquifer and the potential for the movement and transport of anthropogenic and natural contaminants. The majority of hydrogeologic studies of sediment and colloid transport and associated contaminant transport have been limited to porous media such as unconsolidated sediments and other types of fractured rock. Sediment transport in karst groundwater has been studied by few researchers (McCarthy and Shevenell, 1998; Atteia and Kozel, 1997; Mahler, 1997; Thrailkill, 1989). Karst aquifers, large pore diameters and rapid flow velocities can result in turbulent flow and the transport of particles with a wide range of sizes (Thrailkill, 1989). McCarthy and Shevenell (in press) state that larger storms flush more matrix waters into fractures and conduits than smaller storms, and that sediments and colloids transported during precipitation events are controlled by water chemistry and *in-situ* flow dynamics of the carbonate system. Atteia and Kozel (1997) state that varying discharge typical of karst aquifers controls particle size distribution, and that karst drains are washed out during high flow events.

Contaminants such as trace metals, hazardous chemicals, bacteria and viruses have been identified as contaminants that can absorb onto sediments within groundwater flow systems. A variety of organic and inorganic materials absorb onto sediments in groundwater, including macromolecular components of dissolved organic carbon, such as humic substances (McCarthy and Zachara, 1989), mineral precipitates and weathering products, and rock and mineral fragments. Porous media hydrologic regimes such as shale or igneous rocks exhibit slow groundwater flow and usually transport colloid size particles.

The transport of contaminants in the subsurface environment is influenced by chemical, biological and physical changes between solid particles and groundwater. The relationship between these factors and how they affect a specific contaminant in the subsurface environment is commonly referred to as the *fate and transport* of a contaminant in a groundwater system. Whether a contaminant is a dissolved ion or microbial contaminant (*e.g.* virus or bacterium), the ability of the contaminant to attach or absorb onto sediments is an important factor in contaminant transport. Shallow epikarstic and karst groundwater networks are likely more susceptible to contamination than deeper fractured (*i.e.* shale) rock. This is due to a *higher* potential impact in shallow areas (sinkholes and springs) that are susceptible to dumping and near surface point and non-point source pollution. The significance of the possible differences between carbonate and other fractured rock will be discussed here as well.

Methodology for Determining Sediment Size and Composition

Numerous methods of particle size distribution analysis are currently available. These include filtration, ultra-centrifugation, single particle counting and diffraction or dynamic light scattering. During this research, seasonal filtration was performed using 0.45, 3 and 5 μm filters. The storm sediment samples were analyzed using 0.45, 1, 3 and 5 μm filters. The 1 μm filter paper size was used in the analysis of storm sampling to possibly further define the particulate ranges distributed during high flow events. Sample water was drawn through the filters using a vacuum pump. Approximately 100 ml of water was used for filtration to prevent clogging of the filter paper and vacuum system, and to establish a relative baseline filter volume for all sampling events during research.

The filtering and fractionation of sediment sizes were completed using a Cenco Hyvace 2 vacuum pump powered by a GE electric motor and Millipore filters (0.45 μm, 1 μm, 3 μm and 5 μm filters). The filter paper was weighed prior to filtration and drying. The material left on the filters was dried and weighed. The difference in weight between the filter paper and paper with dried filtrate was the recorded amount of material for that size fraction. The samples were weighed using a Mettler electronic balance. The sediment samples were collected from the same sampling points as the aqueous samples, and at the same time. The samples were collected between January, 2000 and January, 2001, with the same equipment and methodology previously described as for the seasonal aqueous samples. A 40 mL amber glass vial was used to collect groundwater for sample storage in quart size glass, amber bottles.

The biweekly samples from the initial karst spring and monitoring well were collected from January, 2000 to January, 2001 and analyzed for sediment variability both seasonally and in response to a high-intensity rain event. The second karst spring and shale spring sediment samples were collected biweekly from September, 2000 to January, 2001. It should be noted that from November, 2000 to January, 2001 the Stockton spring was "dry" or exhibited low flow and thus samples could not be obtained. The collected samples were used to determine variability in sediment size and transport in the karst groundwater, both seasonally and during high flow events; as well as for comparison of sediment transport in karst versus fractured rock. The spring was sampled during a rain event using an ISCO™ Auto-sampler. The auto-sampler collected a 300 mL sample every hour for 24 hours. The monitoring well was not sampled during the storm.

Sediment Transport Variability

The variation in sediment size and amount of materials transported in this karst hydrogeologic groundwater regime is dynamic. The distribution of sediments in this system is depicted in the time-series profiles generated from the collected data (Figures 21 and 22), which present the amount of sediment transported through the conduit network encountered by the monitoring well and springs. The profiles of varying sediment size and sediment discharge in the groundwater system during seasonal changes showed that the spring and well discharged larger amounts of sediment during the beginning and final stages of research (winter and autumn respectively).

The initial sediment yield in the spring was 4 mg/L of the > 5 μm fraction, 3 mg/L of the 3 μm to 5 μm fraction (hereinafter referred to as the 3 μm fraction) and 1 mg/L of the 0.45 μm to 3 μm fraction (hereinafter referred to as the 0.45 μm fraction). The spring discharged a maximum of approximately 9 mg/L on September

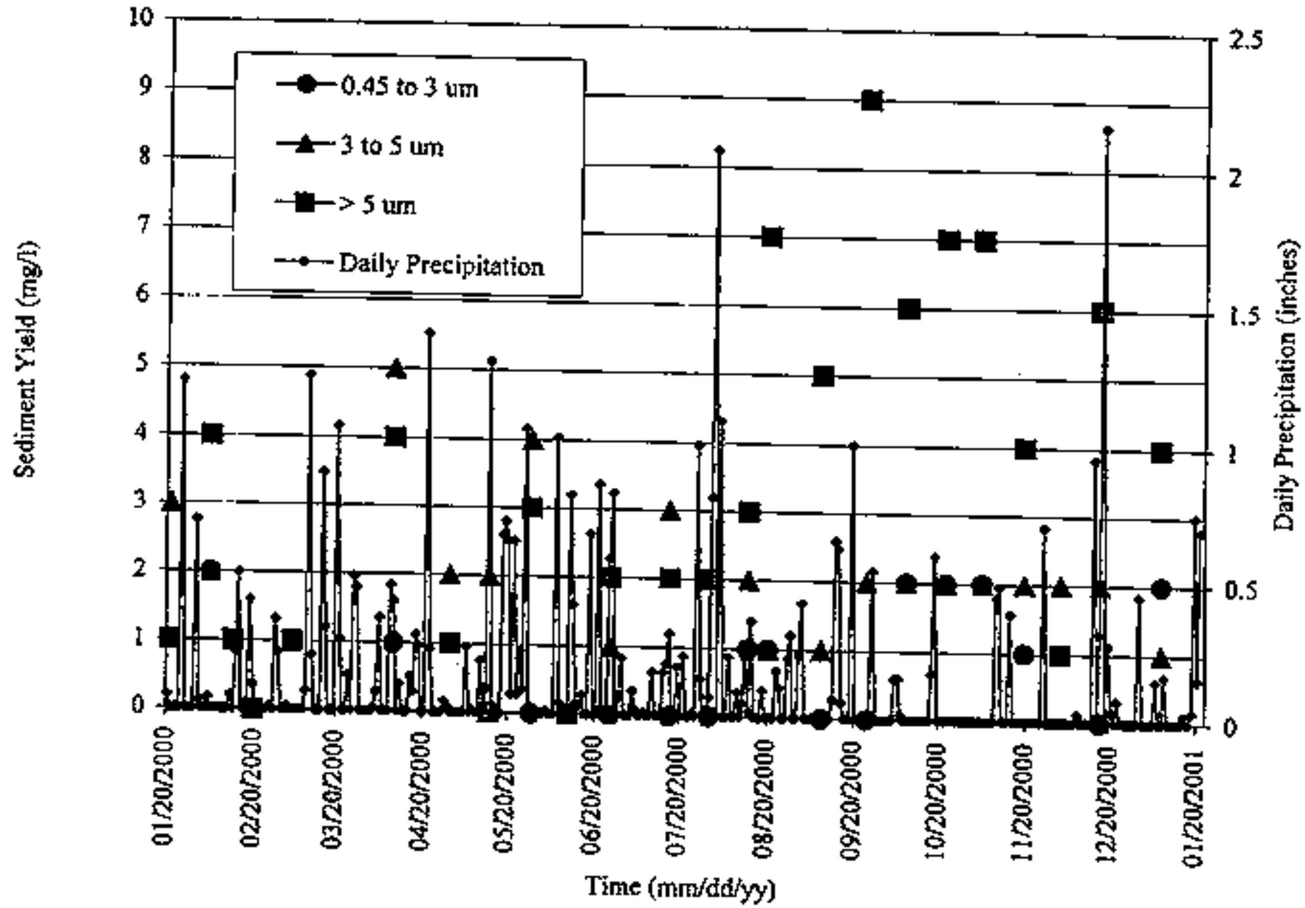

Figure 21 Variation in Sediment Yield in Spring No. 1 (Epler Formation). Sediment transport increases with less precipitation and decreases with higher precipitation. Note: 0 mg/L sediment yield is equivalent to < 0.45 mm sediment transported.

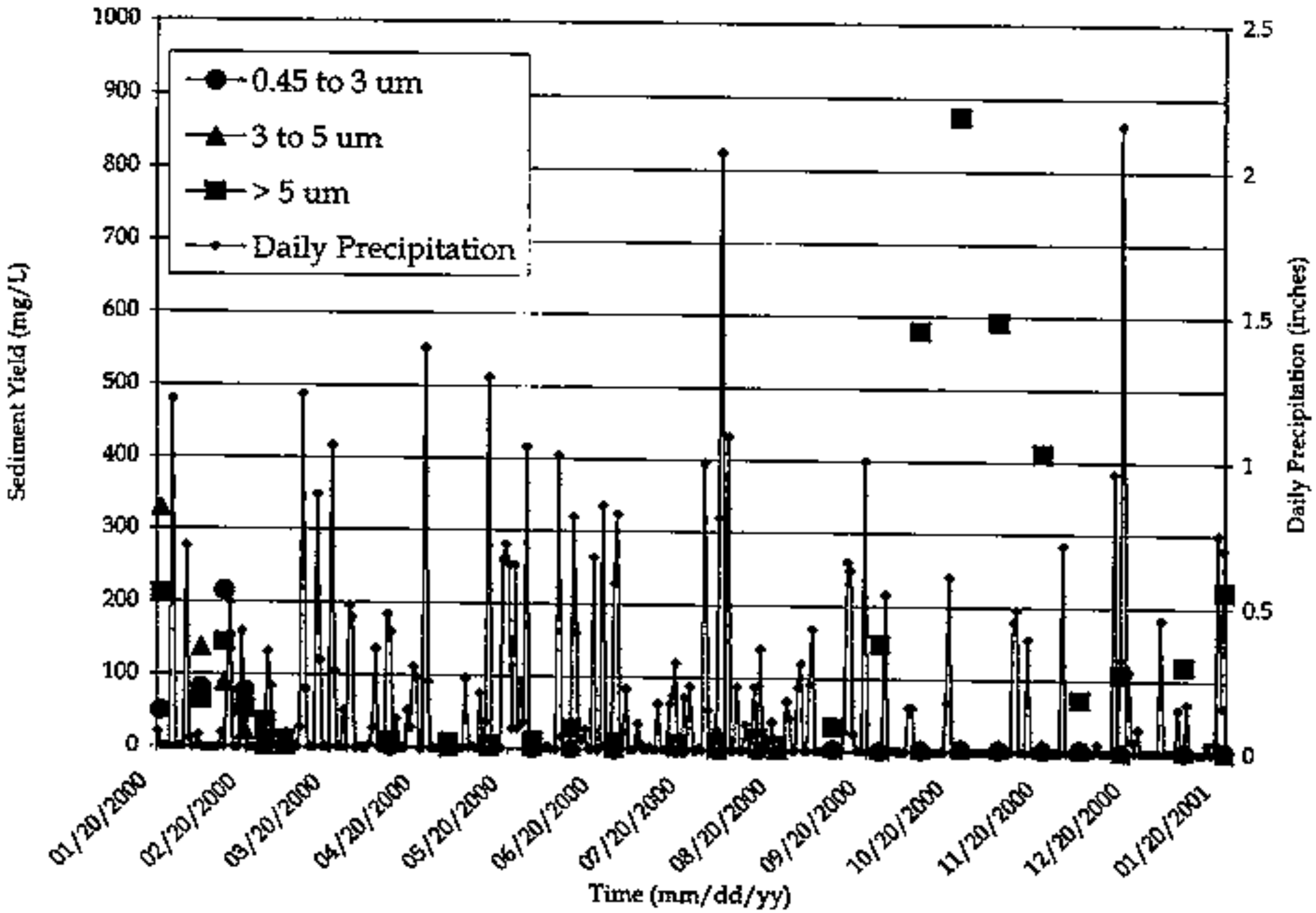

Figure 22 Variation in Sediment Yield in Monitoring Well (Epler Formation). Sediment transport increases with less precipitation and decreases with higher precipitation. Note: 0 mg/L sediment yield is equivalent to < 0.45 μm sediment transported.

23, 2000, and the well discharged a maximum of approximately 875 mg/L on October 25, 2000. Each of these maximum values were of the > 5 μm size fraction. Throughout the winter of 1999, spring and summer 2000, the sediment yield in the monitoring well decreased to nearly 0 mg/L. In this same period, the spring exhibited a noisy sediment signal. During the late spring and summer, the > 5 μm fraction decreased from 4 mg/L in April, 2000 to 2 mg/L in July, 2000. Similarly, the 0.45 μm fraction decreased from 2 mg/L in February, 2000 to 0 mg/L during summer months (May to August, 2000). The 3 μm fraction did not reveal obvious trends in the > 5 and 0.45 μm size fractions. The 3 μm fraction varied from 2 to 4 mg/L during the summer months and remained constant at 2 mg/L during the fall of 2000, decreasing to 2 mg/L during the final month of sampling.

In the fall and early winter months of 2001, the > 5 μm fraction sediment yield increased in the monitoring well. The initial sediment yield in the monitoring well was 211 mg/L of the > 5 μm fraction, 329 mg/L of the 3 μm fraction and 50 mg/L of the 0.45 μm fraction. The initial rise in the well began in late September, 2000 to 148 mg/L and peaked at 875 mg/L in late October, 2000. The sediment yield decreased to 73 mg/L in early December, 2000, but finished the research period at 222 mg/L. This final sediment yield value is similar to the sediment yield from one year ago (211 mg/L). In contrast, the 0.45 and 3 μm size fractions were low (less than 5 mg/L) up to and at the end of the monitoring period (January, 2001). The spring's sediment yield also increased from the lower ambient signal observed during the spring and summer months. In late August, 2000 the sediment yield increased to

7 mg/L and peaked at 9 mg/L in late September, 2000. The sediment yield was constant at a yield of 5-6 mg/L up to and at the end of the monitoring period.

In September, 2000 a second spring was monitored to determine if the sediment yield in karst springs is constant throughout a local discharge area. Figure 23 presents the sediment discharge from the second spring (located 50 feet south of the primary spring sampled the entire year for sediment and water chemistry variability). Upon comparison, the sediment discharge in the second spring differed less than 1-2 mg/L from the primary spring. For example, the first September, 2000 sample showed 4, 2 and 0 mg/L for the > 5, 3 and 0.45 size fractions respectively, whereas the primary spring discharged 5, 1 and 0 mg/L for the > 5, 3 and 0.45 size fractions over the same period. The December 16, 2000 sampling event showed 4, 1 and 0 mg/L for the > 5, 3 and 0.45 size fractions respectively, whereas the initial spring discharged 6, 2 and 0 mg/L for the > 5, 3 and 0.45 size fractions for the same period.

The monitored storm occurred during an intense spring rainfall of 1.17". The storm series profile (Figure 24) presents the variation in sediment size and discharge. The > 5 μm sediment fraction size increased from an average of 3 mg/L in the first hour to 13 mg/L during the 8^{th} hour. The smaller sediment sizes varied between 0 and 6 mg/L throughout the monitored storm event.

In comparison to the sediment variation in karst groundwater, the size and sediment yield variation in fractured rock of the Stockton Formation monitored from

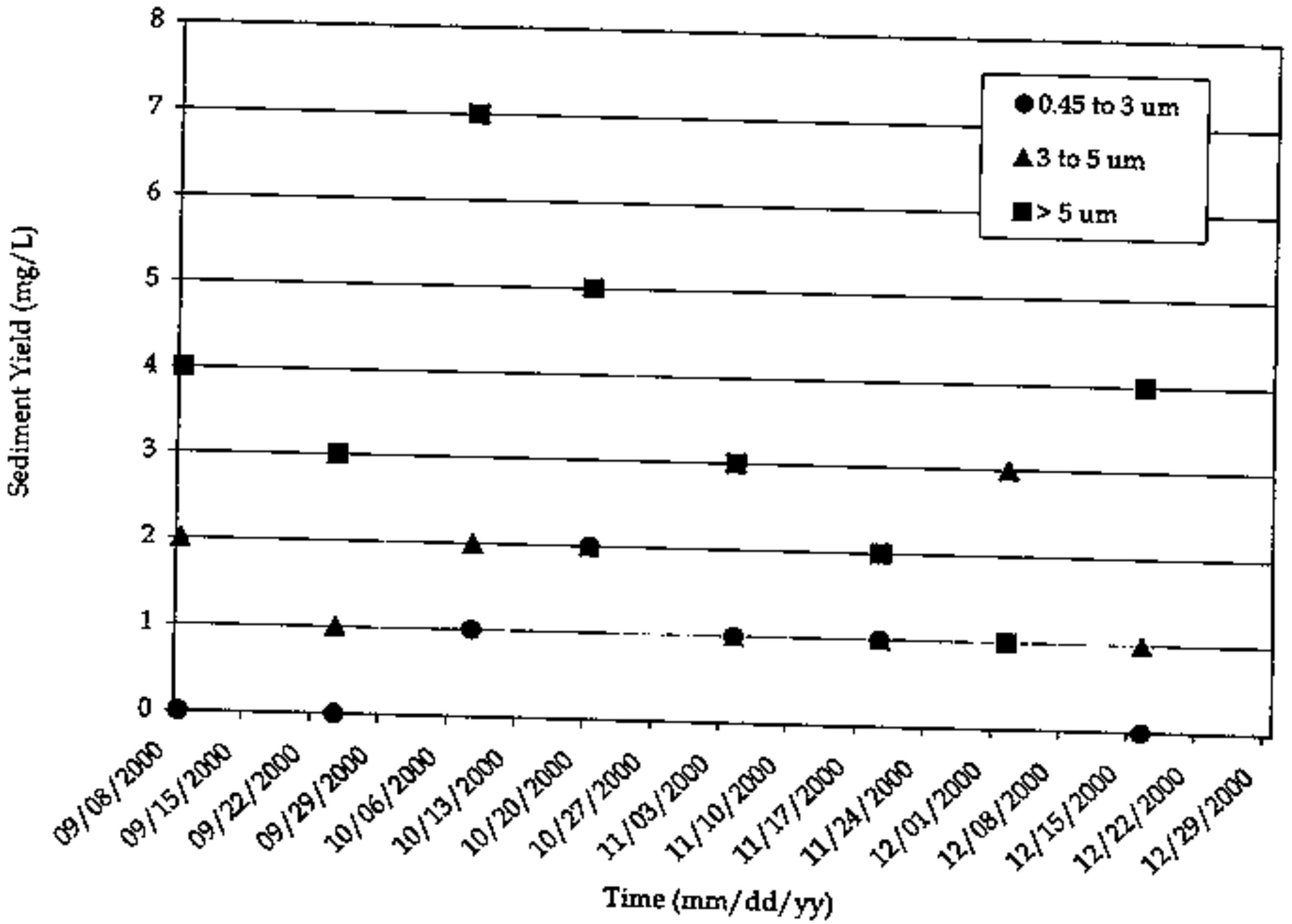

Figure 23 Variation in Sediment Yield in Spring No. 2 (Epler Formation). Note: 0 mg/L sediment yield is equivalent to < 0.45 μm sediment transported.

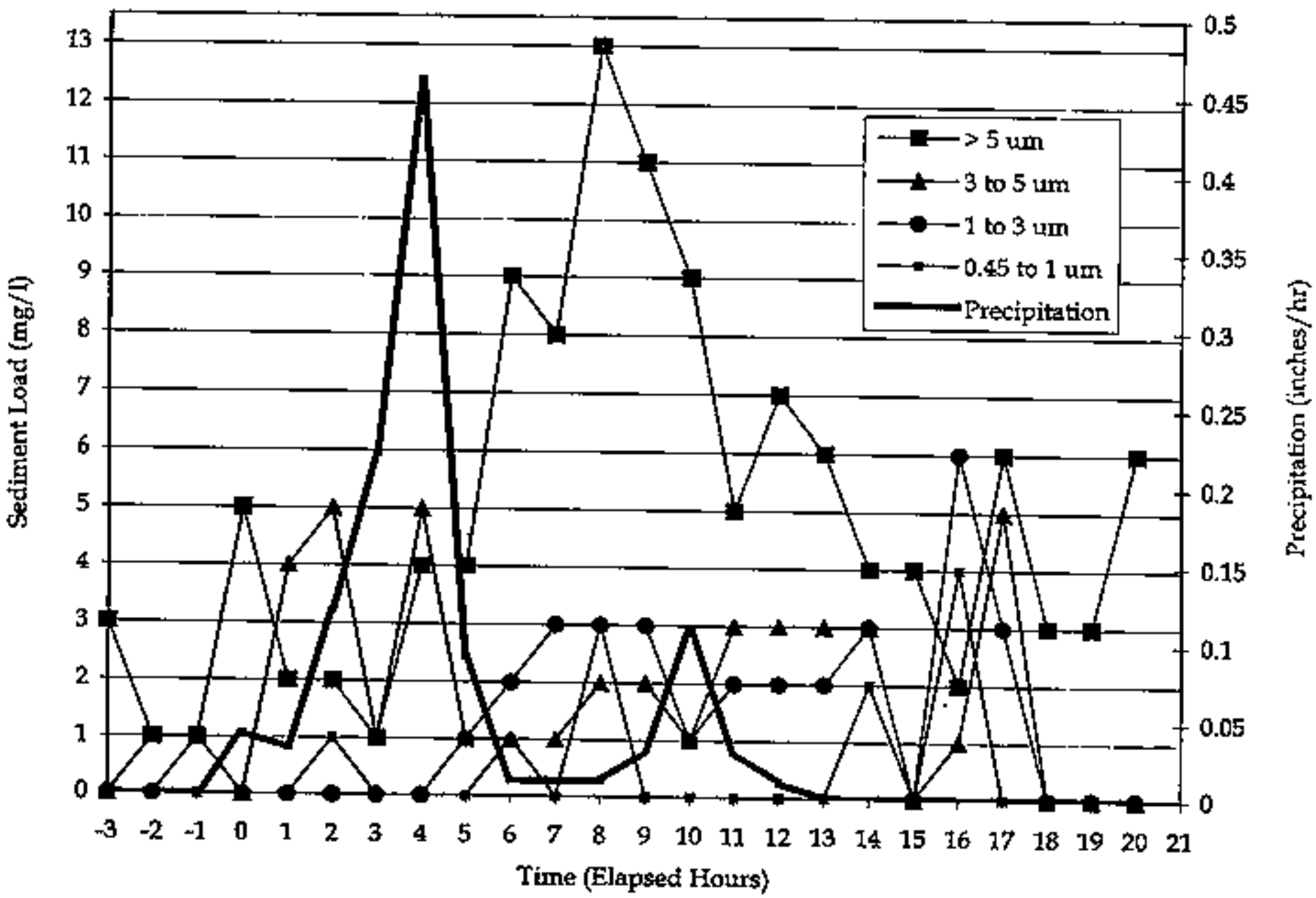

Figure 24 Variation in Sediment Yield in Spring No. 1 During the Storm. The sediment yield increases to a maximum of 13 mg/L subsequent to the peak of the storm. Note: 0 mg/L is equivalent to < 0.45 μm size fraction.

September to January, 2001 was not recorded for a sufficient length of time to permit a thorough discussion of these two rock types and their associated sediment transport variability. For the period that could be measured (September 2000 through November 200), the Stockton spring yielded between 2 mg/L and 1 mg/L. No increase in sediment yield was observed in the fall. The Stockton spring was not monitored from January to August 2000.

Clay Materials and Variability of Transport

In order to further understand which materials are transported in the local groundwater discharging to the Bushkill Creek, X-ray diffraction (XRD), analysis was performed on sediment samples taken from the monitoring well in the late winter of 2000. Additional dates chosen for analysis included January 20, February 19, June 10, October 22, and November 4, 2000 to represent each season. The low amount of sediment discharged in the spring throughout the monitoring period prevented representative XRD analysis. The XRD slides were prepared by filtering 100 mL of water through a 0.45 μm Type HA filter paper. The materials remaining on the filter paper were subsequently rolled onto a clean glass slide with a rubber roller and dried prior to analysis.

The slides were then placed into the XRD powder diffractometer (Rigaku), which utilized a horizontal goniometer, Cu k∞ radiation, and computer automated control. The samples were run from 4°-30° 2θ at 35 kv at 15 ma. The XRD instrument operates under the principle that x-rays are scattered when they encounter an obstacle (the slide and clay particles). Most of the scattered rays interfere with each other and are destroyed; yet some rays combine constructively, producing a diffraction pattern representative of mineral structure. Specific minerals produce characteristic diffraction peaks, which are recorded by the diffractometer as degrees, two theta (2θ) and intensity, in counts per second.

The results of the XRD analysis on the initial winter 2000 sample showed that illite, kaolinite and quartz were transported in the karst system. (Figure 25). The presence of these 1:1 and 2:1 crystal lattice clays in the karst system suggest that these sediments were derived from a fair to moderately developed and leached soil environment. Illite and various other clay minerals with a 2:1 lattice-work mineralogy have a high cation exchange capacity. The 2:1 clays can absorb contaminants at exchange sites, thus acting as a transport mechanism.

Quartz and clay are the remnants of chemical weathering. Since chemical weathering occurs both at the surface and in the subsurface, these materials can be autochonous (*in-situ*) and allocthonous (*ex-situ*) materials. Sediments collected in sinkholes and streambeds may contain a very low or high proportion of clay minerals, depending on local flow regimes. Clays tend to remain in suspension and either enter the aquifer with recharge or overland flow.

XRD analyses of the additional samples showed the same materials transported in the karst up to the late winter, 2000 sample. Signature peaks for kaolinite and illite were identified, as well as quartz. One additional peak identified

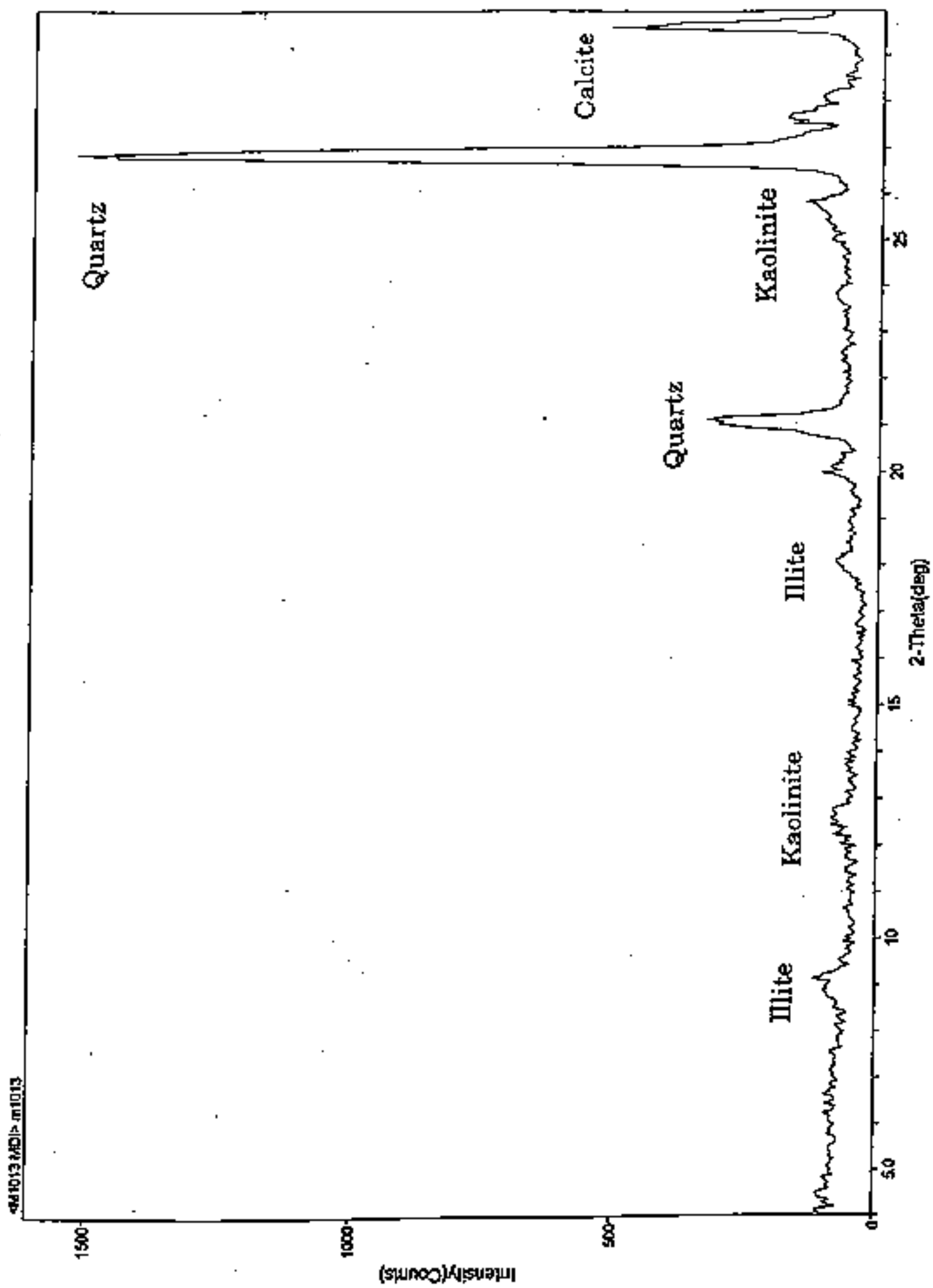

Figure 25 X-ray Diffraction Results for the Monitoring Well. The y-axis in the plot represents intensity measured in counts per second and the x-axis is degrees 2θ.

in the January 20, 2000 sample is a peak at approximately 30.3 2θ. This peak is the signature for calcite.

Interpretation

The initial high values of sediment yield in the spring and monitoring well, both seasonally and storm related, may be attributed to the decrease of infiltrating water into the karst groundwater system, thus increasing sediment load in a given volume of water. The increase of infiltrating water introduces additional sediment from the soil, epikarst and conduits, then flushes this material through the groundwater. The spring is likely receiving more water as a discharge point, and as a result will be more dilute than the monitoring well in terms of sediment load and water chemistry.

During the winter and early spring of 2000, Northampton County, Pennsylvania was struck by two snowstorms. The snow melted by late February and early March. In addition, March through May had nine rain storms greater than ½ inch of rain. The snowmelt coupled with the precipitation throughout the spring and summer could have washed out the groundwater flow system of sediment in the local area. Visually, the collected samples from the monitoring well became less cloudy as the spring ended and the summer began, and more cloudy as the fall and winter began. This is a good indicator that a dilution or wash-out mechanism exists, precluding the transport of more materials until an influx of sediment or decrease in precipitation (and infiltration) occurs.

In addition, the variation in seasonally and storm related sediment size may be attributed to the physical nature and properties of different size sediments. Smaller particles tend to be more cohesive and possess a greater drag coefficient than other particles due to their platy habit. They require a greater erosional force to entrain than larger particles, but remain in suspension at lower velocities than larger particles (Mahler, 1997). Thus, the increase in particle size greater than 5 μm at the end of the sampling period following the March storm may be due to decreasing flow velocities in which larger particles are deposited. At the same time, smaller particles remain suspended and transported in the groundwater. The identification of calcite in the system suggests that bedrock materials are transported in the groundwater system, or possibly calcite is mineralizing by outgassing of carbon dioxide at the spring locations.

The presence of epikarst might also explain the variation in initial sediment yield both seasonally and storm related. Although studies of epikarst were not performed at the research site, different conduit networks may exist and interact differently during high and low flow events within the system. Solution conduits were observed using the downhole camera and identified using geophysical investigations. As a result, a shallow conduit system may be hydraulically connected to the ultimate discharge network to Bushkill Creek.

Summary

An analysis of the amount and type of sediment transported through a karst aquifer was performed seasonally and during a storm event. On the order of hundreds of mg/L of sediment was transported through the karst aquifer during the beginning of the research period (January through March 2000) in the monitoring well, and on the order of mg/L in the monitored spring discharge point. The maximum amount of transport occurred in the > 5 μm size fraction in both the monitoring well and spring. This large amount of sediment transport in the spring and well decreased to no sediment in the spring and tens of mg/L transported in the monitoring well from March to late summer and early autumn. The March 16-17, 2000 storm showed a peak in the > 5 μm fraction approximately four hours after the peak of the storm. The smaller size fractions did not show a peak sediment transport value. A second monitored spring showed similar discharge values to that of the initial spring. Precipitation leads to the variation in flow regime of the karst groundwater network, fluctuations in water chemistry, and type of sediment transported (*i.e.* quartz, calcite and clay). These all are critical factors in karst aquifer sediment variability.

CHAPTER 6
DISCUSSION

Analysis and Interpretation

Two hypotheses may explain sediment increase and decrease in karst groundwater and varying geochemical conditions during certain times of the year. These hypotheses include: 1) a flushing mechanism and 2) a dilution mechanism. Even though dilution of groundwater may lower the amount of sediment and ionic species in the aquifer during the year, specifically during wet and rainy months, flushing may also occur and increase sediment concentrations. The following discussion examines the evidence for each mechanism.

A year of data showed that the sediment yield in the study area is low in the late spring and summer months, but higher during the fall and winter months. The summer months, in comparison to the fall and winter months, show an increased amount of precipitation when normalized for the number of months in each period. The total cumulative precipitation from January 21, 2000 to the first day of spring (March 20) and the first day of autumn (September 22) to January 20, 2001 was 16.82" (with an average of 2" per month). The total precipitation from March 21, 2000 to September 21, 2000 was 27.98" (with an average of 5" per month). The difference in precipitation from the late spring and summer and the fall and winter is 11.16". The previously discussed time-series profiles of sediment yield versus precipitation showed that during periods of low precipitation, the sediment yield is higher (by hundreds of mg/L in the well and 3-5 mg/L in the spring), and lower during periods of high daily and average precipitation.

The possibility of correlation between sediment yield and precipitation was studied. A weak correlation was seen with the water chemistry and water levels. The correlation with sediment yield could be similar, weaker, or stronger. Again, correlation with water levels was used to represent wet versus dry conditions. Precipitation is not an accurate measure of water flow in the karst system because an individual event may not increase flow, but rather an accumulation of events may increase flow and sediment flushing.

First, I looked for a correlation between sediment yield and calcium in either the spring or monitoring well. There was no correlation (R^2 of .08 and 0.01 respectively), suggesting different mechanisms control their concentrations. Evidence for correlation between spring stage and well water elevation versus sediment yield was observed in two regression graphs that compared water stage and water level in the spring and well respectively (Figures 26 and 27). The correlations are 0.35 and 0.36, which indicate a slightly stronger relationship than water chemistry and water levels. More importantly the correlations show two separate data populations. Despite the correlation, the data do not appear to be linear. When a line is drawn down the middle of Figures 26 and 27, two distinct data populations are apparent. An increased sediment yield occurs at a particular water level threshold. The monitoring well's sediment yield increases from approximately 50 mg/L to a variation between 100 and 800 mg/L once the static water level reaches 54 feet below

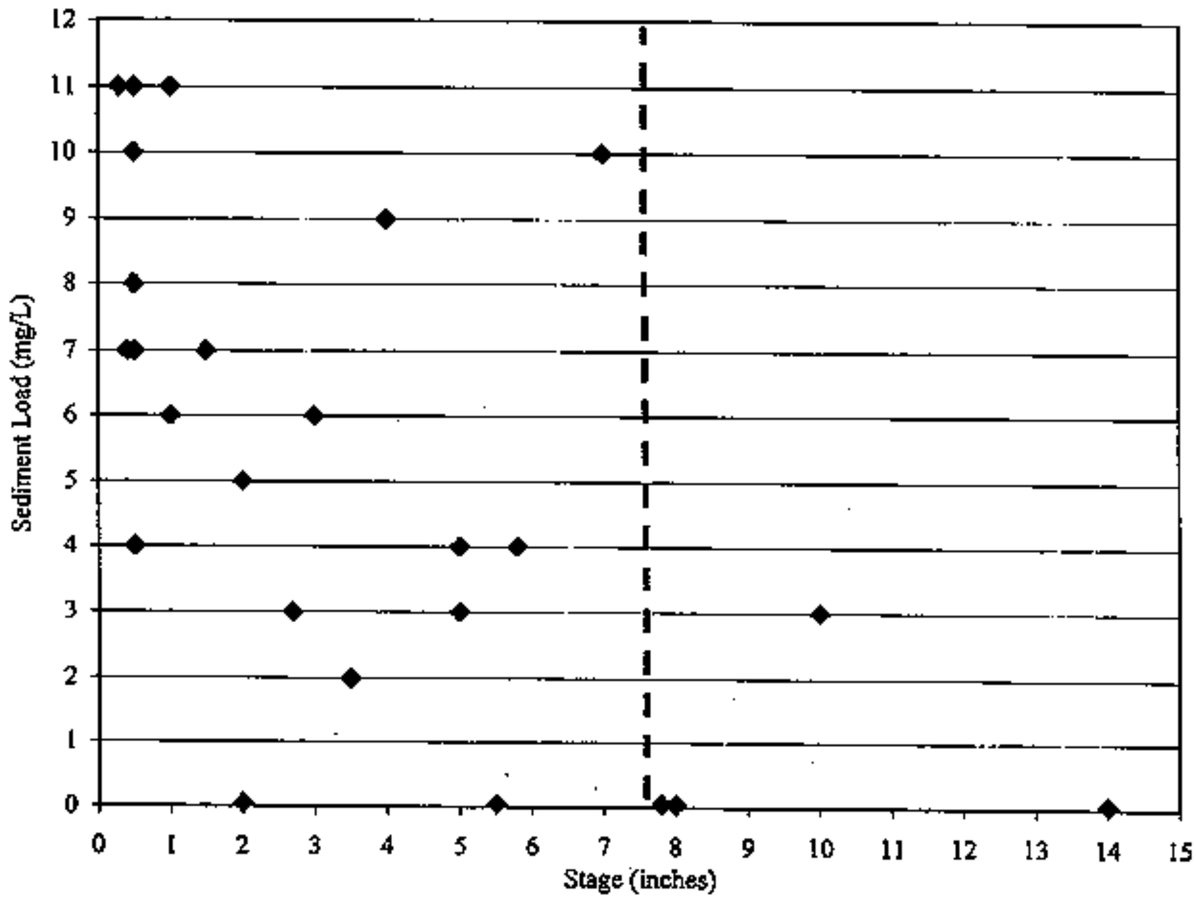

Figure 26 Correlation Between Water Stage and Total Sediment Yield in Spring No. 1. Two data populations exist as shown by the dotted line. The greatest amount of sediment transport occurs during lower water stage in the spring.

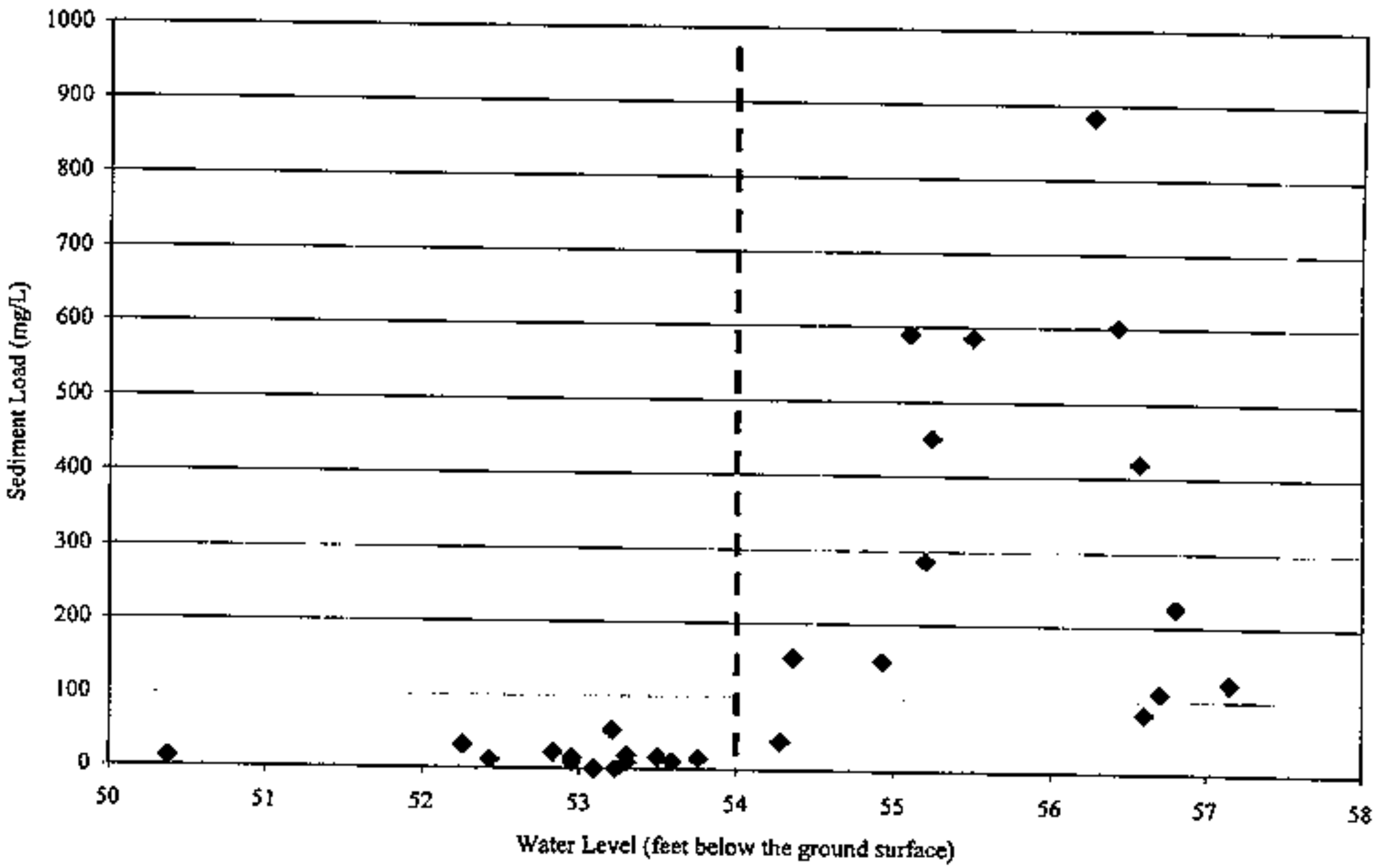

Figure 27 Correlation Between Water Level and Total Sediment Yield in the Monitoring Well. Two data populations exist as shown by the dotted line. The greatest amount of sediment transport occurs during lower water stage in the monitoring well.

the ground surface. The spring's sediment yield increases from 0-3 mg/L to a variation between 1 and 11 mg/L once the spring stage is lower than 7.5 inches.

The lack of significant correlation between water levels in the spring and monitoring well show that the flushing of sediment from the karst network is not a linear process as previously considered. The transport and flushing of sediment in a karst system may be controlled by certain thresholds, which may have to be reached in order to entrain and mobilize sediments. In addition, the two distinct populations on the correlation graphs show that periods of low water level coincide with increased sediment transport in both the monitoring well and spring. This further suggests that transport and mobilization may be further influenced by differing groundwater flow regimes during periods of a high and low groundwater table. There is variability within the two populations because individual storms can have different groundwater velocities, as evidenced by travel times calculated using the two storm temperature spikes.

To determine if the sediment yield and water chemistry variability in the spring and monitoring well was not just a consequence of dilution, the behavior of calcium and sediment yield was compared (Figure 28). The time-series profiles presented in the earlier water chemistry chapter show that dilution occurs to some extent to ions, as represented by calcium. The fluctuation in water volume, velocity and location of the water table caused variability in the calcium concentration throughout the year (Figure 28). In contrast, the sediment yield shows seasonal variation. Sediment mass in the karst system increased during periods of low

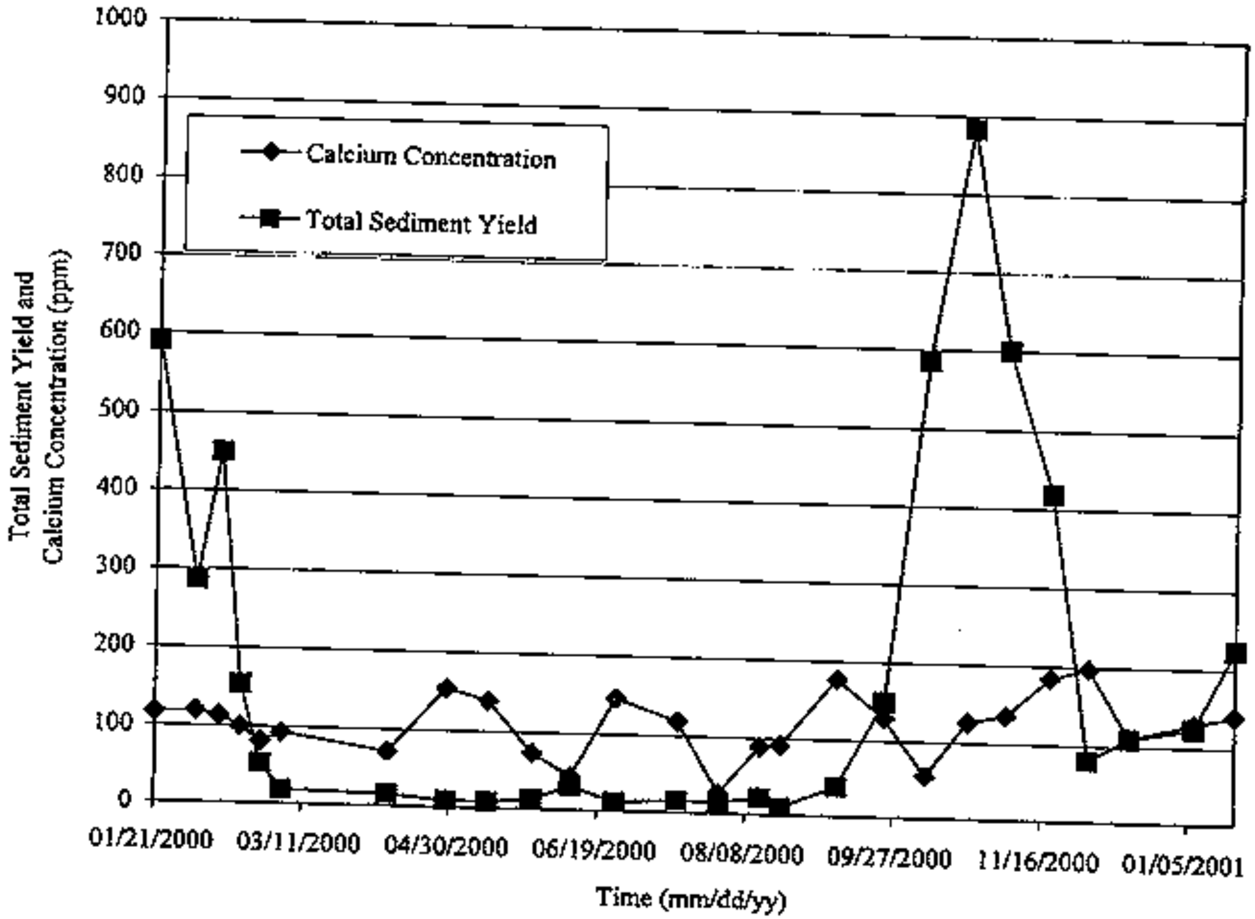

Figure 28 Total Sediment Yield and Calcium Concentration (Monitoring Well) Over the Course of the Year. Calcium varies with individual storms and sediment yield varies seasonally.

seasonal precipitation and subsequent to peak conditions of a storm. Individual storms seem to have more influence on calcium, whereas antecedent conditions (seasonality) seems to have more influence on sediment transport.

The important difference between the sediment and water chemistry changes is evident in the storm sampling. Storm monitoring in the spring showed the peak sediment discharge during the lowest ionic concentrations (Figure 29). The sediment increase due to high velocity stormwater is concurrent with dilution of the ion concentrations. The decrease in ionic concentrations occurs subsequent to the peak of a storm and during periods of higher seasonal precipitation.

Remaining Questions

Current research in karst aquifers suggests that the unique flow systems of karst groundwater and a flushing mechanism may play an important role in sediment transport and consequently contaminant transport. Mahler (1997) stated that dry conditions observed in Mammoth Cave, KY attributed to an increase in hardness during the flushing of water stored in the diffuse part of the aquifer. This washout after periods of precipitation resulted in elevated ionic concentrations. It was also discovered by Chess (1987), similar to Mahler's observations, that increased soil moisture during spring thaws flushed nitrates accumulated during the winter months out of a karst system. The accumulation of precipitation associated with the flushing of sediment out of the system, as hypothesized in the previous chapter, can also be

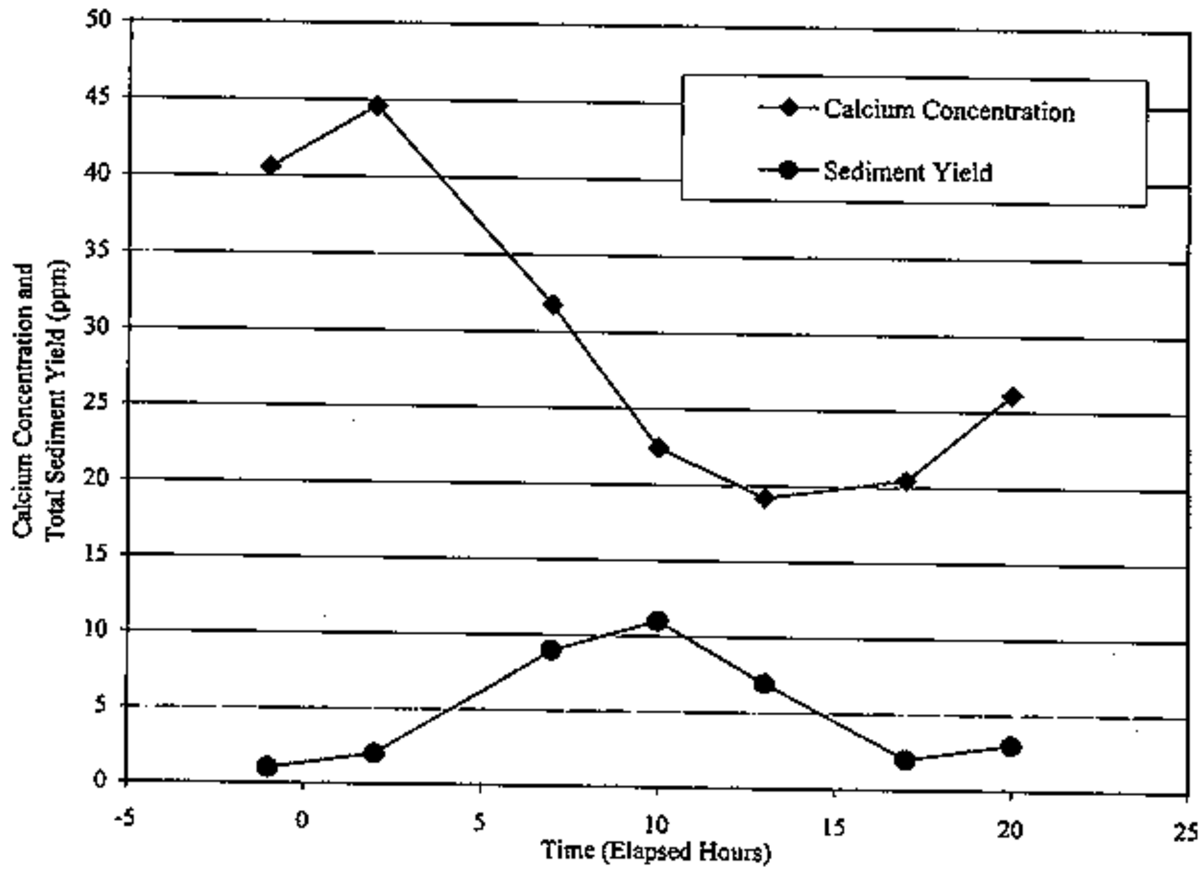

Figure 29 Total Sediment Yield and Calcium Concentration During the March Storm. The lower calcium concentration declines as the sediment yield increases.

seen in the higher water levels and seasonal decreases in ionic concentrations after storms.

The above review of how subsurface flushing is related to sediment transport and ion variability in karst groundwater poses additional questions. Three main conceptual issues remain: 1) is large-scale and varied sediment transport solely a karst phenomenon? 2) why are only certain size(s) fractions transported at different times? and 3) how can we more qualitatively and quantitatively understand the variation in sediment size, mineralogy and amount?

The initial question asked was if large-scale and varied sediment transport is solely a karst phenomenon. McCarthy and Shevenell (1998) discovered that the size distribution of colloids is different in carbonates and shales. A summary of constituents for all wells in McCarthy and Shevenell's (1998) study showed that the mass measured in the limestone formation were in the > 0.1 μm size fraction. Shevenell and McCarthy (in press) also state that recharge events in karst systems can result in either:

> (1) a decrease in ionic strength in the conduits as waters that are more rapidly, and directly recharged (*e.g.*, through sinkholes) mix with resident waters in the fractures and conduits, or (2) an increase in ionic strength and pH when recharge is more diffuse, resulting in longer residence time matrix water being displaced into the fracture and conduit network.

They further state that the unbalanced hydrologic and geochemical nature of karst can create an environment with a greater amount of material transported through the aquifer. Shear forces may mobilize more sediment from the bottom and walls of fractures and conduits, and if conditions preclude it, *in-situ* generation. An example provided by Shevenell and McCarthy (1998) showed that decreases in ionic strength, changes in ionic composition from Ca^{2+} to Na^{+}, or increases in pH have resulted in increased release of colloids and sediment by decreasing attachment forces. Release of sediment and colloidal material can also be promoted by changes in flow velocity, even in the absence of any change in solution chemistry. As a result, the interaction of physical and chemical mechanisms (*i.e.* flushing, chemical reactions and dilution) increase and decrease loads of sediment and concentrations of ions prior, or subsequent to, precipitation events. It should be noted that a storm event in Austin, Texas transported up to one metric ton of sediment material through the Barton Springs Aquifer within 24 hours of a rain event (Mahler, 1997). This unbalanced hydrologic and geochemical nature of karst can create an environment with increased generation of materials being transported through the aquifer.

The second question asks why only certain size fractions of sediment are transported at certain times in karst aquifers. The hydrodynamic factors introduced in earlier chapters aid in explaining the behavior of the particles in the spring during the storm and seasonally. Large particles should settle in the aquifer due to the slow water velocity during recession periods. The size of the particles could be predicted using the Hjulstrom diagram for sediment transport if velocities could be measured in the karst network. Such data are not typically available. As the large particles are flushed out of karstic drains, the large particle content quickly decreases (Atteia et al., 1997). When significant rainfall occurs, the water flux and velocity swiftly increase, which may resuspend the large particles. When evaluating the large range of sediment size variability in karst, velocity and discharge changes in karst groundwater should be considered. Furthermore, when evaluating the large range of sediment load and sediment size variability in karst, velocity and discharge changes in karst groundwater should be considered. The HOBO temperature logger and primary spring discharge values permitted approximate velocities and residence times of the groundwater to be calculated.

Shevenell and McCarthy (in press) also found that regardless of storm size, maximum turbidity (a function of particle mass) occurs after the peak water level measured in individual wells during storms. Shevenell and McCarthy (in press) state that this behavior suggests that chemical factors alone cannot account for changes in turbidity (*e.g.* material stability and mobility) observed during storms. They further suggest that mobilization of particles occurs due to increases in the groundwater flow rate. Evidence for this was observed when changes in turbidity during a series of storms were unrelated to changes in water chemistry parameters or ionic composition, but were correlated to the rise in water level as a result of precipitation events. Based upon my results and cited reviews, it appears that the increased sediment loads and varying size fractions transported in karst groundwater are attributable to varying periods of precipitation that infiltrate into karst networks, the geochemistry of the aquifer, the type of karst system present (diffuse or conduit), residence time, storm duration and velocity of groundwater in a karst groundwater system.

A third important question is how the transport of sediment varies with the ability of sediment to be stored in the karst system, as well as how transport velocity varies with time. Review of research performed by Loop and White (2001) offers some insight to this, as well as work needed to more satisfactorily accomplish this task.

Loop and White (2001) state that conduit systems provide a set of storage sites that have no analog in nonkarstic aquifers. The main mass of water moves through the conduit as an open channel or as pipe flow. They also state that velocities in the conduits range from centimeters per second to meters per second, but are many orders of magnitude faster than groundwater flow velocities in porous media aquifers, or in the fracture and matrix portion of karst aquifers.

Loop and White (2001) also suggest that the main mechanisms for transporting contaminants, and ultimately sediments through karst aquifers, are determined by a series of transport thresholds. These thresholds are described as: 1) a continuous transport threshold, 2) a threshold for free product contaminants, 3) a bedload transport threshold and 4) a threshold for complete entrainment. Loop and White's (2001) discussion of transport thresholds does not quantify the discharge needed to partition these thresholds, nor does the study presented herein quantify discharge values for transport versus the washout hypothesis presented. In order to satisfactorily explain thresholds for sediment transport and possibly a velocity and discharge threshold for sediment washout in karst aquifers, "quantitative expressions for each of the identified mechanisms, as well as the episodic movement of bulk sediment" (Loop and White, 2001), requires further research.

In an attempt to further understand how sediment transport varies throughout the year and better define the mechanism of transport both seasonally and during storms, future work should include a study of hydrogeologic controls. The hydrogeologic controls that should be studied are continuous real-time measurements of water levels and discharge in multiple monitoring wells and spring discharge points to determine the controls of water level and discharge on sediment transport and water chemistry. This monitoring should be performed seasonally and during multiple storm events. In addition, testing of how well percolation occurs toward the water table from both the overlying soil and sinkholes can help with initial loading conditions to the aquifer. An engineering component of this would include the amount of precipitation that infiltrates the ground surface versus runoff, evaporation, or precipitation captured by anthropogenic activity (*e.g.* storm drains and basins).

Development of sediment transport models in karst aquifers should include the integration of further tracer and geophysical tests for mapping and determining the physics and paths of groundwater flow. Continuous sampling of karst groundwater monitoring points (springs and wells), as performed in this study, for contaminants and identification of materials transported in the aquifer will permit a more thorough understanding of sediment transport in karst aquifers both seasonally and during storm events.

CHAPTER 7
CONCLUSIONS

I examined the temporal changes in sediment transport in a karst aquifer. Sediment transport variation was recorded in a limestone conduit intercepted by a monitoring well and a spring discharge location into the Bushkill Creek, Northampton County, Pennsylvania. The amount and type of sediment transported through a karst aquifer was measured for a year and during a storm event. Hundreds of mg/L of sediment was transported through the karst aquifer during the beginning of the research period (January through March 2000) in the monitoring well and on the order of mg/L in the monitored spring discharge point. This large amount of sediment transport in the spring and well decreased to no sediment transported in the spring and tens of mg/L transported in the monitoring well from March to late summer and early autumn. The maximum amount of transport occurred in the > 5 μm size fraction in both the monitoring well and spring.

Seasonal variation of precipitation affected the transport of sediment and ions through this karst system. Total precipitation was 11 inches higher during the late spring and summer, which increased the height of the water table and likely affected discharge volume. The water chemistry fluctuations were attributable to individual storm events and seasonal variability in precipitation.

The contrast between sediment and water chemistry variation was evident in the storm sampling and late spring and early summer seasonal sampling. Storm monitoring showed the peak sediment discharge (13 mg/L) during the lowest ionic concentrations (both at approximately the 8^{th} hour on the profile). The sediment is not diluted like the ions, rather it is flushed through by the higher storm velocity. Seasonally, sediment loading increased during lower overall precipitation (fall and winter). During periods of high precipitation in the spring and summer, flushing of the system reduced the sediment load.

The contrasting behavior of sediment and ion concentration during a storm and the decrease in sediment transport during the rainy season suggests that in addition to dilution, sediment transport in a karst aquifer is affected by washout. This study showed the importance of sampling during storms and frequently during each season to determine the effects of precipitation on the variability of karst systems.

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APPENDIX A

MONITORING WELL (MW-1) BORING LOG

LAFAYETTE COLLEGE

TEST BORING LOG

PROJECT: RESISTIVITY BORINGS
LOCATION: METZGAR FIELDS EASTON PA - NSF

BORING: B105
G.S. ELEV.:
FILE:
SHEET 1 OF 2

GROUNDWATER DATA			
FIRST ENCOUNTERED			
DEPTH	HOUR	DATE	ELAPSED TIME

METHOD OF ADVANCING BOREHOLE				
HSA	FROM	0	TO	12.5'
CORE	FROM	12.5'	TO	35'
	FROM		TO	
	FROM		TO	
	FROM		TO	

DRILLER: D. FLAHERTY
HELPER: [illegible]
INSPECTOR: B. GUZAS
DATE STARTED: 8-12-99 (1:36 PM)
DATE COMPLETED: 8-13-99 (8:10 AM)

DEPTH	A	B	C	DESCRIPTION	REMARKS
0	SS-1	9-12-12			GRINDING @1-2 FEET
5	SS-2	10-8-9			
10	SS-3	2-6-6			SOFT ZONE 10-12'
	R-1	REC 1.6' RQD = 1.3/1.6		12.5' - AUGER REFUSAL GRAY LIMESTONE 13.5' SOIL - REDDISH TAN CLAYEY SILT	12.5' - GRINDING 13.5' - LOST WATER RETURN
15	R-2	REC 0.3' RQD: 0/5.0		ROCK FRAGMENTS	
20	R-3	REC 2.2' RQD: 0/5.0		22.5' 23.5' CORE RECOVERED GRAVEL [illegible] WATER ERODED MATERIAL 24.0' SOIL IN THE SOIL SECTION 25.1' 26.0' 26.1' 27.5'	
25	R-4	REC 2.1' RQD: 1.9/5.0		GRAY LIMESTONE	
30	R-5	REC 5.0' RQD = 3.4/4.5		APPROX. 0.5' OF CORE LEFT IN THE HOLE (RECOVERED ON NEXT [illegible]) 32.5' SMALL FRACTURE 33.5'-33.8' - [illegible] WEATHERED FRACTURE	STOPPED FOR NIGHT [illegible]
35					

DRN.
CKD.

LAFAYETTE COLLEGE

TEST BORING LOG

PROJECT: Resistivity Borings
LOCATION: Metzgar Fields, Easton PA NSF

BORING: B105 con't
G.S. ELEV.:
FILE:
SHEET 2 OF 2

GROUNDWATER DATA			
FIRST ENCOUNTERED			
DEPTH	HOUR	DATE	ELAPSED TIME

METHOD OF ADVANCING BOREHOLE

FROM	TO
FROM	TO
FROM	TO
FROM	TO
FROM	TO

DRILLER: C. Flaherty
HELPER: [illegible]
INSPECTOR: [illegible] Guzas
DATE STARTED: 5-12-99
DATE COMPLETED: [illegible]-13-99

DEPTH	A	B	C	DESCRIPTION	REMARKS
	R-6	REC 5.0' RQD: 4.5/5.0		Good bedrock w/ some fractures @ ~70°	
40	R-7	REC 5.0' RQD: 4.5/5.0		Few weathered fractures @ ~70°	
45	R-8	REC 5.0 RQD: 4.6/5.0			
50	R-9	REC 4.4' RQD: 3.4/5.5		53.3'	52.9' - suspected water table. Drilling fluid lost
55	R-10	REC 0' RQD = 0/3.0		Void 58'	Water table: Time / Depth: 11:48AM 51.5'; 12:50 PM 52.1'
				Mud / soft soil	
60	R-11	REC 1.0' RQD = 0/5.0		62.8'	
				63.2' Weathered limestone, fractures [illegible]	
	R-12	REC 1.9' RQD: 1.6/2.0			
65				End of boring @ 65'	
				→ NOTE: Hole screened from 50 ft - 60 ft - cased w/ PVC from 0 ft - 50 ft	
70					

DRN.
CKD.

APPENDIX B

FIELD AND LABORATORY DATA PACKAGE

Spring No. 1 Field Data

Time (mm/dd/yy)	pH	TDS (ppm)	SC (umhos/cm)	T ©	Alkalinity (ppm)	Spring Level (inches)	Stream Stage (inches)
01/21/2000	8.64	259	383	7	161.04	NS	NS
02/04/2000	7.16	293	427	7.6	162.26	NS	NS
02/12/2000	8.43	247	411	9.7	140.3	2.7	6
02/19/2000	8.33	268	390	10.1	142.74	5.5	18
02/26/2000						10	23
03/04/2000	8.28	288	368	9.9	95	7	20
03/16/2000						7.8	16
03/17/2000						14	25
04/09/2000	7.62	285	413	10.2	94	5.8	12
04/29/2000	8.21	273	382	10.5	110	3.5	8
05/13/2000	8.01	259	371	12.5	98	1.5	6
05/28/2000	7.89			12.4	68	8	12
06/10/2000	7.15	259	453	12.9	76	5	8
06/25/2000	7.3	254	632	13.6	195	2	6
07/16/2000	7.81	201	543	14	87	5	11
07/30/2000	8.47	258	487	12.5	175	3	7
08/13/2000	8.52	231	509	12.8	215	4	7
08/20/2000	7.79	290	460	13.3	156	2	4.5
09/08/2000	7.7	261	530	13	298	1	4
09/24/2000	8.94	178	501	13.2	265	1	3
10/08/2000	9.36	271	588	4.4	267	0.5	3
10/22/2000	9.61	229	494	3.8	262	0.3	4
11/04/2000	8.62	224	470	10.9	269	0.5	3
11/19/2000	8.59	230	478	6	212	0.4	3
12/02/2001	8.79	223	414	10.5	231	0.5	4
12/16/2001	9.27	142	412	8.4	136	0.5	12
01/07/2001	8.62	142	420	7.3	127	NS	1
01/21/2001	8.65	155	403	4.8	114	NS	8

Note:
2/26/00 - Spring inundated by stream water during flood
3/16 - 3/17/00 - Storm Monitoring
5/28/00 - Instrument failure

Monitoring Well Field Data

Time (mm/dd/yy)	pH	TDS (ppm)	Spec. Conductivity (umhos/cm)	T ©	Alkalinity (ppml)	SWL (ft)
01/21/2000	8.22	364	552	5.5	405.04	55.1
02/04/2000	7.34	475	704	6	326.96	55.2
02/12/2000	8.42	432	655	8.6	390.4	55.24
02/19/2000	8.41	664	498	8.8	406.26	54.36
02/26/2000	7.3	356	519	10	241	53.21
03/04/2000	7.22	422	601	11.6	192	53.3
03/16/2000	7.54	442	588	12.3	364	53.23
03/17/2000	7.32	381	543	10.4	342	53.09
04/09/2000	7.3	421	532	11.9	419	52.95
04/29/2000	8.13			13.6	382.37	53.21
05/13/2000	7.51			15.1	342.4	53.3
05/28/2000	7.14			17.2	219	50.38
06/10/2000	7.05	401	709	20.9	265	52.26
06/25/2000	7.65	431	988	21.5	327	52.43
07/16/2000	6.84	405	853	16.1	316	53.5
07/30/2000	7.3	412	832	15.7	372	53.76
08/13/2000	7.46	421	778	16.3	376	52.83
08/20/2000	7.51	414	502	14.2	341	53.59
09/08/2000	7.08	458	769	13.9	462	54.28
09/24/2000	8.26	371	802	12.8	453	54.93
10/08/2000	8.55	429	824	7.3	342	55.5
10/22/2000	8.53	381	769	1.7	371	56.27
11/04/2000	8.09	390	815	12.3	458	56.42
11/19/2000	7.75	440	863	5.6	531	56.56
12/02/2001	8.32	410	816	8.2	548	56.6
12/16/2001	8.79	420	780	8	432	56.7
01/07/2001	8.07	357	920	7.5	456	57.15
01/21/2001	8.48	411	899	8.3	412	56.8

Note:
3/16 - 3/17/00 -Storm Monitoring
4/29, 5/13, 5/28 - Instrument failure

Spring No. 1 Laboratory Analytical Data

(all units in ppm)

Time (mm/dd/yy)	Na	K	Mg	Ca	Cl	NO3	SO4	CaCO3
01/21/2000	7.82	3.07	16.05	57	13.97	4.13	56.33	161
02/04/2000	7.38	3.08	15.01	56.1	13.56	4.05	56.5	162
02/12/2000	8.09	3.01	14.71	53.8	14.79	3.9	54.52	140
02/19/2000	8.99	2.95	13.12	51.9	18.31	4.04	52.82	143
02/26/2000								
03/04/2000	8.13	2.62	11.15	44.6	19.23	4.11	51.87	95
03/16/2000								
03/17/2000								
04/09/2000	8.18	2.81	10.98	40.6	14.07	3.38	44.06	94
04/29/2000	6.4	2.76	16.11	69.4	16.85	4.57	50.56	134
05/13/2000	6.35	2.83	19	78.4	16.77	5.11	55.25	137
05/28/2000	7.17	9.76	23.68	78.1	23.73	4.38	51.63	162
06/10/2000	7.16	3.82	29.59	99.2	17.66	5.73	58.87	205
06/25/2000	3.58	19.09	14.14	46.2	55.93	5.5	57.66	88
07/16/2000	6.97	3.76	26.01	87.6	17.71	4.62	53.42	189
07/30/2000	8.51	4.09	27.39	56	15.07	6.06	60.05	178
08/13/2000	8.05	4.26	29.39	101	15.64	6.51	62.98	221
08/20/2000	8.43	3.81	31.11	97	26.77	6.6	64.84	223
09/08/2000	10.06	15.92	30.08	102	10.09	5.3	24.41	298
09/24/2000	10.26	5.83	29.4	99.1	15.32	6.75	64.57	265
10/08/2000	11.02	6.66	28.52	102	18.28	6.05	65.96	267
10/22/2000	9.96	4.21	31.16	103	17.51	5.57	68.72	262
11/04/2000	8.75	4.57	29.41	97.6	14.41	4.31	57.15	269
11/19/2000	9.17	4.05	24.69	85.3	15.68	4.03	59.76	212
12/02/2001	9.89	4.36	22.74	80.2	15.55	3.66	60.16	231
12/16/2001	12.29	3.69	12.53	48.6	19.86	2.48	49.73	136
01/07/2001	10.76	4.22	10.57	45.9	15.83	2.79	47.77	127
01/21/2001	20.13	4.18	9.64	42.5	36.21	2.14	45.47	114

Note:

2/26/00 - Spring inundated by stream water during flood

3/16 - 3/17/00 - Storm Monitoring

Monitoring Well Laboratory Analytical Data

(all units in ppm)

Time (mm/dd/yy)	Na	K	Mg	Ca	Rb	Li	F	NH4	Cl	NO3	SO4	CaCO3
01/21/2000	3.87	7.53	24.68	118	0	0	0.25	0	7.79	3.37	26.72	405.04
02/04/2000	2.19	2.75	25.19	119	0	0	0.18	0	5.09	3.91	24.77	345
02/12/2000	2.52	2.54	24.22	114	0	0	0	0	5.04	4.05	25.9	390.4
02/19/2000	2.82	2.28	23.95	100	0	0.01	0	0	4.36	3.93	23.68	366
02/26/2000	2.06	2.7	20.88	81.7	0	0	0	0	4.21	4.02	23.18	241
03/04/2000	2.67	2.47	24.12	93.4	0	0.01	0	0	4.12	3.83	22.61	265
03/16/2000	[redacted]											
03/17/2000												
04/09/2000	2.72	3.12	36.06	72.3	0	0.01	0.3	0	3.07	5.1	25.7	278
04/29/2000	2.44	3.04	36.55	154	0	0	0.91	2.44	3.39	2.04	20.55	424
05/13/2000	1.3	2.73	33.82	139	0	0	0.58	0	3.51	3.2	23.62	373
05/28/2000	3.3	3.62	45.25	74	0	0.02	0.04	0	8.34	4.18	20.64	419
06/10/2000	3.31	3.39	39.93	44.9	0	0	0	0	7.41	4.96	29.11	265
06/25/2000	3.52	3.43	39.08	146	0	0	0	0	8.01	5.25	30.6	392
07/16/2000	2.41	3.42	56.38	119	0	0	0	0	3.69	1.81	24.14	421
07/30/2000	4.08	4.4	43.02	27	0	0	0	0	2.06	2.75	19.41	267
08/13/2000	2.68	3.43	42.86	88.9	0	0	0	0	4.8	6.27	21.41	376
08/20/2000	4.05	23.7	48.78	91.8	0	0	0	0	21.6	5.59	22.44	341
09/08/2000	5.25	9.83	46.77	177	0	0	0	0	16.6	5.22	59.07	462
09/24/2000	3.95	4.09	49.21	129	0	0	0	0	4.51	3.57	21.93	453
10/08/2000	4.35	3.99	46.1	56	0	0	0	0	3.59	4.41	22.21	342
10/22/2000	3.38	2.94	32.05	126	0	0	0	0	3.4	2.85	15.15	371
11/04/2000	2.31	3.86	57.33	136	0	0.01	0	0.22	3.73	2.98	25.51	458
11/19/2000	2.74	3.33	52.6	185	0	0	0	0	3.88	3.76	24.73	531
12/02/2001	2.8	3.32	49.49	198	0	0	0	0	4.38	4.36	25.16	548
12/16/2001	3.29	6.12	33.1	110	0	0	0	0	6.75	2.95	20.83	432
01/07/2001	3.23	2.93	32.39	130	0	0	0	0.32	4.38	2.78	20.98	456
01/21/2001	2.76	3.16	32.5	141	0	0	0	0	4.86	2.77	20.93	412

Note:

2/26/00 - Spring inundated by stream water during flood

3/16 - 3/17/00 - Storm Monitoring

Sediment Laboratory Analytical Data

(all units in mg/L)

Time (mm/dd/yy)	Spring No .1 0.45 um	Spring No .1 3 um	Spring No .1 5 um	Monitoring Well 0.45 um	Monitoring Well 3 um	Monitoring Well 5 um	Spring No. 2 0.45 um	Spring No. 2 3 um	Spring No. 2 5 um
01/21/2000	1	3	1	50	329	211			
02/04/2000	2	2	4	82	138	66			
02/12/2000	1	1	1	215	90	145			
02/19/2000	0	0	0	78	22	54			
02/26/2000				15	2	36			
03/04/2000	1	1	1	6	2	11		N	
03/16/2000								O	
03/17/2000									
04/09/2000	1	5	4	2	5	9		D	
04/29/2000	1	2	1	1	1	7		A	
05/13/2000	0	2	0	2	2	5		T	
05/28/2000	0	4	3	0	2	11		A	
06/10/2000	0	0	0	0	3	29			
06/25/2000	0	1	2	0	2	10			
07/16/2000	0	3	2	3	4	9			
07/30/2000	0	2	2	1	2	12			
08/13/2000	1	2	3	1	4	17			
08/20/2000	1	1	7	1	1	8			
09/08/2000	0	1	5	2	4	33	0	2	4
09/24/2000	0	2	9	0	2	148	0	1	3
10/08/2000	2	2	6	2	4	580	1	2	7
10/22/2000	2	2	7	4	5	875	2	2	5
11/04/2000	2	2	7	3	5	593	1	1	3
11/19/2000	1	2	4	2	6	411	1	1	2
12/02/2001	1	2	1	4	4	73	1	3	1
12/16/2001	0	2	6	1	1	108	0	1	4
01/07/2001	2	1	4	1	3	120			
01/21/2001	3	1	4	2	1	222			

Note:
2/26/00 - Spring inundated by stream water during flood
3/16 - 3/17/00 - Storm Monitoring

APPENDIX C

SATURATION INDICES

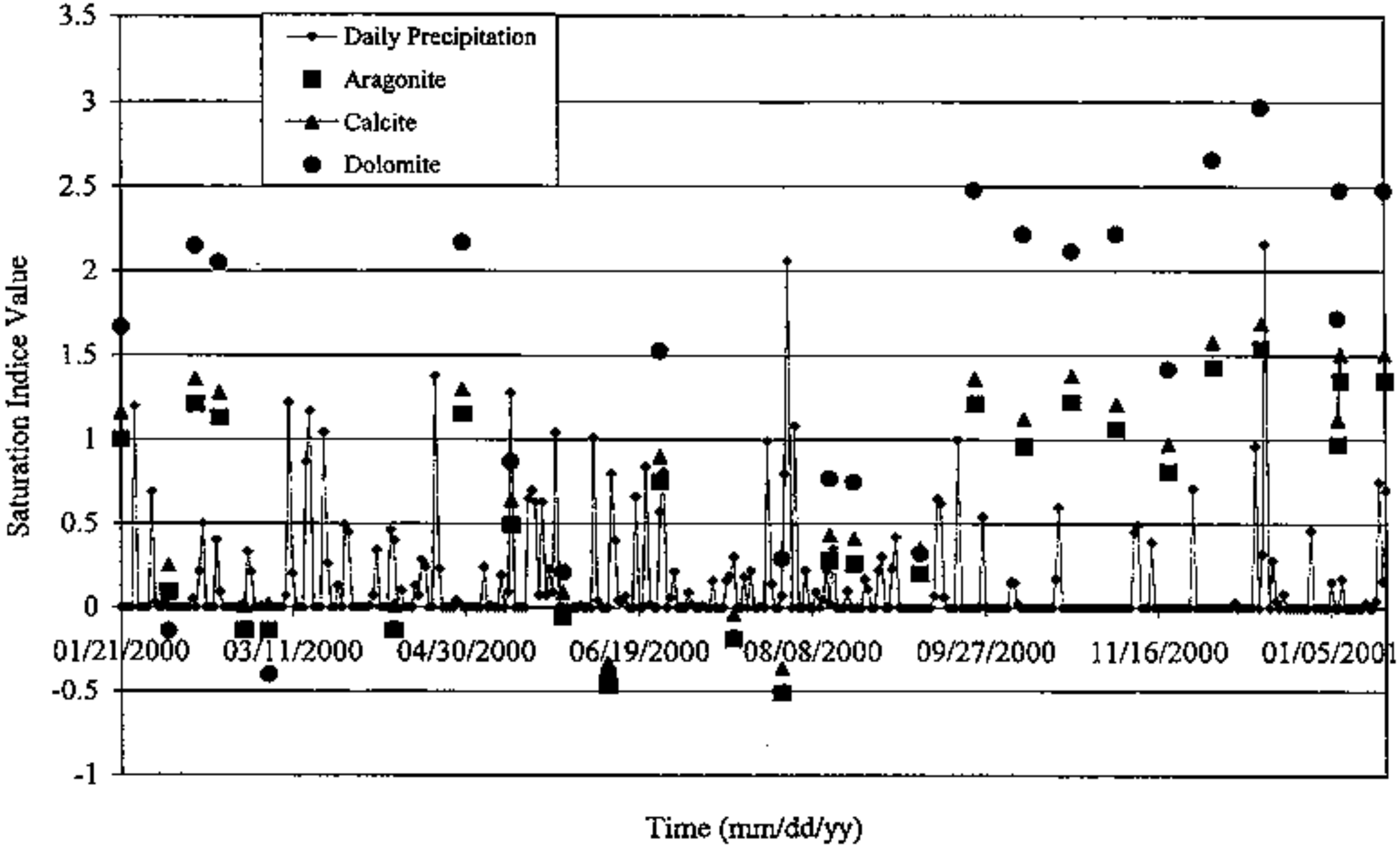
PHREEQCI: SATURATION INDICES

Monitoring Well

Date	Aragonite	Calcite	Dolomite
01/21/2000	1.00	1.16	1.67
02/04/2000	0.09	0.25	-0.14
02/12/2000	1.21	1.36	2.15
02/19/2000	1.13	1.28	2.05
02/26/2000	-0.14	0.01	-0.13
03/04/2000	-0.14	0.02	-0.40
04/09/2000	-0.14	0.01	-0.13
04/29/2000	1.15	1.30	2.17
05/13/2000	0.49	0.64	0.87
05/28/2000	-0.06	0.09	0.21
06/10/2000	-0.47	-0.33	-0.41
06/25/2000	0.75	0.90	1.53
07/16/2000	-0.19	-0.04	-0.18
07/30/2000	-0.51	-0.36	0.29
08/13/2000	0.28	0.43	0.77
08/20/2000	0.26	0.41	0.75
09/08/2000	0.20	0.35	0.32
09/24/2000	1.21	1.36	2.48
10/08/2000	0.96	1.12	2.22
10/22/2000	1.22	1.38	2.12
11/04/2000	1.06	1.21	2.22
11/19/2000	0.81	0.97	1.42
12/02/2000	1.43	1.58	2.66
12/16/2000	1.54	1.69	2.97
01/07/2001	0.97	1.12	1.72
01/21/2001	1.35	1.51	2.48

Spring No. 1

Date	Aragonite	Calcite	Dolomite
01/21/2000	0.76	0.92	1.36
02/04/2000	-1.02	-0.92	-2.02
02/12/2000	0.49	0.64	0.54
02/19/2000	0.44	0.59	0.72
03/04/2000	-0.35	-0.65	-1.49
04/09/2000	-0.52	-0.36	-1.17
04/29/2000	0.31	0.56	0.41
05/13/2000	0.31	0.46	0.48
05/28/2000	0.25	0.41	0.46
06/10/2000	-0.29	-0.13	-0.62
06/25/2000	-0.78	-0.62	1-.57
07/16/2000	0.31	0.46	0.58
07/30/2000	0.71	0.86	1.58
08/13/2000	1.07	1.23	2.09
08/20/2000	0.37	0.53	0.74
09/08/2000	0.43	0.58	0.82
09/24/2000	1.49	1.64	2.95
10/08/2000	1.69	1.85	3.19
10/22/2000	1.82	1.98	3.48
11/04/2000	1.20	1.35	2.34
11/19/2000	0.96	1.12	1.74
12/02/2000	1.21	1.37	2.33
12/16/2000	1.10	1.34	2.90
01/07/2001	0.57	0.73	0.90
01/21/2001	0.48	0.64	0.67



Monitoring Well Saturation Indice Values versus Precipitation