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QUANTITATIVE STUDIES OF SUSPENDED SEDIMENT IN KARST AQUIFERS

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by

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ABSTRACT

Though sediment transport is an intrinsic part of the functioning of fluviokarst aquifers, this flux has not received the attention devoted to spring chemistry and discharge. The fluviokarst conduit system acts as a mixing chamber where sediments from multiple sources are sorted and rearranged. The storm recharge in the basin largely controls the sediment transport through the drainage to the spring. Continuous and event-based monitoring at five karst springs in Pennsylvania over the past four years offered insight into the basic functioning of storms and sediment transport in fluviokarst aquifers.

The episodic nature of storm flows can make prediction of sediment transport and flow quite difficult. To this end, researchers have employed conceptual models based on both surface water and groundwater flow to describe flow response in karst. Frequently, karst is envisioned as a mid-point between surface water and groundwater resources or some mix of the two types. Analysis of the flow at multiple springs points to complications with employing this approach. Different karst springs fall at multiple locations on the surface to groundwater continuum, and the relationship between location on the continuum and specific physical properties is difficult to deduce. Understanding the functioning of storm flow in karst systems has direct impact on comprehending sediment transport.

The composition of the fine-grained portion transported through the aquifer even during minor storms is dependent on source area, mixing within the aquifer, and transport mechanisms. Composition can vary substantially in composition from spring to spring. This portion can also reveal aspects of the flow behind the spring mouth that aren't

apparent from detailed chemistry and flow monitoring. Nolte Spring in Lancaster County, Pennsylvania, discharged a variety of calcite sediments in spite of being undersaturated with respect to calcite. This unique sediment discharge enabled deduction of processes not visible in the karst system, and pointed to the idea that sediment discharge at the spring mouth can reveal a complex signal of washed through, conduit-sourced, and stored sediment at any particular time.

Additional observations at Arch Spring in Blair County, Pennsylvania confirmed this complex signal in sediment transport. Exceptional runoff events can lead to sediment transport where concentrations increase an order of magnitude, and thresholds required to mobilize stored sediment in the conduits are exceeded. Though such thresholds in flow and transport have been discussed in the literature for decades, very few have been captured through direct monitoring and no similar sediment transport event has been captured. This monitoring during large storm events also quantified a threshold in the flow system where any excess water beyond a certain level flows on the surface rather than through the conduit system.

Though much additional work remains in the field of karst sediment transport, long-term continuous and event-based monitoring revealed these complicated aspects of the five karst aquifers. The nature of these behaviors would not have been uncovered through periodic site visits, and results presented here reinforce the necessity of long-term monitoring protocols in karst.

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Chapter 1

Introduction

The primary focus of this work is fluxes through karst aquifers of both water and sediment. Although water fluxes through karst have been studied for decades (see for example Shuster and White, 1971), the sediment loads they entrain have been largely neglected by researchers with rare exception (White and White, 1968; Mahler and Lynch, 1999; Drysdale et al., 2001; Massei et al., 2002; Massei et al., 2003; Bosch and White, 2004; Dogwiler and Wicks, 2004; Hart and Schurger, 2005). Studies have generally been on deposits accumulated in caves (see for example Sasowsky et al. 2003) rather than the active processes of sediment transport and deposition in the system.

This thesis presents work to be published and work in press regarding both sediment and water fluxes through karst aquifers. My primary interest is in assessing the agents that control movement of sediment through the system and identifying the sediments themselves. Through long-term monitoring of spring water level, chemistry, temperature, and sediment load at five sites, the research group I work with is seeking to assess the importance of storm flows to sediment transport. This work was completed under the auspices of a cooperative grant from the National Science Foundation to Laura Toran of Temple University and William B. White of Penn State University (Award Numbers 125601 and 125551).

Chapter 2 is a review paper designed to advise the community of the current state of research into sediment transport and deposition in karst. Because so much of this subfield is unexplored, this paper's value comes mostly from recommending future work that needs to be completed before we can have an accurate picture of transport in karst aquifers. My contribution to Chapter 2 amounts to 75% of the work product. My co-authors are Laura Toran and William B. White.

The temporal variability of storm flows required assessment of the nature of the response of karst discharge to the perturbation of storms before sediment transport during storms can be assessed. Four of the springs we monitored were analyzed in terms of temporal response to storms. Chapter 3 of this thesis presents the resultant paper. Each of the springs displayed a different inertia in transmitting and maintaining the storm signal in terms of water level. The largest spring, Arch Spring, did display the strongest inertia in responding to storms, but the response was not consistent from year to year. This persistence of the storm signal and maintenance of high water levels for varying durations has implications on how sediment may be transported and deposited in the aquifer system. Attenuated storm signals may diminish sediment mobilization, but keep already mobilized sediment in transport longer than storm signals in low inertia systems.

Chapter 3 was submitted to the Journal of Hydrology early in 2006. The Journal's reviewers returned the paper suggesting moderate revision to the content and re-submission within three months. I am responsible for 85 to 90% of the work effort represented by Chapter 3. My co-authors on this paper are Laura Toran and William B. White.

Chapter 4 presents information on suspended sediments discharging from three springs and the attendant water chemistry. The results of this study were somewhat surprising in that a spring that is below saturation with respect to calcite was discharging calcite as sediment. The sediment composition at the other two springs was predominantly siliciclastic and very fine-grained, both during storm and base flow. Chapter 4 has been accepted for publication, after review and re-submission, by Hydrogeology Journal. The article will be on-line soon and will be published in the paper version of the journal before the end of the year. My work effort contributed 25% toward this paper. All co-authors, Laura Toran, Jennifer Tancredi, and William B. White, contributed similarly to this publication.

Chapter 5 presents results from one monitored spring in Central Pennsylvania, Arch Spring, during extreme rain events in 2004. Though similar records exist for several of the springs, Arch Spring exhibited transient behaviors during large storms that were substantially different from its behavior during small to moderate storms. The storms revealed an upper limit on the flow that can be discharged from Arch Spring during rain events and a transition in sediment discharge with substantial quantities of sediment from the stored fraction being mobilized during extreme events.

Chapter 5 will be submitted to the Journal of Hydrology before the end of 2006. The chapter is in a format acceptable to that journal. I am responsible for 85-90% of the work effort in Chapter 5. My co-authors are Laura Toran and William B. White.

In addition to these papers, the research group has authored two additional papers during the course of this project. The first was published in a GSA special volume, and my contribution to the work amounted to 25% (Toran et al., 2006). The second has been accepted for publication in Groundwater, and I contributed roughly 5% of the work product (Toran et al., in press).

References

Bosch, R.F. and White, W.B., 2004. Lithofacies and transport of clastic sediments in karstic aquifers. In *Studies of Cave Sediments*, I.D. Sasowsky and J. Mylroie, Eds., Kluwer Academic, New York, p.1-22.

Dogwiler, T. and Wicks, C.M., 2004. Sediment entrainment and transport in fluviokarst systems. Journal of Hydrology, 295(1-4): 163-172.

Drysdale, R., Pierotti, L., Piccini, L. and Baldacci, F., 2001. Suspended sediments in karst spring waters near Massa (Tuscany), Italy. Environmental Geology, 40(8): 1037-1050.

Hart, E.A. and Schurger, S.G., 2005. Sediment storage and yield in an urbanized karst watershed. Geomorphology, 70(1-2): 85-96.

Mahler, B.J. and Lynch, F.L., 1999. Muddy waters: temporal variation in sediment discharging from a karst spring. Journal of Hydrology, 214(1-4): 165-178.

Massei, N., Lacroix, M., Wang, H.Q., Mahler, B.J. and Dupont, J.P., 2002. Transport of suspended solids from a karstic to an alluvial aquifer: the role of the karst/alluvium interface. Journal of Hydrology, 260(1-4): 88-101.

Massei, N., Wang, H.Q., Dupont, J.P., Rodet, J. and Laignel, B., 2003. Assessment of direct transfer and resuspension of particles during turbid floods at a karstic spring. Journal of Hydrology, 275(1-2): 109-121.

Sasowsky, I.D., Sebela, S. and Harbert, W., 2003. Concurrent tectonism and aquifer evolution > 100,000 years recorded in cave sediments, Dinaric karst, Slovenia. Environmental Geology, 44(1): 8-13.

Shuster, E.T., and White, W.B., 1971. Seasonal fluctuations in the chemistry of limestone springs; a possible means for characterizing carbonate aquifers. Journal of Hydrology, 14 (2): 93-128.

Toran, L., Herman, E.K., and White, W.B., in press. Comparison of flow paths to a well and spring in a karst aquifer. Groundwater.

Toran, L., Tancredi, J.H., Herman, E.K., and White, W.B., 2006. Conductivity and sediment variation during storms as evidence of pathways in karst springs. In *Perspectives on karst geomorphology, hydrology, and geochemistry – A tribute volume to Derek C. Ford and William B. White*, R.S. Harmon and C. Wicks, Eds., Geological Society of America Special Paper, 404: 169-176.

White, W.B. and White, E.L., 1968. Dynamics of sediment transport in limestone caves. Natl. Speleol. Soc. Bull., 30, 115-129.

Chapter 2

Sediment fluxes in fluviokarst aquifers: Storm pulses, thresholds, and fluid dynamics of mixing storage and transport

Abstract

Carbonate aquifers with well-developed conduit systems (fluviokarst aquifers) carry a flux of clastic sediment as an intrinsic aspect of their functioning. Sources of clastic sediments include sediments carried by sinking streams, soil wash-down from the epikarst, plug injection by sinkhole piping failures, and residual insoluble material from the dissolution of the limestone. The conduit system acts as a mixing chamber where the injected materials are sorted and rearranged. Information on the sediments and their transport processes can be obtained by investigating the source areas, by inspection of cave sediments, and by monitoring clastic sediment discharged from springs as a function of flow conditions.

The engine that drives the sediment transport system is the storm recharge in the ground water basin drained by the conduit system. Fine-grained clastics move during ordinary storms and can be captured easily at springs, but movement of coarser materials requires high-intensity, therefore infrequent, storms so that most of the sediment flux is episodic with long periods of storage interspersed with short periods of movement. Fluid mechanics provided the basis for calculations of both bedload and suspended load components. However, these calculations could not take into account the discharge-dependent shifts from pipe flow to open channel flow or the effect of blockages due to

breakdown and other barriers. Ultimately, these questions will have to be resolved through solutions using a computational fluid dynamics modeling package.

Introduction

Active karst drainage systems contain and transport a flux of clastic sediment. Some of these materials can be seen in caves as deposits of clays, sands, silts, and occasional cobbles and boulders. These are usually derived from sandstone, limestone, and other rocks in the same drainage basin and subsequently transported into the cave system. Other evidence for clastic sediment transport can be seen at karst springs which often become turbid or muddy during storm flow and which may eject coarse clastics during extreme storms.

It was demonstrated long ago (White and White, 1968) that any karstic drainage basin with a component of allogenic recharge must carry a sediment load. Tributary surface streams remove weathered rock material and carry it into the underground system at their swallets. The clastic material must also ultimately be transported out of the underground system through resurgences at springs. If the transport processes for the clastic materials were not sufficient to remove the load being carried into the system by sinking streams, the subterranean drainage system would simply clog up. The underground drainage would then be forced to return to surface routes. In spite of this requirement for long term steady state transport of clastics in the karstic system, it is apparent that the transport of these sediments is not at a constant rate. The transport is episodic, related to extreme storm events that move very large quantities of water and sediment into and through the karstic system. The sediments move through the karst system as a series of pulses rather than as a continuous flow, and these pulses may be interspersed with periods of substantial sediment storage within the aquifer. Furthermore, there should exist a threshold in the conduit flow velocity, below which the sediments of a specific size will not move. Under sub-threshold conditions, the majority of sediments will simply pile up in the conduit system. Only when the threshold is exceeded will a large pulse of clastic material be flushed through and out of the conduit system. It is important to note that, while a general steady state must be maintained to keep the karstic system from filling, there may be sediments deposited in underground systems which are stored for thousands of years before their thresholds for movement are again surpassed (Schmidt, 1982; Kiernan et al., 2001; Sasowsky et al., 2003).

Our purpose in the present paper is to review the state of knowledge of clastic sediment fluxes as an intrinsic aspect of the hydrology of carbonate aquifers, to establish some criteria for sediment movement, and to present some analysis of the episodic nature of sediment movement in terms of the repeat frequency of severe storms.

Historical Background

White (in press) notes that historically, clastic cave sediments received very little attention in the early karst hydrological literature. Caves sediments become a significant part of cave science in the 1960's with an important symposium (Dell'Oca, 1961) and the comprehensive research of Renault (1967, 1968). The paleoclimatic significance of clastic sediments was recognized in European alpine caves by Schmid (1958). The first two English language textbooks on caves (Jennings, 1971; Sweeting, 1972) had chapters devoted to cave sediments although the coverage was predominantly on chemical sediments. Clastic sediment research in the United States got underway in the mid-1960's with the work of Frank (1966) on the caves of Texas and later work in Australia (Frank, 1969; 1971). Many of these early studies treated clastic sediments in caves as a peculiar sort of sedimentary rock with emphasis on in-cave stratigraphy and provenance of the sediment. One of the most comprehensive studies of sediment source and deposition was an unpublished Ph.D. thesis (Wolfe, 1973) describing cave sediments in the Greenbrier karst of West Virginia.

Sediment Inputs

Overview: The Fluviokarst Drainage Basin and Its Sediment Flux

The karst aquifer acts as a mixing chamber for sediments injected into the system from sinking streams (allogenic recharge), soil washdown through the epikarst (the corroded bedrock surface), and the episodic collapse of sinkhole features. Autochthonous sediment, either in the form of residuum from dissolution or new precipitation products (e.g., calcite precipitated in aquifer segments above saturation with respect to calcite) may also be added to the mix (Figure **2-1**). In fluviokarst settings, these autochthonous components are generally neglected as much smaller in magnitude than the other sediment components, though our recent work indicates autochthonous sediment, particularly precipitated calcite sediments, may be significant in certain small systems (see Chapter 4) (Herman et al., in press).

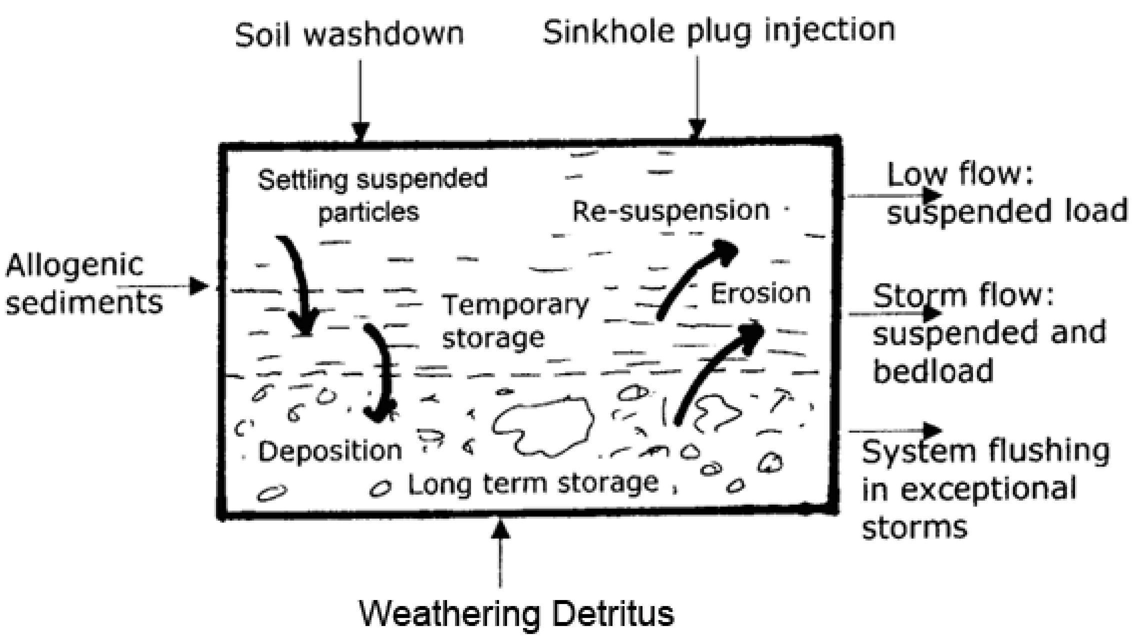


Figure 2-1: The conduit system as a mixing chamber. Sketch shows principal inputs, storage, rearrangement, and transport.

It is possible to write a sediment budget, much in the same manner as a water budget.

$$S_{OUT} = S_a + S_k + S_p + S_r \pm S_s \qquad 2.1$$

where S_{OUT} is the sediment discharge from the spring, S_a is sediment carried into the aquifer by sinking allogenic streams, S_k is soil washdown from the overlay karst surface, S_p is plug injection from soil piping failures in sinkholes, S_r is insoluble residuum from dissolution of the bedrock, and S_s is sediment in storage within the aquifer. Like water budget equations, this simple expression hides some great complications because each term in the equation is a complex function of time. An important constraint on the system is that the sediment inputs cannot exceed the sediment output over long time periods. This can be expressed by the storage term:

$$\left[\frac{\partial S_s}{\partial t}\right]_{AVE} \leq 0 \qquad \textbf{2.2}$$

In the fluviokarst aquifer, the sediment added is either washed through the system to the spring resurgence immediately or is transferred to storage in the conduits and fractures of the system. Residence time may range from short-term on the order of hours to days (e.g., Massei et al., 2003) to very long-term on the order of millennia (e.g., Kiernan et al., 2001). This variation in residence time is a function both of the frequency of storm flows adequate to mobilize stored sediment and of the actual storage itself in the form of conduit morphology.

Though there is dissolution of the bedrock in fluviokarst conduits, in general, this takes place at too slow a rate for removal by dissolution to play a major role in accommodating sediment in the system. The swiftest dissolution occurs early in conduit development, when fractures are being enlarged to conduits, and flow is transitioning to fully turbulent. To develop a 1-cm diameter conduit from a fracture takes between 10,000 and 100,000 years (Palmer, 1991). Further dissolution of the conduit once the 1-cm threshold is exceeded will be at a slower rate and unlikely to be sufficient to accommodate sediment storage on the appropriate time scales.

Compacted sediments, even of fine grain size, require stronger basal shear stresses to mobilize than uncompacted sediments. Uncompacted stored sediments or recent siltation appear quite commonly in fluviokarst basins. Most of our knowledge of these sediments comes from direct observation in the conduit system by cave divers. The springs of Pennsylvania, in particular Arch Spring, are famous among cave divers for their slurry of sediment that sits on the cave walls and ceilings waiting for the slightest brush of a dive fin to be remobilized into an obscuring cloud. Most published reports by cave divers are concerned with their explorations (e.g., Boon, 1977; Farr, 1991; Exley, 1994), but hidden within these texts are many accounts that demonstrate that loose, uncompacted, extremely fine grained sediment is very common. The uncompacted sediment requires much less shear stress to remobilize into the active flow than the compacted fraction. Additional research, particularly with cave divers involved and actively pursuing these research questions, will be required to delineate the contributions from the compacted stored sediment and the recent siltation component.

Sediment Injection by Sinking Surface Streams

Allochthonous sediment washed in by the allogenic recharge of a sinking surface stream can be the major component of sediment addition in a fluviokarst basin. This sediment is washed through the system or stored in the karst system to be re-mobilized during some storm events (Mahler et al., 1998; Massei et al., 2003; Herman et al., in preparation). The allochthonous component washed into and through the conduit system is a complex function of the discharge and basal shear stress of the sinking stream and the sediment available upstream of the conduit systems. As with surface water systems, sinking streams where the sediment capacity exceeds the available sediment can be classified as sediment-starved systems. Also similarly to surface streams, sinking streams may carry excess sediment from human alterations to the landscape (James, 1993; Chandler and Bisogni, 1999).

Composition of allochthonous sediment is largely controlled by sediment available to be washed into the system. In some areas like the Nolte Spring in Lancaster County, Pennsylvania, the sediment added in this manner can be distinguished from other sediments in the system because composition differs adequately and identifiably (Herman et al., in press). However, this separation is quite difficult in many karst springs as the springs discharge sediment derived from clastic rocks upstream of the karst aquifer and frequently the soil mantle above the karst system contains much of this same material. Some attempts have been made in various locations to separate sediment sources (Murray et al., 1993; Bottrell et al., 1999; Mahler et al., 1999; Drysdale et al., 2001). New methods such as labeling clays to track the progress of sediment through the system may prove useful in this pursuit (Mahler et al., 1998).

Soil Washdown from the Epikarst

Soil mantled epikarst is a common feature in fluviokarst systems. The term epikarst is generally applied to the highly corroded bedrock surface and its infilling of regolith (Jones et al., 2003). Sinkholes and other features that put the surface in direct contact with the conduit system are not included in the epikarst. Epikarst features can range from small bedrock sculpturing to dramatic features on the order of tens of meters. The degree of development of epikarst undoubtedly plays a role in how efficient the system is in delivering sediment to the karst aquifer (Bono and Percopo, 1996), but there has been little work in this area.

Researchers are actively pursuing quantification of water addition through the epikarst, both during baseflow and storm flow (Lakey and Krothe; 1996; Chandler and Bisogni, 1999; Lee and Krothe; 2001; Kogovsek and Sebela, 2004; Einsiedl, 2005; Aquilina et al., 2005; Aquilina et al., 2006) and are identifying the unique fauna that occupy the epikarst region (Pipan and Culver, 2005; Brancelj, 2006; Pipan et al., 2006). Others have considered the role of the epikarst and its sediments in contaminant storage and transport (Loop and White, 2001; Panno et al., 2001) and how the different chemistry of the epikarst might affect the colloidal fraction carried in karst aquifers (Shevenell and McCarthy, 2002). Quantification of sediment added to the aquifer through soil washdown and characterization of the sediments contributed through the epikarst will likely become active areas of research in the near future.

Plug Injection and Soil Piping Inputs

Perhaps the least predictable of sediment injection events is soil piping failure and plug injections from sinkholes. Contributions of sediment in this fashion can be quite substantial, on the order of thousands of cubic meters, and very swift, sometimes occurring across a single day or within hours. Removal of water from the karst aquifer either through pumping for water supply or through activities such as quarry and mine de-watering is likely to increase the frequency of sinkhole failures and dramatic sediment additions. Sinkhole failures are commonly associated with the same high magnitude rain events that mobilize large sediment fluxes from allogenic discharge and from the stored sediment in conduits (see for example Gutierrez-Santolalla et al., 2005). Hart and Schurger (2005) found that sediment contributions from sinkholes to the Upper Pigeon Roost Creek karst system in Tennessee were episodic and that such random events were a primary contributor to the overall sediment budget of the basin.

Sediment Output: Sediment Fluxes from Karst Springs

Springs are the primary site of observations for most karst systems, and their discharges have been used to deduce information ranging from conduit structure to input sources for storm water (e.g., Shuster and White, 1971; Hess and White, 1988; Lee and Krothe, 2001). Springs are attractive to researchers because they are easily accessible compared to the majority of the karst aquifer and because they represent an integrated output of the karst system.

Researchers interested in a variety of topics have looked at the water and sediment discharging from springs. These studies range from determining how contaminants and sediment interacted in the karst system (Mahler et al., 2000; Boyer and Kucynska, 2003; Dussart-Baptista et al., 2003; Vesper and White, 2003, 2004; Guitierez et al. 2004; Davis et al., 2005) to characterization of the sediments themselves (Drysdale et al., 2001; Herman et al., in press). Other researchers have attempted to deduce aquifer dynamics based on the interplay of discharge, chemistry, and sediment outflow, frequently using turbidity as a proxy for suspended sediment (Ryan and Meiman, 1996; Massei et al. 2003; Herman et al., submitted). It is the last category of study that offers the richest opportunity for differentiating between sediments washing directly through the system and those mobilized from storage.

In addition to observations at springs, several researchers have used wells drilled into conduit systems to observe sediment as it is being transported through the system (Mahler et al., 1999; Mahler et al., 2000; Massei et al., 2002; Shevenell and McCarthy, 2002; Toran et al., in press). Results from these studies varied in that some found the wells showed sediment of differing character from springs while others found little to differentiate well sediment from spring sediment. These results underscore the difficulty of working on such issues in karst and suggest that viewing any karst system through a single window may be mis-leading, regardless of the specific window.

Residua from Sediments in Transit: Cave Sediments

Sediment Observations in Caves: The Facies Concept

A great deal of information can be gleaned about the behavior of creeks and rivers by examination of the sediments that accumulate in stream channels, in natural levees and backswamps, and on the floodplains. Similar observations can be made on conduit systems by taking advantage of active stream caves and of abandoned conduits accessible in dry caves. Transferring concepts developed for surface streams with relatively continuous slopes to conduit systems with irregular slopes and alternating reaches of open channel flow and closed conduit flow requires replacing channel slopes with both hydraulic gradients and pressure heads. Other idiosyncrasies such as collapses and other channel constrictions must also be considered.

Simple observation shows that a variety of clastic sediments occur in caves. Particle sizes vary over a wide range. Some sediments are bedded or sorted and some are not (Figure 2-2). These observations lead naturally to a facies concept introduced in a previous paper (Bosch and White, 2004). Cave sediment facies are not merely descriptive; they also have hydraulic significance.

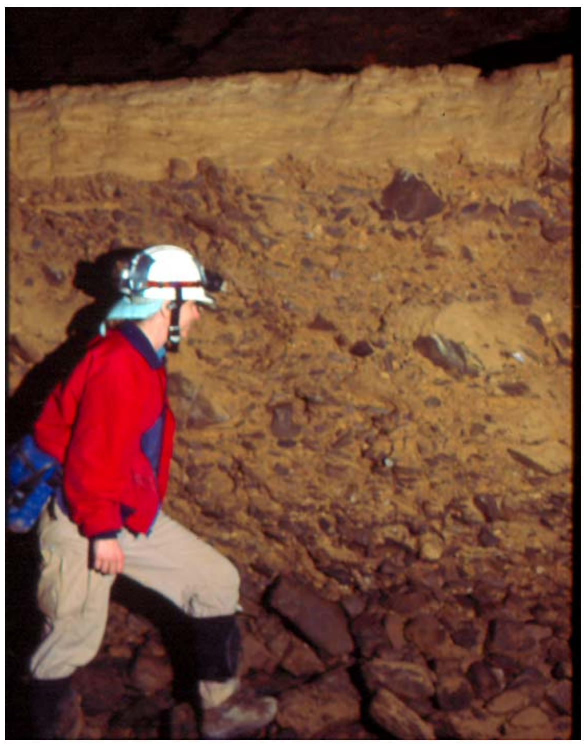


Figure 2-2: Cave sediments with no bedding. Photo of sediment transported and deposited in Butler Cave, Bath County, VA.

The Channel Facies

The clastic sediments that make up the channel facies are the largest component in terms of volume. These sediments have been transported by stream action, mostly as bedload and have been deposited as the shear stress and velocity dropped below the minimum required to maintain movement (Figure **2-3)**. There is a large literature of sediment transport, written for the most part by civil engineers (Graf, 1971; Vanoni, 1975). Laboratory experiments using flumes with uniform particle size beds have established empirically the mechanisms and thresholds for sediment transport in homogeneous beds. Theoretical calculations based on idealized sediments and fluids have added to our understanding of this variety of transport. The critical shear stress for movement of bedload provides a threshold below which sediment of a specific size does not move.

a) b)

Figure 2-3: Channel Deposits in a) Carroll Cave, Missouri and b) Lee Cave, Kentucky

Many experiments establish the relationship of critical shear stress to particle size (Vanoni, 1975). A fitted equation is

$$T_c = 0.067\,D_{50}^{1.08} \qquad \textbf{2.3}$$

where T_c is the critical shear stress required to mobilize the particle in N/m^2 and D_{50} is the median particle size in mm. Other workers express the relationship between critical shear and diameter in terms of the dimensionless Shields parameter (Θ)

$$\tau_c = \Theta(\rho_S - \rho_W)gD_{50} \qquad \textbf{2.4}$$

where τ_c is the critical shear stress in N/m^2, ρ_s is the density of the particle(kg/m^3), ρ_w is the density of the fluid (kg/m^3), and g is the acceleration due to gravity (m/s^2). The sediment grains are assumed to be equant spheres in this calculation.

The required critical shear stress for incipient motion is in part a function of whether the grain entrains by rotating or sliding. Work by Carling et al. (2002) established the following relationship for critical shear stress (τ_C) for sliding grains:

$$\tau_C = \mu_f g(\rho_s - \rho_w)V \qquad \textbf{2.5}$$

where μ_f is the frictional coefficient dependent on the grain and substrate material and V is the volume of the grain. The grains are assumed to be tabular blocks in this calculation.

The boundary shear (τ_0) for the special case of open channel flow under steady uniform conditions is determined by hydraulic radius, R, and channel slope, S.

$$\tau_0 = \gamma R S \qquad \textbf{2.6}$$

where γ is the specific weight of water. When τ_0, exceeds τ_C sediment entrainment is possible.

The relationships above were all assessed in open channel flow and can yield first approximations of sediment entrainment in karst conduits. The largest water-transported sediment grains observed in karst conduit deposits occasionally exceed 1 m, but much of the sediment in channel facies is gravel to cobble-sized. Based on a range of the dimensionless Shields parameter from 0.04 to 0.25 (Dogwiler and Wicks, 2004), to mobilize 8-cm diameter cobbles off a cobble bed by rotating requires between 5.7 and 32

Pa of shear stress. To mobilize much larger sediment, on the order of 0.5 m in diameter, by rotating would require 360 to 2000 Pa of shear stress. The μ_f factor in the equation describing entrainment by sliding depends on the material of the grain and the substrate. Limestone sliding on limestone has a lower coefficient of 0.7 while sandstone on limestone has a coefficient of 0.85 (Carling et al., 2002). For blocks with an equal volume to a 8-cm diameter cobble, the threshold for movement is much lower than a round grain $3x10^{-3}$ to 3.5×10^{-3} Pa. Moving a large tabular boulder, with a volume similar to that of a 0.5-m diameter round boulder, requires higher shear stress of 740 to 860 Pa. Slopes in water table karst aquifers are similar to many slopes in surface water, from 0.0001 to 0.001. With this range of slopes in a 2-meter by 4-meter karst channel, it is possible generate adequate shear stresses (0.98 to 9.8 Pa) to move the smaller fractions, but additional shear stress must be generated to move the larger sediment.

In karst aquifers these relations of shear stress to bedload sediment movement thresholds must hold. It is the shear stress itself which is likely to be of different magnitude, particularly in areas where the flow shifts from open channel to pipe full flow. The rising limb of the hydrograph recorded at karst springs is frequently not composed of recently added storm water. Rather, the water that first arrives at the spring is that flushed out of the fractures, conduits, and matrix that accompanies a pressure pulse transmitted through the aquifer to the spring (Hess and White, 1988). This water is frequently higher in dissolved solids that the low conductivity storm water, and displays a different isotopic signature (Lakey and Krothe, 1996; Lee and Krothe, 2001). These stored waters can also carry a significant suspended and bed sediment load as the pressure pulse increases their velocity and attendant shear stress, and this is perhaps the most unique feature of sediment transport in karst aquifers. The sediment moved through the system in response to a storm pulse not only reflects sediment mobilized by storm water, but also sediment mobilized by accelerating stored waters. To accurately depict these systems, shear stress distribution and sediment mobilization for the special case of karst flow need to be developed further.

The Thalweg Facies

For any sediment transfer, the threshold for bed movement must be exceeded. The channel facies require flow volumes and flow velocities expected from annual high flows and from moderate floods. Stormwater facies require high floods to provide the necessary shear stress to move the cobble and boulder beds. Moderate flows of more frequent recurrence serve to extract silt and sand size particles leaving only the very coarse part of the bedload to await infrequent high floods. These smaller particles may move as suspended load during high flow events, but during flows of lower magnitude they may move as either suspended or bedload, depending on local conditions. The winnowed deposits of larger clast sizes left behind may be considered thalweg facies. Some work in karst has shown that even moderate flows can move the majority of a cobble-sized bed (Dogwiler and Wicks, 2004).

The Slackwater Facies

Fine-grained particles requiring minimal velocities to remain suspended are common in the fluviokarst environment. Much of the material collected at a variety of springs in Pennsylvania was of such small diameter that even base flow kept it in suspension (Toran et al., 2006). As velocities increase during storm flows, an increasing fraction of sizes may be further entrained as suspended load. Stokes' Law governing settling velocities (V_s) is a very sensitive function of particle size:

$$V_s = \frac{d^2 g(\rho_s - \rho_w)}{18\mu} \qquad \textbf{2.7}$$

where d is the particle diameter, g is acceleration due to gravity, and μ is the dynamic viscosity of the fluid. In turbulent flows the net upward momentum flux must be overcome by the grain weight for particles to settle. Only in very slow to motionless water, where the flow becomes laminar and the net upward velocity due to turbulence is eliminated, will the very fine fraction settle. The deposition of this material is not uncommon in karst aquifers. Substantial clay to silt sized banks frequently appear in fluviokarst conduits where the conduit widens. Additional fine deposits occur in rarely utilized conduits where water no longer connected to the main flows slows, and the fine fraction can settle out. These fine deposits are classified as slackwater facies.

Complete Entrainment – Debris Flows – Diamicton Facies

A second threshold must be exceeded to achieve complete entrainment of the clastic sediment deposits in the conduit system or on the surface. The entrainment threshold is exceeded only during extreme floods and deposition of these flows results in the diamicton facies, consisting of unsorted sediments with a wide range of particle sizes. In flows of these varieties, the shear of the fluid is far less important than the particle to particle interactions. Flows of this variety must be modeled using plastic or rigidplastic rather than fluid rheology (Bagnold, 1954; Iverson and Vallance, 1985). These deposits in karst environments are frequently associated with glacial melt events or catastrophic floods (Gillieson, 1986).

Role of Clastic Sediments in the Evolution and Interpretation of the Conduit Systems

Scour and Erosion in High Velocity Conduits

Dissolution has long been considered the primary operator in karst conduit formation. This is clear from both interpretations of karst development history and karst development models. However, some early work pointed out that, past threshold for sediment transport, sediment tooling and abrasion should play an active role in conduit formation (Bretz, 1942). The idea since that time has largely remained uninvestigated, though some unpublished modeling has considered how the presence of sediment affects conduit development (Annable et al., 2004). This work did not examine the tooling capabilities of sediment but rather how its presence affects the chemistry of the system. For accurate modeling of conduit development, the role of suspended and bed load sediments will have to be included once turbulent flows adequate to mobilize the sediment have been achieved.

Sediment Pads and Conduit Self-Perching

Conduit systems evolve as surface stream base levels lower. If there is the correct balance between conduit gradient and sediment load, the conduit stream will downcut following the surface base level and the results will be a high underground canyon with the stream flowing on the bottom. In many caves, however, the observed pattern is that of a sequence or tier of large master conduits stacked one above the other. It has been argued, although hard data are sparse, that the veneer of clastic sediments on the floors of these low gradient trunk conduits is sufficient to retard the downcutting so that the system response is to initiate a new conduit at some lower level. Cosmogenic isotopic dating of quartz from the clastic sediments in these master conduits has been an important means of establishing a chronology for conduit system development (Granger et al. 2001; Anthony and Granger, 2004).

Calculations of Past Flow from Residual Sediments

Springer and Kite (1997) did use deposits of sediment in the conduit system of the Cheat River caves to deduce information about paleofloods. However, their primary interest was in river behavior rather than flow in the cave. Additional work on cave sediment deposits has yielded information about the age of sediment deposits, conduits, and incision (Sasowsky et al., 1995; Granger et al., 2001). Little work has focused on using the remnant sediments to deduce past flow conditions in terms of shear stresses, discharges, and velocities in karst. This work has been explored to a large extent in paleoflood deductions in the fluvial literature (see for example Kochel et al., 1982; Baker, 1994; Grimm et al., 1995).

Conclusions

Clastic sediments in caves can be classified according to the flow regimes required to transport them. Examination of the flow velocities and shear stresses required to transport clastic sediments suggests that flood events of various magnitudes provide the power source necessary to transport the flux of clastic sediments through karst aquifers. Though the physical processes of sediment entrainment and transport (i.e., the basic interaction between moving water and sediment grains) in karst are similar to the processes in surface water, the descriptions of flood-based transport in surface waters do not directly apply to questions of sediment transport in karst. Shifting flow conditions and the unique geometry in karst aquifers make the transport regimes different from surface water sediment transport and deposition.

Relatively little research has been completed in karst sediment transport, but an understanding of this transport is essential to predicting contaminant transport and water quality in karst water resources. The sparse observation points in karst systems, usually in caves, at springs, or in the occasional well, have limited our ability to generalize about these systems. The conceptual models presented here of both sediment addition and facies description are intended to encourage exploration of the basic sediment transport processes in karst and the more complicated storm flow transport.

References

Annable, W.K., Sudicky, E.A. and Ford, D., 2004. Numerical simulations evaluating the effect of vertical jointing and recharge on the development of proto-conduits in limestone aquifers at depth. Abstracts with Programs - Geological Society of America,.36 (5): 106

Anthony, D.M. and Granger, D.E., 2004. A late Tertiary origin for multilevel caves along the western escarpment of the Cumberland Plateau, Tennessee and Kentucky, established by cosmogenic ^{26}Al and ^{10}Be. Journal of Cave and Karst Studies 66: 46-55.

Aquilina, L., Ladouche, B. and Dorfliger, N., 2005. Recharge processes in karstic systems investigated through the correlation of chemical and isotopic composition of rain and spring-waters. Applied Geochemistry, 20(12): 2189-2206.

Aquilina, L., Ladouche, B. and Dorfliger, N., 2006. Water storage and transfer in the epikarst of karstic systems during high flow periods. Journal of Hydrology, 327(3-4): 472-485.

Bagnold, R.A., 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 225 (1160): 49-63.

Baker, V.R., 1994. Geomorphological understanding of floods. Geomorphology, 10(1-4): 139-156

Bono, P. and Percopo, C., 1996. Flow dynamics and erosion rate of a representative karst basin (Upper Aniene river, central Italy). Environmental Geology, 27(3): 210-218.

Boon, J.M., 1977. Down to a Sunless Sea. Stalactite Press, Edmonton, Alberta, 105 pp.

Bosch, R.F. and White, W.B., 2004. Lithofacies and transport of clastic sediments in karstic aquifers. In *Studies of Cave Sediments*, I.D. Sasowsky and J. Mylroie, Eds., Kluwer Academic, New York, p.1-22.

Bottrell, S., Hardwick, P. and Gunn, J., 1999. Sediment dynamics in the Castleton karst, Derbyshire, UK. Earth Surface Processes and Landforms, 24(8): 745-759.

Boyer, D.G. and Kuczynska, E., 2003. Storm and seasonal distributions of fecal coliforms and Cryptosporidium in a spring. Journal of the American Water Resources Association, 39(6): 1449-1456.

Brancelj, A., 2006. The epikarst habitat in Slovenia and the description of a new species. Journal of Natural History, 40(7-8): 403-413.

Bretz, J.H., 1942. Vadose and Phreatic Features of Limestone Caves. Journal of Geology, 50: 679-811.

Carling, P.A., Hoffmann, M., and Blatter, A.S., 2002. Initial motion of boulders in bedrock channels. Water Science and Application, 5: 147-160.

Chandler, D.G. and Bisogni, J.J., 1999. The use of alkalinity as a conservative tracer in a study of near-surface hydrologic change in tropical karst. Journal of Hydrology, 216(3-4): 172-182.

Davis, R.K., Hamilton, S. and Van Brahana, J., 2005. Escherichia coli survival in mantled karst springs and streams, northwest Arkansas Ozarks, USA. Journal of the American Water Resources Association, 41(6): 1279-1287.

Dell'Oca, S., 1961. Riempimenti naturali di grotte: Rassegna Speleologica Italiana, Como, Italy, 277 pp.

Dogwiler, T. and Wicks, C.M., 2004. Sediment entrainment and transport in fluviokarst systems. Journal of Hydrology, 295(1-4): 163-172.

Drysdale, R., Pierotti, L., Piccini, L. and Baldacci, F., 2001. Suspended sediments in karst spring waters near Massa (Tuscany), Italy. Environmental Geology, 40(8): 1037-1050.

Dussart-Baptista, L., Massei, N., Dupont, J.P. and Jouenne, T., 2003. Transfer of bacteria-contaminated particles in a karst aquifer: evolution of contaminated materials from a sinkhole to a spring. Journal of Hydrology, 284(1-4): 285-295.

Einsiedl, F., 2005. Flow system dynamics and water storage of a fissured-porous karst aquifer characterized by artificial and environmental tracers. Journal of Hydrology, 312(1-4): 312-321.

Exley, S, 1994. Caverns Measureless to Man. Cave Books, St. Louis, Missouri, 325 pp.

Fairchild, I.J., Killawee, J.A., Hubbard, B. and Dreybrodt, W., 1999. Interactions of calcareous suspended sediment with glacial meltwater: a field test of dissolution behaviour. Chemical Geology, 155(3-4): 243-263.

Farr, M., 1991. The Darkness Beckons. Cave Books, St. Louis, Missouri, 280 pp.

Frank, R., 1966. Petrologic study of sediments from selected central Texas caves. Bulletin - Houston Geological Society, 8(8): 16-17.

Frank, R., 1969. The clastic sediments of Douglas Cave, Stuart Town, New South Wales. Helictite 7(1): 3-13.

Frank, R., 1971. The clastic sediments of the Wellington Caves, New South Wales. *Helictite 9(1): 3-26.*

Gillieson, D., 1986. Cave sedimentation in the New Guinea Highlands. Earth Surface Processes and Landforms, 11(5): 533-543.

Graf, W.H., 1971. Hydraulics of Sediment Transport. McGraw-Hill, New York, 513 pp.

Granger, D.E., Fabel, D. and Palmer, A.N., 2001. Pliocene-Pleistocene incision of the Green River, Kentucky determined from radioactive decay of cosmogenic ^{26}Al and ^{10}Be in Mammoth Cave Sediments. Geological Society of America Bulletin, 113: 825-836.

Grimm, M.M., Wohl, E.E. and Jarrett, R.D., 1995. Coarse-sediment distribution as evidence of an elevation limit for flash flooding, Bear Creek, Colorado. Geomorphology, 14(3): 199-210.

Gutierrez, M., Neill, H. and Grand, R.V., 2004. Metals in sediments of springs and cave streams as environmental indicators in karst areas. Environmental Geology, 46(8): 1079-1085.

Gutierrez-Santolalla, F., Gutierrez-Elorza, M., Marin, C., Desir, G. and Maldonado, C, 2005. Spatial distribution, morphometry and activity of La Puebla de Alfinden sinkhole field in the Ebro river valley (NE Spain): applied aspects for hazard zonation. Environmental Geology, 48(3): 360-369.

Hart, E.A. and Schurger, S.G., 2005. Sediment storage and yield in an urbanized karst watershed. Geomorphology, 70(1-2): 85-96.

Herman, E.K., Tancredi, J.H., Toran, L. and White, W.B., in press. Mineralogy of suspended sediment in three karst springs. Hydrogeology Journal.

Herman, E.K., Toran, L., and White, W.B., submitted. Quantifying the place of karst aquifers in the groundwater to surface water continuum: a time series analysis study of storm response in Pennsylvania water resources. Journal of Hydrology.

Herman, E.K., Toran, L., and White, W.B., in preparation. Threshold events in spring discharge: evidence from sediment and continuous water level measurements.

Hess, J.W. and White, W.B., 1988. Storm response of the karstic carbonate aquifer of southcentral Kentucky. Journal of Hydrology 99:235-252.

Iverson, R.M. and Vallance, J.W., 2001. New views of granular mass flows. Geology 29: 115-118.

James, J.M., 1993. Burial and infilling of a karst in Papua-New-Guinea by road erosion sediments. Environmental Geology, 21(3): 144-151.

Jennings, J.N., 1971. Karst. The M.I.T. Press, Cambridge, MA, 252 pp.

Jones, W.K., Culver, D.C. and Herman, J.S., 2003. Epikarst. Karst Waters Institute Special Publication 9, 160 pp.

Kiernan, K., Lauritzen, S.E. and Duhig, N., 2001. Glaciation and cave sediment aggradation around the margins of the Mt Field Plateau, Tasmania. Australian Journal of Earth Sciences, 48(2): 251-263.

Kochel, R.C., Baker, V.R. and Patton, P.C., 1982. Paleohydrology of southwestern Texas. Water Resources Research, 18(4): 1165-1183, Kogovsek, J. and Sebela, S., 2004. Water tracing through the vadose zone above Postojnska Jama, Slovenia. Environmental Geology, 45(7): 992-1001.

Lakey, B. and Krothe, N.C., 1996. Stable isotopic variation of storm discharge from a perennial karst spring, Indiana. Water Resources Research, 32(3): 721-731.

Lee, E.S. and Krothe, N.C., 2001. A four-component mixing model for water in a karst terrain in south-central Indiana, USA. Using solute concentration and stable isotopes as tracers. Chemical Geology, 179(1-4): 129-143.

Loop, C.M. and White, W.B., 2001. A conceptual model for DNAPL transport in karst ground water basins. Ground Water, 39(1): 119-127.

Mahler, B.J., Bennett, P.C. and Zimmerman, M., 1998. Lanthanide-labeled clay: A new method for tracing sediment transport in karst. Ground Water, 36(5): 835-843.

Mahler, B.J. and Lynch, F.L., 1999. Muddy waters: temporal variation in sediment discharging from a karst spring. Journal of Hydrology, 214(1-4): 165-178.

Mahler, B.J., Personne, J.C., Lods, G.F. and Drogue, C., 2000. Transport of free and particulate-associated bacteria in karst. Journal of Hydrology, 238(3-4): 179-193.

Massei, N., Lacroix, M., Wang, H.Q., Mahler, B.J. and Dupont, J.P., 2002. Transport of suspended solids from a karstic to an alluvial aquifer: the role of the karst/alluvium interface. Journal of Hydrology, 260(1-4): 88-101.

Massei, N., Wang, H.Q., Dupont, J.P., Rodet, J. and Laignel, B., 2003. Assessment of direct transfer and resuspension of particles during turbid floods at a karstic spring. Journal of Hydrology, 275(1-2): 109-121.

Murray, A.S., Stanton, R., Olley, J.M. and Morton, R., 1993. Determining the origins and history of sedimentation in an underground river system using natural and fallout radionuclides. Journal of Hydrology, 146(1-4): 341-359.

Palmer, A.N., 1991. Origin and morphology of limestone caves. Geological Society of America Bulletin, 103(1): 1-21.

Panno, S.V., Hackley, K.C., Hwang, H.H. and Kelly, W.R., 2001. Determination of the sources of nitrate contamination in karst springs using isotopic and chemical indicators. Chemical Geology, 179(1-4): 113-128.

Pipan, T., Blejec, A. and Brancelj, A., 2006. Multivariate analysis of copepod assemblages in epikarstic waters of some Slovenian caves. Hydrobiologia, 559: 213-223.

Renault, P., 1967. Contribution a l'etude des actions mecaniques et sedimentologique dans la speleogenese; premiere partie, Les actions mecaniques a l'echelle du massif. Mechanical and sedimentologic action in speleogenesis; part 1, Mechanical action on the massif scale. Annales de Speleologie, 22(2): 209-267.

Renault, P., 1968. Contribution a l'etude des actions mecaniques et sedimentologiques dans la speleogenese; deuxieme partie, Les effets mecaniques a l'echelle de la cavite. Mechanical and sedimentologic action in speleogenesis; part 2, Mechanical effects at the cavity scale. Annales de Speleologie, 23(1): 259-307.

Ryan, M. and Meiman, J., 1996. An examination of short-term variations in water quality at a karst spring in Kentucky. Ground Water, 34(1): 23-30.

Sasowsky, I.D., White, W.B. and Shmidt, V.A., 1995, Determination of stream-incision rate in the Appalachian plateaus by using cave-sediment magnetostratigraphy. Geology, 23(5): 415-418.

Sasowsky, I.D., Sebela, S. and Harbert, W., 2003. Concurrent tectonism and aquifer evolution > 100,000 years recorded in cave sediments, Dinaric karst, Slovenia. Environmental Geology, 44(1): 8-13.

Schmid, E., 1958. Höhlenforschung und Sedimentanalyse, Schriften des Institutes für Ur- und Frühgeschichte der Schweiz, 13, 186 pp.

Schmidt, V.A., 1982. Magnetostratigraphy of sediments in Mammoth Cave Kentucky. Science 217:827-829.

Shevenell, L. and McCarthy, J.F., 2002. Effects of precipitation events on colloids in a karst aquifer. Journal of Hydrology, 255(1-4): 50-68.

Shuster, E.T. and White, W.B., 1971. Seasonal fluctuations in the chemistry of limestone springs; a possible means for characterizing carbonate aquifers. Journal of Hydrology 14(2): 93-128.

Springer, G.S. and Kite, J.S., 1997. River-derived slackwater sediments in caves along Cheat River, West Virginia. Geomorphology, 18(2): 91-100.

Sweeting, M.M., 1972. Karst Landforms. Macmillan, London, 362 pp.

Toran, L., Herman, E.K., and White, W.B., in press. Comparison of flow paths to a well and spring in a karst aquifer. Groundwater.

Toran, L., Tancredi, J.H., Herman, E.K., and White, W.B., 2006. Conductivity and sediment variation during storms as evidence of pathways in karst springs. In *Perspectives on karst geomorphology, hydrology, and geochemistry – A tribute volume to Derek C. Ford and William B. White*, R.S. Harmon and C. Wicks, Eds., Geological Society of America Special Paper, 404: 169-176.

Vanoni, V.A., 1975. Sedimentation Engineering. American. Society of Civil Engineers, New York, 745 pp.

Vesper, D.J. and White, W.B., 2003. Metal transport to karst springs during storm flow: an example from Fort Campbell, Kentucky/Tennessee, USA. Journal of Hydrology, 276(1-4): 20-36.

Vesper, D.J. and White, W.B., 2004. Spring and conduit sediments as storage reservoirs for heavy metals in karst aquifers. Environmental Geology, 45(4): 481-493.

White, W.B., in press. Cave sediments and paleoclimate. Journal of Cave and Karst Studies.

White, W.B. and White, E.L., 1968. Dynamics of sediment transport in limestone caves. Natl. Speleol. Soc. Bull., 30: 115-129.

Wolfe, T.E., 1973. Sedimentation in karst drainage basins along the Allegheny Escarpment in southeastern West Virginia, U.S.A. Ph.D. thesis, McMaster University, 455 pp.

Chapter 3

Quantifying the place of karst aquifers in the groundwater to surface water continuum: a time series analysis study of storm response in Pennsylvania water resources

Abstract

Though karst aquifers have commonly been identified as intermediate between ground and surface water, their putative location between these end members is generally descriptive rather than quantitative. Autocorrelation and spectral analysis of data from four karst springs, three wells, and eight stream gauges in Pennsylvania illustrate that specific karst water resources exhibit widely varying inertia with lag times that overlap those of groundwater and surface water.

The four springs display characteristic lag times ranging from 5 to 25 days, compared to 1 to 10 days for streams and 11 to 46 days for wells. Regulation times (impulse persistence) for springs ranged from 2 to 4 days, while streams ranged from 0.6 to 5 days and wells from 3 to 8 days. Physically, karst waters may behave as a mix of porous media, fracture, and open-channel flow, but in temporal terms the balance of this mix results in a range of system response times.

Our comparison of water resources across different time periods revealed that the period considered can have strong effects on results. One spring displayed characteristic lag times of 12 and 25 days for two different time spans. To directly compare water resources over relatively short time scales, precipitation inputs must be similar and data

sets must cover the same period; otherwise, substantial differences in lag and regulation times can be due to data collection differences rather than system characteristics.

Introduction

Many investigators have considered how a karst aquifer alters a storm signal between recharge and spring (Brown, 1973; Dreiss, 1982, 1983, 1989a, 1989b; Mangin, 1984; De Vera, 1984; Padilla and Pulido-Bosch, 1995; Eisenlohr et al., 1997a, b; Halihan et al., 1998; Halihan and Wicks, 1998; Larocque et al., 1998; Bouchaou et al., 2002; Amraoui et al., 2003; Denic-Jukic and Jukic, 2003; Rahnemaei et al., 2005). The storm signal in turn has been used to deduce source waters and aquifer structure (e.g., Smart, 1988; Desmarais and Rojstaczer, 2002; Birk et al., 2004). The time-invariant transfer function is appealing for its simplicity and its method of combining all storms across the monitored time series into a single signal. Non-linear time variant analysis, such as wavelet transforms, further define rainfall-runoff relationships in karst springs and may enable better prediction of input-output relations where non-stationary behavior may occur (Lambrakis et al., 2000; Beaudeau et al. 2001; Labat et al., 2000; Labat et al., 2001; Labat et al., 2002; Majone et al., 2004; Dryden et al. 2005). However, in comparing systems with substantially different signal magnitudes, time invariant transfer functions remain very useful.

Mangin (1984) first applied the calculation of autocorrelation to karst springs in the Pyrenées, characterizing their inertia to assess the time a signal persisted in the system. Additional studies have employed similar techniques with some adding cross-correlation between precipitation and other variables such as discharge and turbidity (De Vera, 1984; Jemcov et al., 1998-1999; Bouchaou et al., 2002; Amraoui et al., 2003; Denic-Jukic and Jukic, 2003; Massei et al., 2006). In the groundwater literature, autocorrelation and cross-correlation are only rarely employed to describe storm responses in wells, largely due to high inertia and long regulation times evident in most wells (Lee and Lee, 2000; Rademacher et al., 2002); these techniques are however implemented in groundwater settings with higher frequency variations like coastal aquifers and wells subject to earth tides (Shih and Lin, 2002; Marechal et al., 2002; Shih et al., 1999). In surface water study, autocorrelation has been used for several decades to characterize catchment response to storms, and has recently been used by climate scientists attempting to separate trends from autocorrelation in long-term stream flow signals (e.g., Yue et al., 2002; Potts et al., 2003; Labat et al., 2004; Coulibaly and Burn, 2005; Kallache et al., 2005; Pagano et al., 2005).

This study focuses on autocorrelation of high-frequency flow and stage data from karst springs, wells, and streams in Pennsylvania. Multiple sites with different characteristics were studied to discover where the karst springs fit in among the groundwater wells and surface streams in terms of inertia. The consistent assumption among hydrogeologists is that streams pass storm signals very quickly, but signals in wells, if present, persist across long periods. We examine this assumption and consider if karst springs fit in the middle, as often described (White, 1988; Ford and Williams, 1989; White, 2002; Lee and Lee, 2000; Pinault et al., 2001; Denic-Jukic and Jukic, 2003; Quinn et al., 2006).

Methods

A time series data set can be separated into two components, overall trend and autocorrelation. Autocorrelation defines the dependence of a data point on prior points. Many climate-oriented hydrologists are interested in removing the autocorrelation of time series to examine the trend in climatic data over time; conversely, the autocorrelation portion of the series, once the trend is removed, reveals important information about the system itself in terms of temporal response to perturbation. Mangin (1984) first popularized the autocorrelation approach of Box and Jenkins (1976) as a measure of system inertia in karst, defining autocorrelation as follows:

$$r_k = \frac{\sum_{i=1}^{n-k}(x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^{n}(x_{i+k} - \bar{x})^2} \qquad \textbf{3.1}$$

where r_k is the autocorrelation coefficient at any point in the series, k is a point in the series, x is the data series with the trend removed, and $\bar{x}$ is the arithmetic mean of the series (Padilla and Pulido-Bosch, 1995; Eisenlohr et al., 1997b; Larocque et al. 1998; Amraoui et al., 2003). The slope of the autocorrelation function illustrates whether individual data points have long-term effects on the entire data series. Because individual rainfall measurements have little to no effect on the preceding and subsequent measurements, the autocorrelation function drops off quickly indicating that precipitation has low inertia. Nonetheless, a karst spring with high storage would be expected to manifest an autocorrelation function with a low slope as an individual measurement of water level should be closely related to subsequent and previous measurements. The characteristic lag time is the lag at which the correlation coefficient, r_k, is equal to 0.2, allowing comparison of different systems (Mangin, 1984). A system where individual measurements are closely related to other measurements will have a longer characteristic lag indicating greater inertia. Below 0.2, the autocorrelation coefficient r_k is essentially identical to the autocorrelation of noise (Mangin, 1984).

Another way of examining the autocorrelation function involves transforming the correlogram of a time series (the function r_k over a series of time lags) into the frequency domain as the following spectral density function:

$$S_f = 2\left[1 + 2\sum_{k=1}^{m} D_k r_k \cos(2\pi f k)\right] \qquad \textbf{3.2}$$

$$D_k = \frac{1}{2}\left(1 + \cos\pi\frac{k}{m}\right) \qquad \textbf{3.3}$$

where f is a given frequency and D_k is the Tukey filter (Larocque et al. 1998; Amraoui et al., 2003).

The regulation time (T_{reg}) of the system determines the impulse response or the length of time the input signal persists in the system. T_{reg} allows comparison of different data series by quantifying the point when the spectral density of the autocorrelation function approaches zero. There is ambiguity in the calculation of T_{reg} in the literature. Some calculate T_{reg} by determining the frequency where the maximum spectral density is reduced by half and inverting that frequency to yield T_{reg} (Larocque et al., 1998). Others use the inverse of a break frequency where spectral density drops off to a certain value (Lee and Lee, 2000; Bouchaou et al., 2002). For the purposes of this study, the second approach is employed, where the break frequency is reached at a spectral density of 0.1% of the maximum. The two measures, time lag and T_{reg}, provide independent measures of memory in the system, but T_{reg} is less sensitive to the sampling interval and correlation between distant events (Larocque et al., 1998).

Site Selection & Data Description

Springs

Four springs in Pennsylvania were monitored for inclusion in this study, Arch Spring in Blair County, Nolte Spring in Lancaster County, and Tippery Spring and Near Tippery Spring in Huntingdon County (Figure **3-1**). Instruments were installed at Nolte Spring from the fall of 2002 through the fall of 2004; at Arch Spring from winter of 2002 to spring of 2005; and at Tippery and Near Tippery from summer of 2004 to winter of 2005. These sites were selected for their varying baseflow discharges (from 0.04 to 0.5 m^3/s) and drainage areas (from 3 to 25 km^2). Key characteristics of each site including drainage basin area, baseflow, periods analyzed, and recording intervals are presented in Table **3-1**a. Portions of the monitoring record at the springs were not used in this study either because the data had substantial gaps or irregularities that could not be corrected.

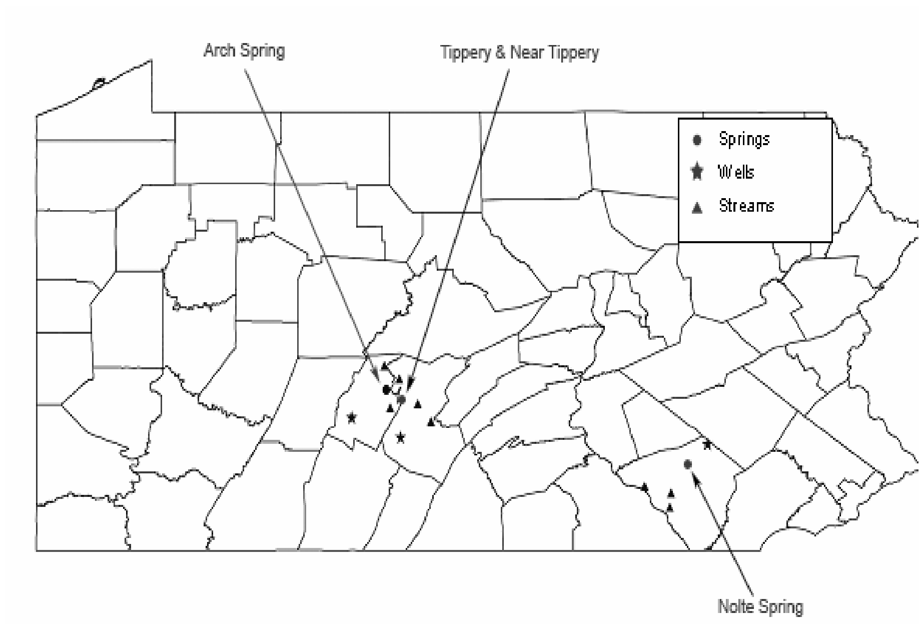


Figure **3-1**: Location map of Pennsylvania with four springs, three wells, and eight gauging stations, county outlines

Table 3-1: Spring, stream, and well characteristics for 15 monitoring sites

a) Springs

Name	PA County	Drainage Area (km^2)	Estimated baseflow (m^3/s)	Periods Analyzed	Recording Interval (min)
Arch Spring	Blair	25	0.5	01/2003 to 12/2003 01/2004 to 12/2004	20 15
Near Tippery Spring	Huntingdon	3	0.04	08/2004 to 05/2005	15
Tippery Spring	Huntingdon	4.1	0.14	08/2004 to 05/2005	15
Nolte Spring	Lancaster	10	0.04	02/2003 to 12/2003	20

b) Streams

Name	PA County	Drainage Area (km^2)	Average annual discharge (m^3/s)	Periods Analyzed	Recording Interval (min)
Bald Eagle Creek at Tyrone	Blair	144.2	2.2 (1945 to 2003)	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Frankstown Branch, Juniata River at Williamsburg, PA	Blair	754	11 (1917 to 2003)	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Juniata River at Huntingdon, PA	Huntingdon	2113	31 (1942 to 2003)	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Juniata River at Mapleton Depot, PA	Huntingdon	5258	72 (1938 to 2003)	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Little Juniata River at Spruce Creek, PA	Huntingdon	570	11 (1939 to 2003)	01/2004 to 12/2004 08/2004 to 05/2005	60
Conestoga River at Conestoga, PA	Lancaster	1217	18 (1985 to 2003)	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Little Conestoga Creek near Millersville, PA	Lancaster	109.6	2.2 (2003 to 2004)	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Susquehanna River at Marietta, PA	Lancaster	67314	1055 (1932 to 2003)	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60

c) Wells

Name	PA County	Geologic Unit of Completion	Length of Open Interval (m)	Periods Analyzed	Recording Interval (min)
Blair County Observation Well USGS BA-74	Blair	Brallier Formation	41	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Huntingdon County Observation Well USGS HU-301	Huntingdon	Pocono Formation	27	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60
Lancaster County Observation Well USGS LN-1351	Lancaster	Hammer Creek Formation	25	01/2003 to 12/2003 01/2004 to 12/2004 08/2004 to 05/2005	60

Each site was equipped with monitoring equipment designed to capture long-term data sets. A Global Water 8-channel logger recorded specific conductance, stage, and temperature at sub-hourly intervals; a sample data set is presented in Figure 3-2. A stormwater sampler was also in place at each site, but those data are not presented here. Site visits spaced up to one month apart confirmed logged conductivity, stage, and temperature values. Hourly precipitation data for the spring areas are available from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) webpage (www.ncdc.noaa.gov).

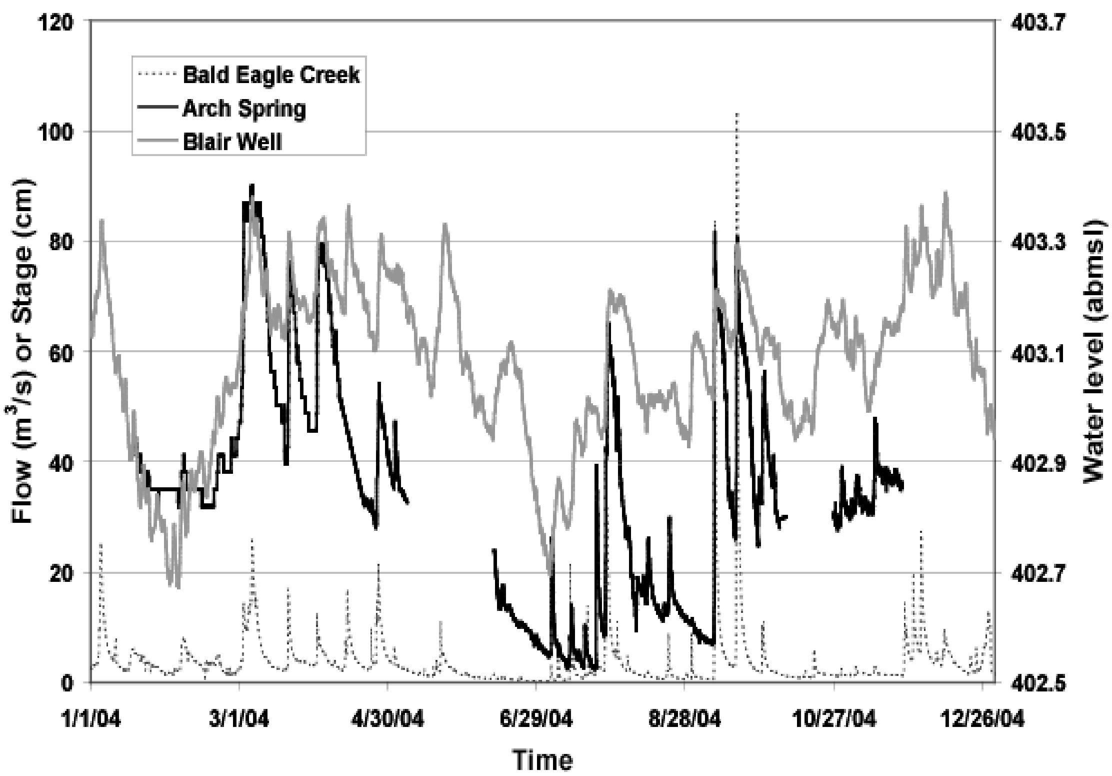


Figure 3-2: Example plot of 2004 data from Blair County water resources: interpolated water level from Arch Spring; interpolated discharge from Bald Eagle Creek at Tyrone; and interpolated water level data from the Blair County drought monitoring well. The gaps in the Arch Spring data in May and October resulted from instrument down time.

Streams

The U.S. Geological Survey (USGS) maintains 532 stream gauge stations in Pennsylvania to measure stage and flow along surface streams, and eight of their gauging stations are in the counties where the springs were located: Blair, Huntingdon, and Lancaster. These streams represent a wide range of baseflow and drainage basin values. All eight gauging stations were considered in the course of this study. Figure **3-1** presents their location; Figure 3-2 illustrates a sample stream data set; and Table 3-1b their relevant characteristics. The gauge on the Little Juniata at Spruce Creek did not consistently record hourly data until the beginning of 2004; as such, data from 2003 are not considered.

Wells

The USGS and Commonwealth of Pennsylvania maintain drought monitoring wells in each of the 67 counties in the state. These wells are sited so as to minimize interference from groundwater pumping systems. The wells are monitored hourly for depth to water (Figure 3-2). Figure 3-1 shows the location of the three county wells used in this study; the wells are sited in the counties where the springs are located. Table 3-1c presents relevant information for the three wells including duration of monitoring, depth of open interval, and formation in which well was completed.

Geology of Spring & Well Systems

The four karst springs occur in Ordovician Carbonates, with Arch Spring outcropping in the Grazier member of Hatter formation, the lowest unit in the Black River Group. Nolte Spring rises in the Epler formation of the Beekmantown group of mixed limestones and dolomites. The Tippery Springs occur in the Benner formation (Berg 1980).

The drought-monitoring wells were sited by the USGS in clastic rocks, not karst formations. For Blair County, the well is drilled into the Devonian Brallier Shale. The Huntingdon County well is cased in the Mississippian Pocono Formation, a mix of conglomerate and dense sandstones. The Lancaster Well is drilled into the sandstones of the Triassic Hammer Creek formation. These wells were sited by the Commonwealth and the USGS with the intent of avoiding interference from other wells and groundwater exploitation in the area.

Data Manipulation

All data sets as collected showed trends in baseflow or well level. For the purposes of this analysis, the autocorrelation must be calculated without the overall trend or the autocorrelation quantifies the trend rather than the impulse response that is the temporal variation away from the trend. A quadratic curve fitted to baseflow or well level was subtracted from each data set. The quadratic trend line represents seasonal fluctuation, as water resources tend to be low at the beginning of the year (also the beginning of most periods analyzed), rise through spring and fall again at the end of the year.

Some data sets had gaps in recording or periods of infrequent records. Because autocorrelation procedures require evenly spaced data, gaps were filled with white noise generated based on the time series mean and variance. Separate calculations of autocorrelation and frequency distribution on the generated white noise periods showed that the white noise added no "false inertia" to the systems as the autocorrelation for these periods always fell to below 0.2 within two lag units.

Results

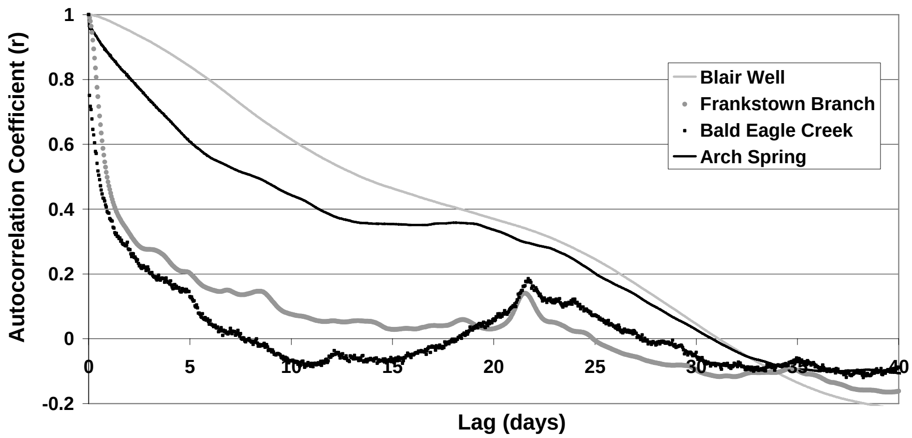
To ensure similarity of precipitation (impulse) input into each system considered, results are compared within each county of Pennsylvania analyzed. That is, the Blair County well is compared to Blair streams and Arch Spring. By examining springs, wells, and streams in similar climatic settings, we eliminate storm frequency considerations and rainfall pattern concerns among different water features. In addition to comparing water resources to others nearby, our results show that like periods must also be analyzed. When comparing a longer data set to a shorter data set, a greater number of storms can give the appearance of greater inertia in the system. As storm shape and response can be different in basins due to a number of factors such as recharge intensity, season, and antecedent conditions, comparing similar periods with the same or similar numbers of storms is essential unless data sets are very long (on the order of decades). Table 3-2 outlines how calculated system lag time is affected by several variations in data set length.

Figures **3-3** and **3-4** present results from Blair County for 2003 (Figure 3-3a & 3-3b) and 2004 (Figure 3-4a & 3-4b). Table **3-2** also outlines the time lags of interest for each of the systems. The autocorrelation function for Arch Spring and the Blair drought monitoring well were very similar both in 2003 and 2004 with gradual declines indicating that inertia is high for both systems, on the order of 12 to 25 days. Conversely, the two creeks show much shorter lag times of 2 to 5 days, and spectral density functions that show strong periodicities. Both these observations are consistent with the creeks having low inertia.

Table 3-2: Characteristic lag time where the auto-correlation function crosses the 0.2 coefficient value & regulation time of each system

Name	Period	Characteristic Lag (days)	T_{reg} (days)
Arch Spring	01/2003 to 12/2003	25.0	3.4
	01/2004 to 12/2004	12.5	3.7
Near Tippery Spring	08/2004 to 05/2005	6.7	1.9
Tippery Spring	08/2004 to 05/2005	5.6	2.4
Nolte Spring	02/2003 to 12/2003	15.1	4.4
Bald Eagle Creek at Tyrone	01/2003 to 12/2003	3.1	0.8
	01/2004 to 12/2004	2.0	0.9
	08/2004 to 05/2005	2.3	1.1
	08/2002 to 05/2005	3.2	N/A
Frankstown Branch, Juniata River at Williamsburg, PA	01/2003 to 12/2003	5.0	1.9
	01/2004 to 12/2004	1.9	1.6
	08/2004 to 05/2005	1.6	1.3
Juniata River at Huntingdon, PA	01/2003 to 12/2003	6.1	1.5
	01/2004 to 12/2004	2.5	1.3
	08/2004 to 05/2005	2.0	1.2
Juniata River at Mapleton Depot, PA	01/2003 to 12/2003	7.1	2.0
	01/2004 to 12/2004	10.0	3.0
	08/2004 to 05/2005	9.3	2.4
	08/2002 to 05/2005	9.5	N/A
Little Juniata River at Spruce Creek, PA	01/2004 to 12/2004	1.9	1.0
	08/2004 to 05/2005	1.7	0.8
Conestoga River at Conestoga, PA	01/2003 to 12/2003	2.0	1.4
	01/2004 to 12/2004	1.3	0.8
	08/2004 to 05/2005	1.9	0.9
Little Conestoga Creek near Millersville, PA	01/2003 to 12/2003	1.0	0.6
	01/2004 to 12/2004	0.7	0.6
	08/2004 to 05/2005	1.0	0.7
Susquehanna River at Marietta, PA	01/2003 to 12/2003	8.8	5.0
	01/2004 to 12/2004	5.3	2.5
	08/2004 to 05/2005	9.1	3.0
	08/2002 to 05/2005	9.9	N/A
Blair County Observation Well USGS BA-74	01/2003 to 12/2003	26.2	9.0
	01/2004 to 12/2004	19.1	4.0
	08/2004 to 05/2005	11.2	3.0
	08/2002 to 05/2005	35.0	N/A
Huntingdon County Observation Well USGS HU-301	01/2003 to 12/2003	23.1	4.4
	01/2004 to 12/2004	21.3	4.2
	08/2004 to 05/2005	11.9	4.2
	08/2002 to 05/2005	30.6	N/A
Lancaster County Observation Well USGS LN-1351	01/2003 to 12/2003	23.8	5.6
	01/2004 to 12/2004	14.5	4.1
	08/2004 to 05/2005	11.3	4.2
	08/2002 to 05/2005	36.2	N/A

a)



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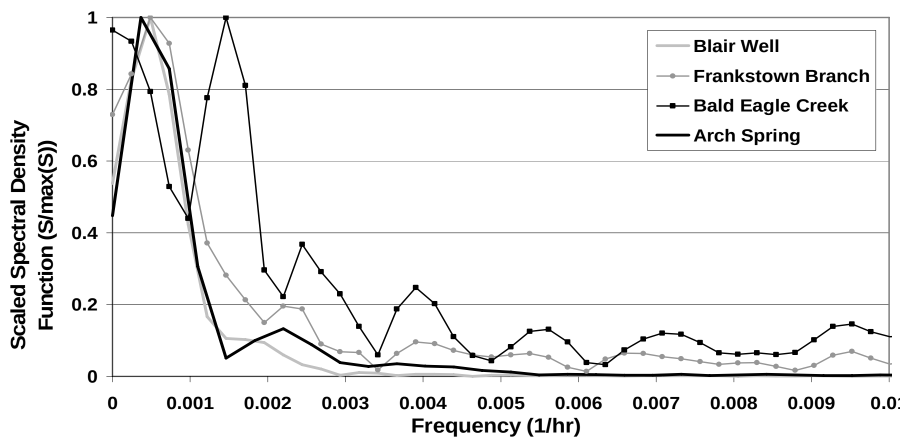
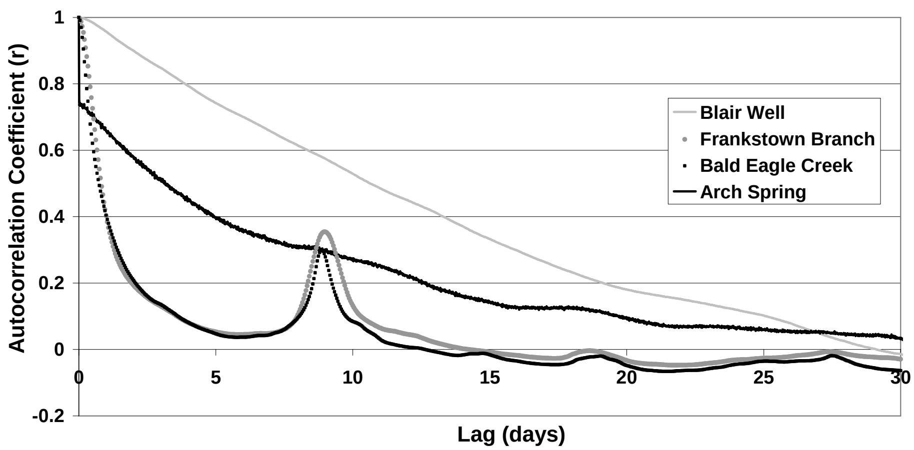
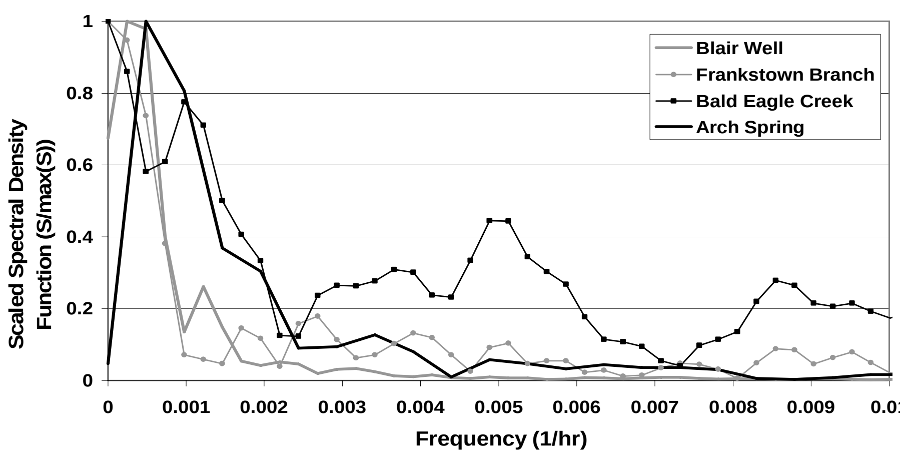


Figure 3-3: a) Plot of 2003 autocorrelation functions for water resources in Blair County: Arch Spring; Bald Eagle Creek at Tyrone; Frankstown Branch of the Juniata River at Williamsburg; and the Blair County drought monitoring well.

b) Plot of 2003 scaled spectral density functions for water resources in Blair County: Arch Spring; Bald Eagle Creek at Tyrone; Frankstown Branch of the Juniata River at Williamsburg; and the Blair County drought monitoring well.

a)





b)

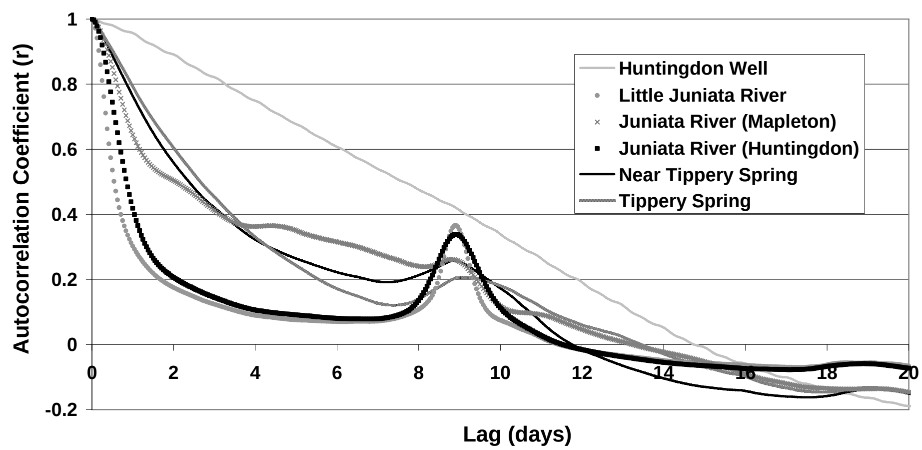
Figure 3-4: a) Plot of 2004 autocorrelation functions for water resources in Blair County: Arch Spring; Bald Eagle Creek at Tyrone; Frankstown Branch of the Juniata River at Williamsburg; and the Blair County drought monitoring well.

b) Plot of 2004 spectral density functions for water resources in Blair County: Arch Spring; Bald Eagle Creek at Tyrone; Frankstown Branch of the Juniata River at Williamsburg; and the Blair County drought monitoring well.

The effects of Hurricanes Frances, Ivan, and Jeanne are visible in the stream autocorrelations and frequency spectrum from 2004 with a strong periodicity at ~8 days. These three large storms came through in quick succession from September 9, 2004 to October 1, 2004. Each storm brought rains of at least 4 cm in a single 24-hour period, with Hurricane Ivan producing some of the worst flooding in Central Pennsylvania since Hurricane Agnes in 1972. Large storms like these can increase the signal of autocorrelation function such that ordinary impulse response is obscured, but in the case of these water resources, the autocorrelation function increase yielded by the hurricanes does not interfere with crossing point of the 0.2 threshold.

Figure **3-5** and Figure **3-6** and Table 3-3 present the autocorrelations and spectral density functions of spring, stream, and well data from Huntingdon and Lancaster Counties, respectively. The small Near Tippery and Tippery Springs display inertia similar to surface water resources within Huntingdon County and have shorter regulation times than the other springs. The Huntingdon County well showed a longer regulation time and much longer characteristic lag. The steeper slope of the spring and stream autocorrelation functions and the shallower slope of the well response illustrate these differences well. Nolte Spring, in contrast to Arch and the Tippery Springs, has inertia midway between surface and groundwater resources in the Lancaster County. The regulation time at Nolte Spring also falls between the streams and groundwater during 2003, with the exception of the Susquehanna at Marietta. Although the Susquehanna, with the highest flow in the system, has a longer regulation time than the spring, the shape of the autocorrelation function is similar to the faster responding streams.

a)



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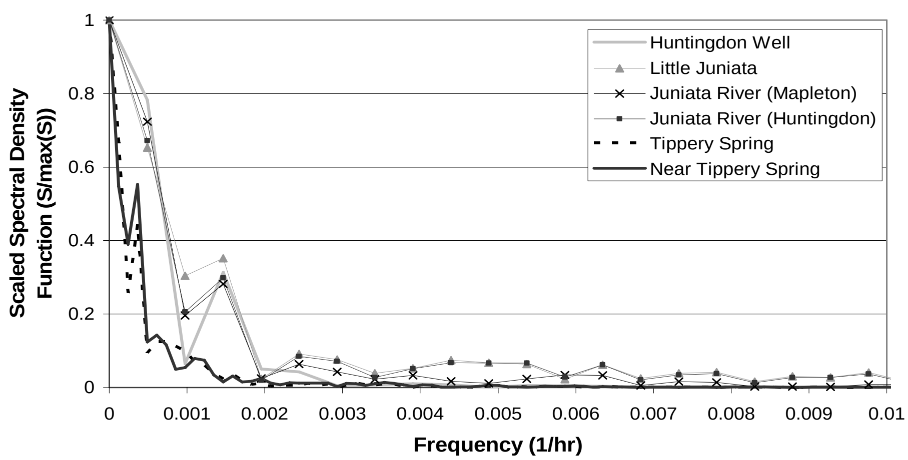
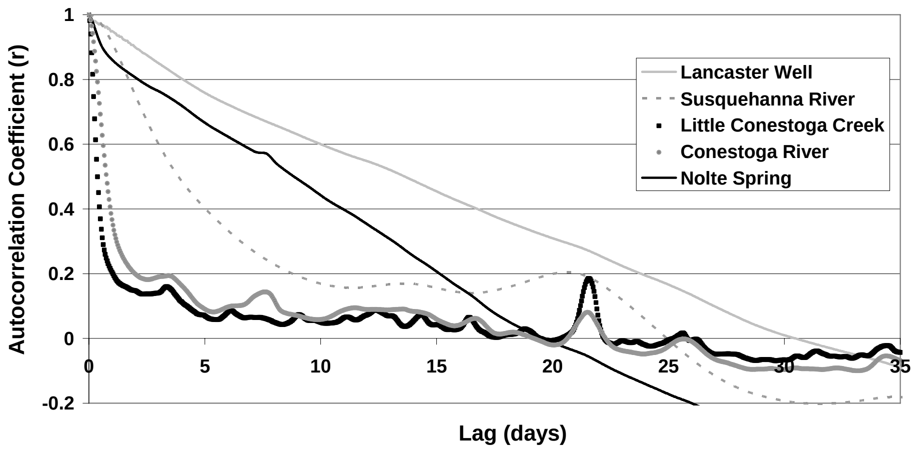


Figure 3-5: a) Plot of autocorrelation functions for Huntingdon County water resources from August 2004 to May 2005: Near Tippery Spring; Tippery Spring; Juniata River at Huntingdon; Juniata River at Mapleton Depot; Little Juniata River at Spruce Creek; and the Huntingdon County drought monitoring well.

b) Plot of scaled spectral density functions for Huntingdon County water resources from August 2004 to May 2005: Near Tippery Spring; Tippery Spring; Juniata River at Huntingdon; Juniata River at Mapleton Depot; Little Juniata River at Spruce Creek; and the Huntingdon County drought monitoring well.

a)



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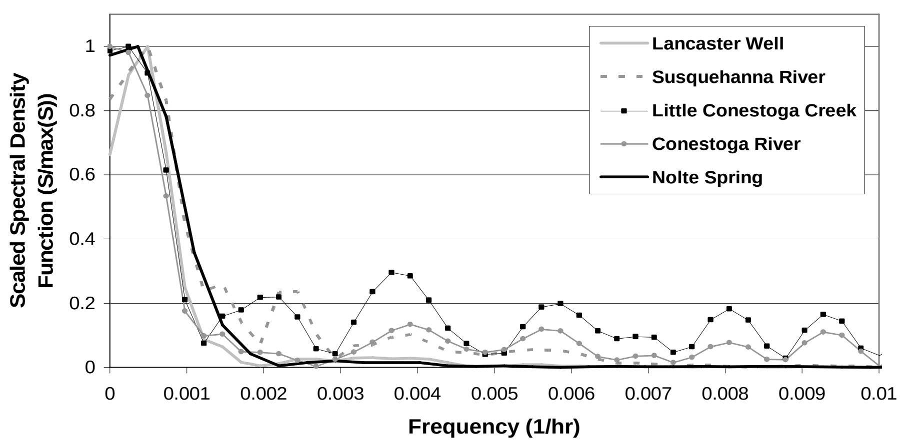


Figure 3-6: a) Plot of 2003 autocorrelation functions for water resources in Lancaster County: Nolte Spring, Conestoga River at Conestoga; Little Conestoga Creek near Millersville; Susquehanna River at Marietta; and the Lancaster County drought monitoring well.

b) Plot of 2003 scaled spectral density functions for water resources in Lancaster County: Nolte Spring, Conestoga River at Conestoga; Little Conestoga Creek near Millersville; Susquehanna River at Marietta; and the Lancaster County drought monitoring well.

Discussion & Implications

Taken as separate groups, the springs, wells, and streams generally showed internally consistent characteristic lags and impulse response. First, system response within groups is described, then comparisons among groups are made.

Springs

In the karst springs, the largest system Arch Spring showed the greatest inertia with storm effects of long duration, in spite of the "flashy" appearance of the hydrograph (see Figure 3-2) and an open cave system with swiftly moving water. The ability of autocorrelation to quantify responses that we term as "flashy," based on qualitative hydrograph interpretation, may be one of the procedure's most useful applications. Arch Spring's very long characteristic lag time and moderate regulation time are likely due to the morphology of the upstream cave rather than the size of the drainage basin. The cave undulates rising and falling through the water table so that portions of the cave are water-filled and others have a substantial free surface flow. These changing hydraulic regimes appear to have effects on the sediment transport (data not reported here) and the spring response to very large storms. The undulations may also increase the duration of the characteristic lag time by providing longer flow paths. We are undertaking modeling of the cave system with a computational fluid dynamics code to determine if the lag time can be controlled by the addition of changing flow regimes.

Nolte Spring has lower discharge than Tippery or Near Tippery Springs but showed a longer lag time and impulse response. However, the aquifer behind Nolte has been previously characterized as diffuse with few points of direct recharge, and storm responses there were observed to be dependent on the intensity of recharge (Tancredi, 2004; Toran and White, 2005). The diffuse nature of Nolte is consistent with long response signals despite its small size.

Near Tippery and Tippery Springs are close in size, though Tippery generally has flow roughly 1.5 times that of Near Tippery. Near Tippery has historically shown less seasonal variation in specific conductance and temperature, and generally specific conductance is higher at Near Tippery than Tippery (current observations; Shuster and White, 1971; Hull, 1980). Near Tippery has been characterized as more diffuse than Tippery though both flows are substantially fed by quick recharge into sinkholes (Shuster and White, 1971). The slightly longer characteristic lag at Near Tippery Spring of 6.74 days compared to 5.55 days for Tippery Spring may reflect this more diffuse flowpath, but the two springs are very similar in temporal terms, and there is little difference between the two springs in inertia.

Streams

Autocorrelation of stream gauge data yielded a complex set of relationships. In general, a larger stream will have a longer autocorrelation time, and more of the signal is attributable to high frequency waves. However, this is not a uniform or a linear relationship. The Susquehanna River at Marietta has a basin area an order of magnitude higher than the next largest stream and average flow almost two orders of magnitude higher, but the characteristic lag time for the Susquehanna basin is not always the greatest and in most cases is within the same order of magnitude for streams even 30 times smaller. To explain the variation in lag times among the streams, additional factors must play controlling roles. Evapotranspiration, water retention in flood control reservoirs, and dams can either increase or decrease discharge, and thus play a controlling role in addition to the dynamics of fluid flow in response to impulses.

Wells

The results for the wells appear to be similar, and all three wells are completed in clastic rock. The differences in lithology (shale versus sandstone) did not result in distinct differences. The swiftly dropping spectral density functions and long regulation times for the wells indicate that the variability in the wells occurred at low frequencies. The gradual drop in the autocorrelation curve results from strong positive association between successive data points, i.e., strong inertia. All of the wells showed a strong direct dependence on data set length in inertial terms with longer data sets showing longer inertia. See Table 3-2.

Comparing Water Resource Groups

In general, characteristic lag times of spring water level were intermediate between the well and stream characteristic lag times. Examination of the spectral density function also shows that wells are the most likely water resources to have spectral density in the low frequencies and show strong dependency from one measurement to the next. Springs showed a wide range of characteristic lag times, and this range can be explained by the varying physical characteristics of the spring systems. Arch Spring, with its undulating cave system, exhibits both quick flow and longer residence time because of the length of the cave system. Tippery and Near Tippery have sinkholes in the recharge area, and thus the quick flow path influences the shape of the response. The conduit system is not as well developed or as extensive, so the response times are not as long as at Arch. Nolte Spring has more diffuse recharge and enlarged fractures rather than conduits. Thus the response is more similar to groundwater (longer and more gradual slopes). It is, however, evident from these results that the physical structures of spring systems or any water resources cannot be deduced from comparing the autocorrelation functions and spectral density functions alone. Other factors that control spring response limit the applicability of this method for interpretations of physical structure.

Autocorrelation can quantify responses in disparate systems, but care should be taken when selecting and processing data sets. The length of data sets, the number of storms in the set, and large magnitude storms all affected the autocorrelation and spectral density function results for these water resources. The effects are not simple to deduce and filter out; for example, expanding a data set from calendar year 2003 to August 2002 to May 2005, increased the lag times in some systems, but decreased those observed in others (Table 3-2). Therefore, it is more useful to compare different water resources in similar climatic settings over similar time periods.

While controlling these issues makes for more useful discussions on autocorrelation and inertia, other system parameters need to be investigated over wide ranges to quantify their effect on inertia in the systems. In particular, though conventional wisdom assigns higher inertia to larger basins, there was an imperfect direct relationship between basin drainage size and inertia. Additional parameters need to be invoked and tested to explain this discrepancy. The type of recharge (diffuse versus concentrated) and extent of conduits influence response in the springs, and dams, water retention, and evapotransporation.

Conclusions

Though springs generally show system inertia somewhere between surface water's quick response and recovery and groundwater's greater inertia, some water resources like Arch Spring respond to storms with hydrograph shapes similar to surface water, but inertia similar to groundwater. The shape of the response may be due to the quick flow paths, but the long inertia may reflect longer flow paths. Karst systems can exhibit both features, which makes them distinct from either the surface water or groundwater systems.

In terms of hydraulic processes, it may be appropriate to think of karst aquifer systems as intermediate between groundwater and surface water, as karst systems manifest flow regimes common to both water sources; however, it may not be appropriate to assume that springs exhibit much shorter impulse responses on much shorter time scales than groundwater resources. Though springs generally show system inertia somewhere between surface water's quick response and recovery and groundwater's greater inertia, some water resources like Arch Spring respond to storms with hydrograph shapes similar to surface water, but inertia similar to groundwater. Caution must be used when applying relationships derived for surface water to karst systems, and monitoring programs in karst should include aspects of both quickflow and longer flow paths.

References

Amraoui, F., Razack, M., Bouchaou, L., 2003. Turbidity dynamics in karstic systems. Example of Ribaa and Bittit springs in the Middle Atlas (Morocco). Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 48, 971-984.

Beaudeau, P., Leboulanger, T., Lacroix, M., Hanneton, S., Wang, H.Q., 2001. Forecasting of turbid floods in a coastal, chalk karstic drain using an artificial neural network. Ground Water 39, 109-118.

Berg, T.M., 1980. Geologic map of Pennsylvania. Pennsylvania Geological Survey, Harrisburg, PA.

Birk, S., Liedl, R., Sauter, M., 2004. Identification of localised recharge and conduit flow by combined analysis of hydraulic and physico-chemical spring responses (Urenbrunnen, SW-Germany). Journal of Hydrology 286, 179-193.

Bouchaou, L., Mangin, A., Chauve, P., 2002. Turbidity mechanism of water from a karstic spring: example of the Ain Asserdoune spring (Beni Mellal Atlas, Morocco). Journal of Hydrology 265, 34-42.

Box, G.E.P., Jenkins, G.M., 1976. Time series analysis: forecasting and control. Prentice Hall: Upper Saddle River, NJ, 575 p.

Brown, M.C., 1973. Mass balance and spectral analysis applied to karst hydrologic networks. Water Resources Research 9, 749-752.

Coulibaly, P., Burn, D.H., 2005. Spatial and temporal variability of Canadian seasonal streamflows:. Journal of Climate 18, 191-210.

de Vera, M., 1984. Rainfall-runoff relationship of some catchments with karstic geomorphology under arid to semi-arid conditions. Journal of Hydrology 68, 85-93.

Denic-Jukic, V., Jukic, D., 2003. Composite transfer functions for karst aquifers. Journal of Hydrology 274, 80-94.

Desmarais, K., Rojstaczer, S., 2002. Inferring source waters from measurements of carbonate spring response to storms. Journal of Hydrology 260, 118-134.

Dreiss, S.J., 1982. Linear kernels for karst aquifers. Water Resources Research 18, 865-876.

Dreiss, S.J., 1983. Linear unit-response functions as indicators of recharge areas for large karst springs. Journal of Hydrology 61, 31-44.

Dreiss, S.J., 1989a. Regional scale transport in a karst aquifer: 1. Component separation of spring flow hydrographs. Water Resources Research 25, 117-125.

Dreiss, S.J., 1989b, Regional scale transport in a karst aquifer: 2. Linear systems and time moment analysis. Water Resources Research 25, 126-134.

Dryden, I., Markus, L., Taylor, C., Kovacs, J., 2005. Non-stationary spatiotemporal analysis of karst water levels. Journal of the Royal Statistical Society Series C - Applied Statistics 54, 673-690.

Eisenlohr, L., Kiraly, L., Bouzelboudjen, M., Rossier, Y., 1997a. Numerical simulation as a tool for checking the interpretation of karst spring hydrographs. Journal of Hydrology 193, 306-315.

Eisenlohr, L., Bouzelboudjen, M., Kiraly, L., Rossier, Y., 1997b. Numerical versus statistical modelling of natural response of a karst hydrogeological system. Journal of Hydrology 202, 244-262.

Ford, D.C., Williams, P.W., 1989. Karst geomorphology and hydrology. Unwin Hyman: London, 601 p.

Halihan, T., Wicks, C.M., 1998. Modeling of storm responses in conduit flow aquifers with reservoirs. Journal of Hydrology 208, 82-91.

Halihan, T., Wicks, C.M., Engeln, J.F., 1998. Physical response of a karst drainage basin to flood pulses: Example of the Devil's Icebox cave system (Missouri, USA). Journal of Hydrology 204, 24-36.

Hull, L.C., 1980. Mechanisms controlling the inorganic and isotopic geochemistry of springs in a carbonate terrane. Ph.D. thesis, The Pennsylvania State University, University Park, PA.

Jemcov, I., Ristic, V., Stefanovic, Z., Prohaska, S., 1998-1999. Application of auto-cross regression model to the analysis and discharge simulation of some karst springs. Theoretical and Applied Karstology 11-12, 125-132.

Kallache, M., Rust, H.W., Kropp, J., 2005. Trend assessment: applications for hydrology and climate research. Nonlinear Processes in Geophysics 12, 201-210.

Labat, D., Ababou, R., Mangin, A., 2000. Rainfall-runoff relations for karstic springs. Part I: convolution and spectral analyses. Journal of Hydrology 238, 123-148.

Labat, D., Ababou, R., Mangin, A., 2001, Introduction of wavelet analyses to rainfall/runoffs relationship for a karstic basin: The case of Licq-Atherey karstic system (France). Ground Water 39, 605-615.

Labat, D., Mangin, A., Ababou, R., 2002. Rainfall-runoff relations for karstic springs: multifractal analyses. Journal of Hydrology 256, 176-195.

Labat, D., Ronchail, J., Callede, J., Guyot, J.L., De Oliveira, E., Guimaraes, W., 2004. Wavelet analysis of Amazon hydrological regime variability. Geophysical Research Letters 31.

Lambrakis, N., Andreou, A.S., Polydoropoulos, P., Georgopoulos, E., Bountis, T., 2000. Nonlinear analysis and forecasting of a brackish karstic spring. Water Resources Research 36, 875-884.

Larocque, M., Mangin, A., Razack, M., Banton, O., 1998. Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). Journal of Hydrology 205, 217-231.

Lee, J.Y., Lee, K.K., 2000. Use of hydrologic time series data for identification of recharge mechanism in a fractured bedrock aquifer system. Journal of Hydrology 229, 190-201.

Majone, B., Bellin, A., Borsato, A., 2004. Runoff generation in karst catchments: multifractal analysis. Journal of Hydrology 294, 176-195.

Mangin, A., 1984. Pour une meilleure connaissance des systemes hydrologiques a partir des analyses correlatoire et spectrale - The use of autocorrelation and spectral analyses to obtain a better understanding of hydrological systems. Journal of Hydrology 67, 25-43.

Marechal, J.C., Sarma, M.P., Ahmed, S., Lachassagne, P., 2002. Establishment of earth tide effect on water-level fluctuations in an unconfined hard rock aquifer using spectral analysis. Current Science 83, 61-64.

Massei, N., Dupont, J.P., Mahler, B.J., Laignel, B., Fournier, M., Valdes, D., Ogier, S., in press. Investigating transport properties and turbidity dynamics of a karst aquifer using correlation, spectral, and wavelet analyses. Journal of Hydrology.

Padilla, A., Pulidobosch, A., 1995. Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. Journal of Hydrology 168, 73-89.

Pagano, T., Garen, D., 2005. A recent increase in western US streamflow variability and persistence. Journal of Hydrometeorology 6, 173-179.

Pinault, J.L., Plagnes, V., Aquilina, L., Bakalowicz, M., 2001. Inverse modeling of the hydrological and the hydrochemical behavior of hydrosystems: Characterization of karst system functioning. Water Resources Research 37, 2191-2204.

Potts, J.M., Hirst, D., Miller, J.D., Edwards, A.C., Elston, D.A., 2003. Comparison of trends in stream water quality. Hydrological Processes 17, 2449-2462.

Quinn, J.J., Tomasko, D., Kuiper, J.A., 2006. Modeling complex flow in a karst aquifer. Sedimentary Geology 184, 343-351.

Rademacher, L.K., Clark, J.F., Hudson, G.B., 2002. Temporal changes in stable isotope composition of spring waters: Implications for recent changes in climate and atmospheric circulation. Geology 30, 139-142.

Rahnemaei, M., Zare, M., Nematollahi, A.R., Sedghi, H., 2005. Application of spectral analysis of daily water level and spring discharge hydrographs data for comparing physical characteristics of karstic aquifers. Journal of Hydrology 311, 106-116.

Shih, D.C.F., Chiou, K.F., Lee, C.D., Wang, I.S., 1999. Spectral responses of water level in tidal river and groundwater. Hydrological Processes 13, 889-911.

Shih, D.C.F., Lin, G.F., 2002. Spectral analysis of water level fluctuations in aquifers. Stochastic Environmental Research and Risk Assessment 16, 374-398.

Shuster, E.T., White, W.B., 1971. Seasonal fluctuations in the chemistry of limestone springs; a possible means for characterizing carbonate aquifers. Journal of Hydrology 14, 93-128.

Smart, C.C., 1988. Artificial tracer techniques for the determination of the structure of conduit aquifers. Ground Water 26, 445-453.

Tancredi, J.M., 2004. Variation in sediment and geochemistry as evidence of changes in flowpaths to a karst spring in Southeastern Pennsylvania. M.S. thesis, Temple University, Philadelphia.

Toran, L., White, W.B., 2005. Variation in nitrate and calcium as indicators of recharge pathways in Nolte Spring, PA. Environmental Geology 48, 854-860.

White, W.B., 1988. Geomorphology and hydrology of karst terrains. Oxford University Press: New York, 464 p.

White, W.B., 2002. Karst hydrology; recent developments and open questions. Engineering Geology 65: 85-105.

Yue, S., Pilon, P., Phinney, B., Cavadias, G., 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes 16, 1807-1829.

Chapter 4

Mineralogy of suspended sediment in three karst springs

Abstract

Springs in karstic carbonate rocks frequently carry a sediment load as well as a dissolved load. Analysis of morphology and mineralogy of suspended sediment from three contrasting karst springs reveals a suite of clastic particles that reflect both source areas and processes that take place within the aquifer. Nolte Spring in Lancaster County, Pennsylvania discharges sediment of apparently precipitated calcite indicating that at some point in the aquifer or vadose zone, water exceeds saturation with respect to calcite. Sediment morphologies and chemical conditions in the aquifer point to two different scenarios for this precipitation. The other two springs, Arch Spring in Blair County, Pennsylvania and Bushkill Spring in Northampton County, Pennsylvania, show no evidence of calcite precipitation. Arch Spring discharges mainly layer silicates while Bushkill Spring discharges mainly silica.

Introduction

Springs draining from carbonate aquifers frequently carry a load of suspended sediments that varies with discharge and other factors. Karst springs often become turbid or completely muddy during storm flow. Sediment fluxes in karst aquifers are clearly episodic. Sediments move mostly during storm flow and fluxes decrease to a low background of small particles during base flow. There has been a good deal of recent interest in the clastic sediments discharged from karst springs because of their importance when the springs are used as water supplies and for the role of clastic particles in contaminant transport.

Much of the literature on clastic sediments in karst drainage basins is concerned with the sedimentary deposits found in caves. In active stream caves, these represent sediments in transit, i.e. sediments carried a certain distance during a previous storm and held in storage waiting for a storm of sufficient magnitude to move them again. When the conduit system is drained, the sediments in residence at the time are trapped in the dry cave where they can be examined and interpreted. A variety of facies have been recognized, ranging from laminated clays to boulder piles (Bosch and White 2004). Cave sediments are of interest, both intrinsically in terms of transport mechanisms, and as archives of paleoclimatic information. However, the sediment piles observed in caves are mostly much coarser material than the small size particle fraction that is easily mobilized and carried from the aquifer to the spring orifice during ordinary storms. These fine-grained suspended sediments are less well studied and are the subject of interest in the present paper.

The conduit system of a karst aquifer acts as both mixing and storage chamber for clastic sediments. Fluxes of sediment are input from sinking streams, from soil piping from sinkhole drains, from soil washdown from the epikarst, and as the residual insoluble fraction remaining after dissolution of the limestone. Materials from these varied sources are mixed in the conduit system, differentiated according to density and particle size, and transported when the storm flows through the aquifer reach necessary thresholds. Most easily moved are the fine-grained, uncompacted sediments and these often appear at springs during low to moderate flows. Coarser materials appear at springs only when flows exceed thresholds and are observed only during exceptional storms (Herman et al., 2005).

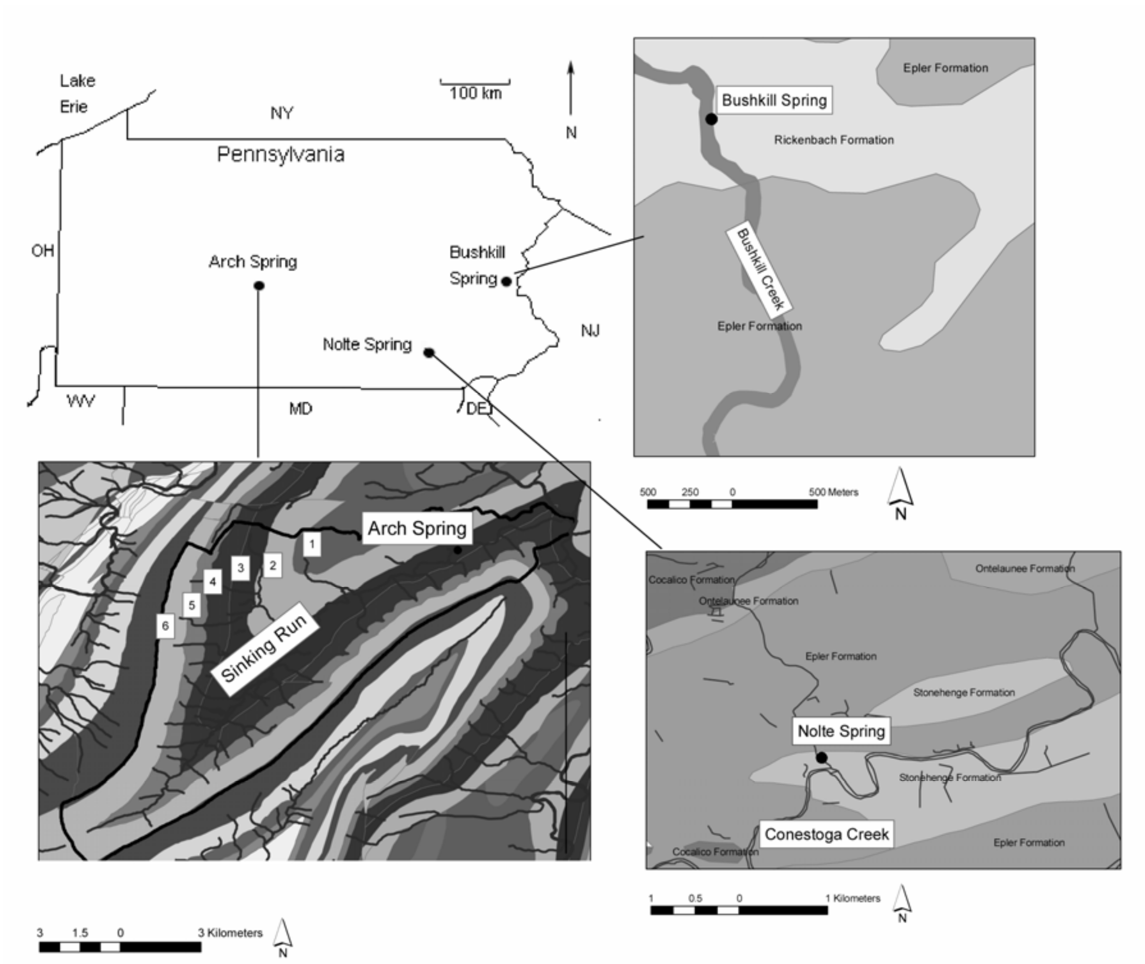
Most of the literature concerning suspended sediments discharged from springs is quite recent and deals with the mechanisms of sediment transport (e.g., Mahler and Lynch 1999; Amraoui et al. 2003; Massei et al. 2003; Peterson and Wicks 2003; Dogwiler and Wicks 2004). Only a few papers address the question of the actual mineralogical content of the suspended sediment (Drysdale et al. 2001; Lynch et al. 2004; Mahler et al. 2004). It has been demonstrated that bacteria (Mahler et al. 2000) and heavy metals (Vesper and White 2003) are carried through karst aquifer systems attached to small sediment particles. Particle mineralogy, composition, and surface morphology would seem to be useful as a possible source of information about internal processes within the aquifer.

The present paper reports sediment particle characterization from three springs in Pennsylvania, shown and described in Figure **4-1**. The three springs investigated were selected to represent different hydrologic settings in terms of the type of recharge and the characteristics of the aquifer feeding the springs. A discussion of storm variation in specific conductance related to sediment transport is being published elsewhere (Toran et al. 2006).

Spring Descriptions

Arch Spring is the downstream outlet of a master conduit system that drains Sinking Valley, Blair County, Pennsylvania. It is the headwater of the lower portion of Sinking Run, which drains into the Juniata River, a tributary of the Susquehanna River. The master conduit can be accessed through Tytoona Cave with an entrance in a collapse sink 1.2 km upstream from the spring, although much of the conduit lies upstream from the collapse sink. Cave divers have explored almost the entire length of conduit between the cave and the spring. The discharge is on the order of 250 – 400 L/s at baseflow. The spring and master conduit are developed in the Grazier member of the Hatter Formation, a lower unit of the Ordovician Black River Group (Rones, 1969). Below this limestone unit, the carbonate sequence consists mainly of dolomite (Fig. **4-1**). The recharge reaching the spring is from mountain runoff that sinks where the Reedsville Shale contacts the limestones and from direct infiltration through the limestone soils of the carbonate valley uplands.

Nolte Spring is located in West Earl Township, Lancaster County, Pennsylvania. It is approximately 4.5 meters in elevation above and 200 meters upstream from Conestoga Creek, the base-level surface drainage for the area. Conestoga Creek is part of the Susquehanna River drainage. The spring orifices are two 15-cm diameter solutionally-widened fractures located in a chamber beneath the pumping station for the West Earl Township Water Authority. The spring was at one time used as a public water supply, but that usage was discontinued because of increased turbidity following storms. The base flow discharge is about 25 L/s. The bedrock at the spring is the Ordovician



Spring	Type of Aquifer	Area of Basin
Arch	Master conduit	~50 km^2
Nolte	Fracture and enlarged fracture	~1-2 km^2
Bushkill	Fracture	Multiple outlets make basin indeterminate

Figure 4-1: **Geology of the spring basins.** Arch Spring has a combination of carbonate and non-carbonate units in the Sinking Run watershed (outline shown on geologic map). The units represented are from oldest to youngest 1) Stonehenge Limestone, 2) Bellefonte Dolomite, 3) Limestones of the Trenton and Black River Groups, 4) Reedsville Shale, 5) Bald Eagle Sandstone, and 6) Juniata formation. Nolte Spring has carbonate Epler and Stonehenge formations in the recharge area; the sandstones and shales of the Cocalico and Onetelaunee are outside the capture area. Bushkill Spring has the smallest capture area, draining limestones of the Epler formation and dolomites of the Rickenbach formation.

Epler Formation, the middle unit of the Beekmantown Group of mixed limestones and dolomites. The catchment area for the spring is a carbonate rock upland with numerous sinkholes but little evidence for allogenic recharge. Most water entering the aquifer must percolate through a soil cover.

Bushkill Spring in Northampton County, Pennsylvania, discharges from a sequence of small openings along bedding planes just above stream level on Bushkill Creek about 12 km upstream from the creek's confluence with the Delaware River. There are multiple discharge points but no distinct solutionally-widened conduit at the surface. The orifice chosen for measurement was about 5 cm wide and had a base flow discharge on the order of one L/s. The spring orifices are close to the contact between the Ordovician Epler and Rickenbach Formations, both consisting of interbedded limestone and dolomite. The recharge area is a carbonate upland that includes an athletic field that has been plagued with sinkholes, but a hydraulic connection between the sinkholes and the spring has not been determined. Although an integrated conduit system has not been demonstrated, the drainage basin is small and flow paths are short.

Sediment Sampling and Analytical Methods

During site visits to each spring, samples were collected for suspended sediment analysis, major cation and anion analysis, and alkalinity titration. Site visits were spaced from two weeks to one month apart depending on the time of year and storm frequency, and the sampling period continued from July 2002 to August 2004 at Bushkill and Nolte Springs and December 2003 to December 2005 at Arch Spring. In addition to monthly samples, ISCO™ automatic samplers placed at each of the springs collected water samples when triggered by a rise in water level. The sampler took 24 samples spaced at pre-set intervals. The intervals were selected based on the typical storm duration at a spring.

The samples collected for water chemistry were filtered in the field and refrigerated until analysis by ion chromatography and by titration for alkalinity. The pH and temperature of samples were recorded in the field. The stormwater samples and one set of monthly samples were filtered in the laboratory to remove suspended sediments from the water for analysis. The samples were filtered sequentially on 5 μm and 0.45 μm mixed-cellulose or cellulose nitrate membrane filters. Because sediment concentrations were low during storms at Nolte Spring, much of the information on Nolte is based on monthly samples. The other springs generally showed higher suspended sediment concentrations during storms.

A scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDX) was used to examine filtered sediments from the three springs. The SEM was useful for surveying the filtered sediment and investigating questions of morphology, while the EDX determined the chemical composition of various target grains of sediment. The combination of morphology and bulk chemistry allowed identification of most mineral grains to a low degree of specificity. X-ray diffraction (XRD) to determine mineralogy of crystalline phases was used on the few samples for which there was adequate crystalline sediment for analysis.

While composition results for filtered sediment have provided insight into spring behavior, attempts to determine sediment size distributions have to date not been particularly successful. Clumping of sediment, particularly clay-rich sediment, on the 5.0 μm filters prevented the use of different-sized filters for sizing, and the irregular shape of most particles made other sizing methods impractical.

Mineralogy and Composition of Suspended Sediments

Arch Spring

Some representative images of Arch Spring sediment, shown in Figure **4-2**, display a range of morphologies with fossil fragments and some coarse-grained minerals easily visible. However, the bulk of the material was fine-grained even at the SEM scale in low vacuum mode so that morphologies and bulk composition of individual particles could not be determined. EDX analysis showed silicon and aluminum to be the dominant components with concentrations of potassium and iron appearing in some samples. Figure **4-2**a features a sample taken on the recessing limb of the hydrograph following a minor storm, while Figure **4-2**b depicts a sample taken on the recession limb following a larger storm and at the beginning of one of the largest storms collected. Figure **4-2**c is from the same storm as Figure **4-2**b, but the water level had already risen 20 cm illustrating that, regardless of discharge at the spring and timing in relation to a storm event, clay minerals and silica are the most common particles at Arch Spring. The presence of potassium indicates that illite or possibly muscovite is likely present although the characteristic micaceous morphology was not apparent. Iron-rich grains may be iron oxyhydroxides. One flake of a calcium-rich grain was detected in a storm sample from

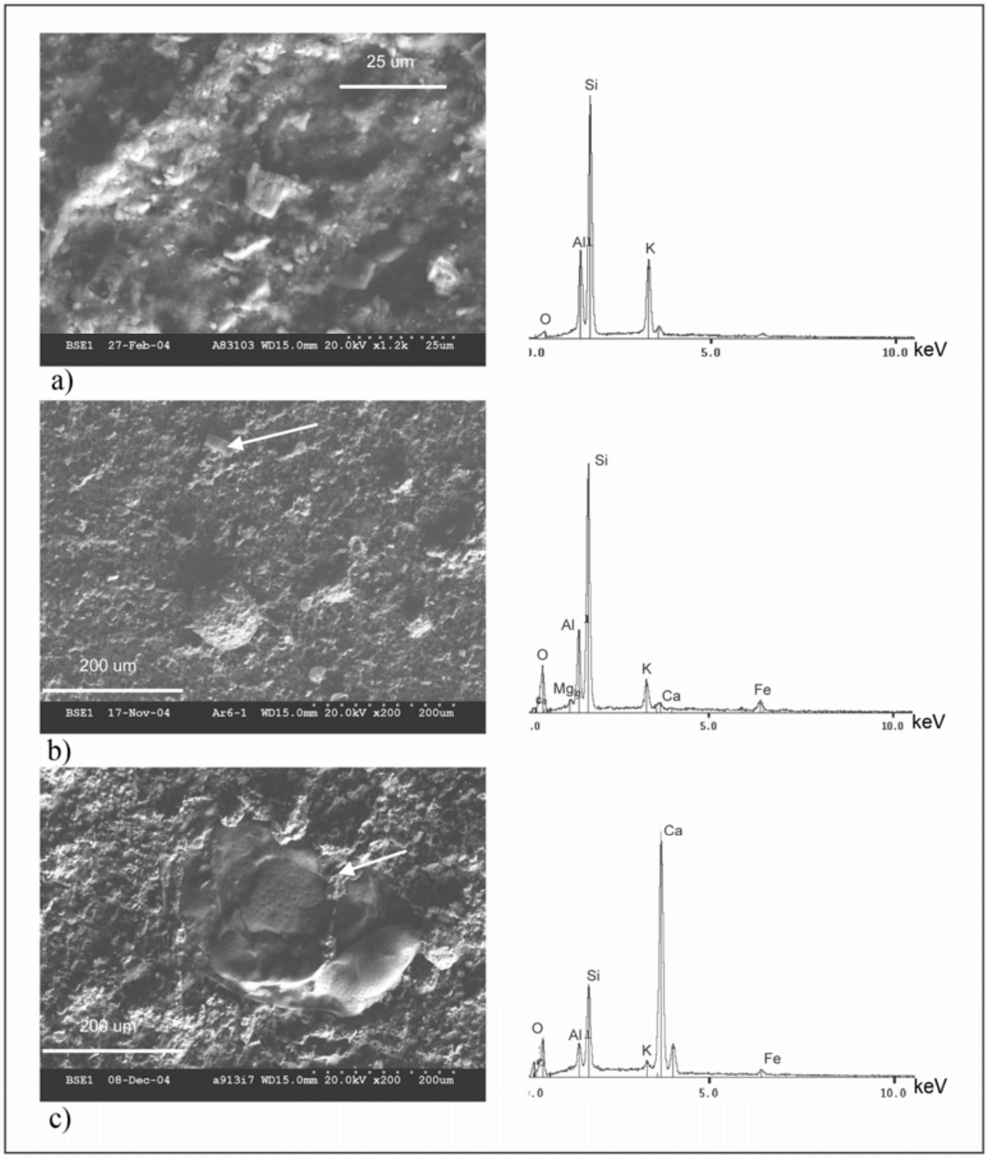


Figure 4-2: **SEM images and EDX spectra from three Arch Spring storm samples.** From top: a) August 31, 2003; b) September 1, 2003, 2:56am; and c) September 1, 2003, 11:56am. All three samples showed predominantly layered silicates based on EDX analysis, but the 9/1/03, 11:56am, sample had a particle of calcium-rich sediment. The EDX spectrum shown in 4-2a covers the entire area pictured; in 4-2b, the spectrum targeted the largest mass visible in the bottom center of the image; the spectrum in 4-2c covers the area of the single calcite grain, which incorporates some of the sediment resting on and around the grain. The arrow in Figure 4-2b points to a diatom skeletal fragment representative of fragments common in the Arch Spring samples. In Figure 4-2c the arrow marks the rim of the calcite particle dominating the micrograph.

September 1, 2003 (Figure 4-2c). This appeared to be biologically precipitated calcite, but was unique among the Arch Spring samples investigated and therefore not a common component.

The water from Arch Spring over the course of this study and in a previous study (Shuster and White 1971) consistently remained well below saturation with respect to calcite and dolomite, as the saturation indices of calcite (SI_C) and dolomite (SI_D) were negative and CO_2 partial pressure (P_{CO2}) was high. Tytoona Cave upstream of Arch Spring was also undersaturated. The silicate-dominated sediment discharged from Arch Spring was consistent with the relatively low specific conductance (from about 80 μS/cm to 260 μS/cm) and low SI_C of the water (-1.01 to -0.76).

Nolte Spring

The sediments from Nolte Spring were surprising in that they contained substantial amounts of calcite as shown in Figure 4-3. Because of the substantial variation in calcite morphology in monthly samples, further data on temporal variation in Nolte spring geochemistry are also presented. Representative examples of the calcite morphologies observed with SEM are shown in Figure 4-4, and discussed further below.

In a few samples, the quantity of sediment was sufficient to allow mineral identification by XRD. The X-ray pattern of a July 9, 2003 sample revealed calcite almost exclusively (Figure 4-3a). Other samples, like one taken September 15, 2003 (Figure 4-3b), consisted of a mix of quartz, calcite, muscovite, and chlorite. Siliciclastics predominated in some samples (Figure 4-3c), but sediment concentrations of the calciterich samples were generally higher than those of the siliciclastic samples as illustrated in Figure **4-5**. It was more difficult to assign a specific mineral composition to samples with sparse sediment and no calcite. In these samples, individual particles were indistinguishable (Figure **4-3**b), or there were only a few small particles with indistinct morphology on which to base the determination (Figure **4-3**c).

Variations in sediment concentration through time at Nolte Spring are shown in Figure **4-5**. Monthly samples had higher concentrations of sediment than storm samples even when the monthly samples were collected shortly before the storm. For example, the September 22, 2002 storm samples had less than 1 mg/L of sediment, even though the stage was the lowest of the monitoring period and the baseflow sediment concentration was about 30 mg/L prior to the storm. Although the spring had lower sediment concentration during storms, the sediment flux (sediment concentration multiplied by the discharge) was higher overall (Tancredi 2004).

There was little evidence of a seasonal effect on sediment concentration or type. During the fall of 2002 and the summer of 2003, though hydrologic conditions were very different, there were high concentrations of calcite observed in the sediment (Figure **4-5**). During the remainder of the sampling period, the sediment was either dominantly siliciclastics in the form of clay and silit, or a mix of calcite and siliciclastics.

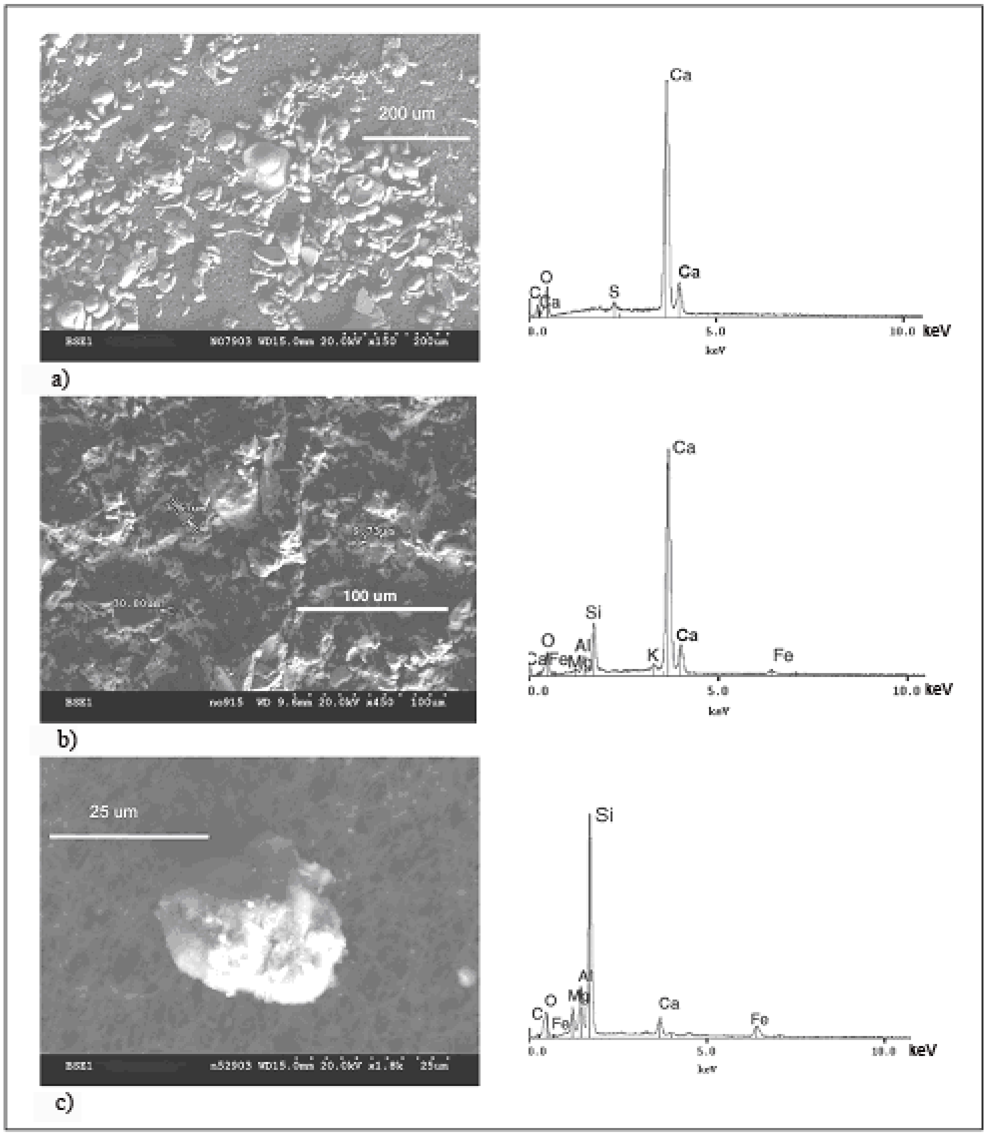


Figure 4-3: SEM images and EDX spectra from three Nolte Spring monthly samples. From top: a) July 9, 2003; b) September 15, 2003; and c) May 29, 2003. The 7/9/03 sample had the highest sediment concentration of the monitoring period, and the EDX spectrum over the area shown in the image has a high calcium peak, indicating that most of the particles in the image are composed of calcite. The 9/15/03 sample was classified as a mixture of calcite and clay, and XRD indicated the presence of quartz, calcite, muscovite, and chlorite on this sample. The particle from May 29, 2003 was siliciclastic. Most samples primarily composed of siliciclastics had small amounts of sediment, so XRD could not be used to identify the mineralogy.

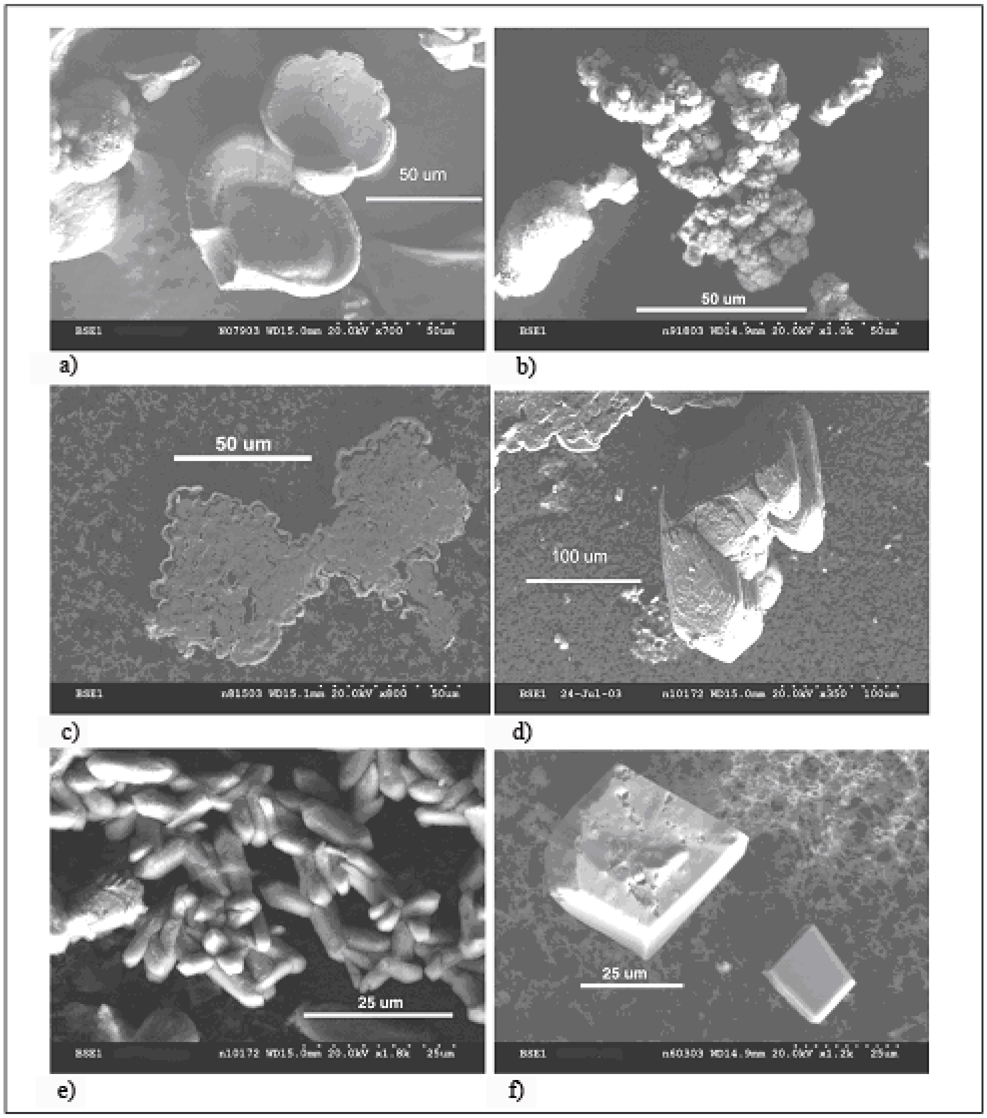


Figure 4-4: **Morphologies of calcite from Nolte Spring observed with SEM.** Micrographs of samples collected on the following dates: a) July 9, 2003; b) September 18, 2003; c) August 15, 2003; d) March 7, 2003 (storm sample) e) October 17, 2002; and f) June 3, 2003 (storm sample). The morphology of the July 9, 2003 sample suggests that calcite was broken off from a precipitation site and transported to Nolte Spring. The prismatic calcite grains in the October 17, 2002 sample appear to have grown together (e). Popcorn (b), flakes (c), and pitted crystals (d) are also present.

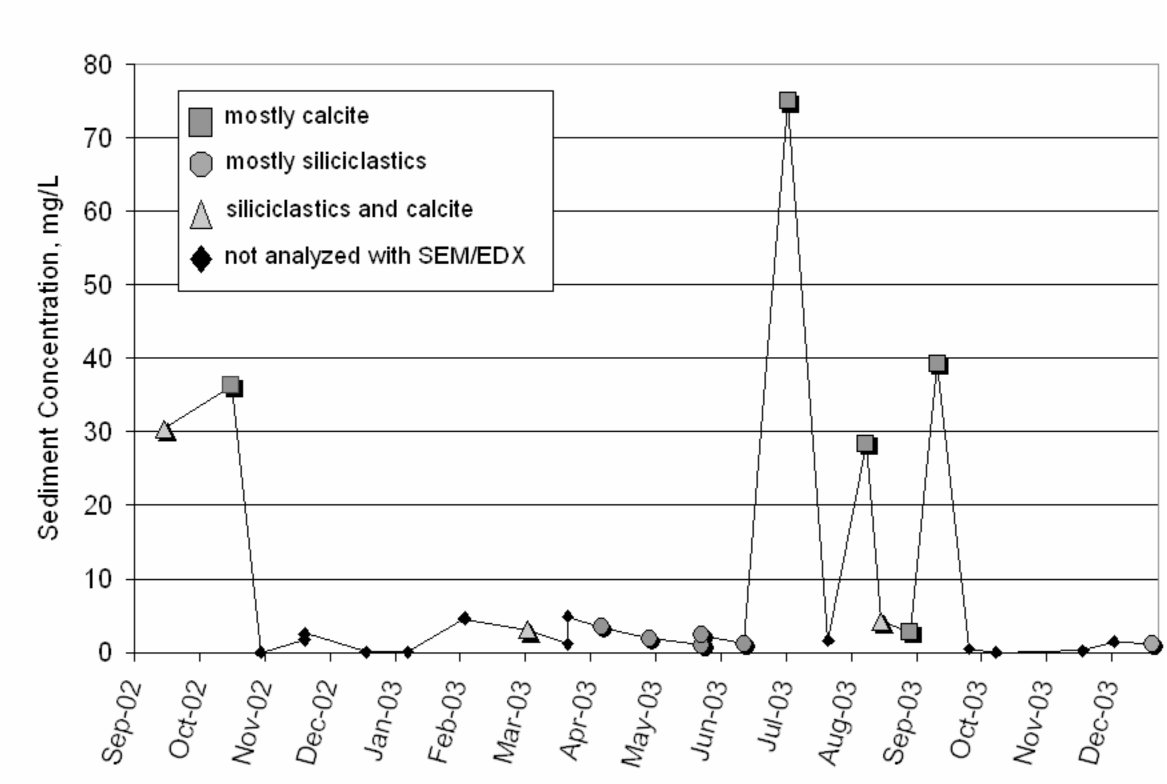


Figure 4-5: **Sediment concentration and mineralogy for monthly samples from Nolte Spring for September 2002 through December 2003.** Data points marked with a symbol for mineralogy were analyzed with SEM/EDX. Samples with high concentrations of sediment had some calcite. Calcite was observed in the samples from early fall 2002 and summer 2003, whereas mostly siliciclastics were observed during the winter and spring 2003 seasons. After December 2003, sediment concentrations of samples collected were generally less than 5 mg/L, and no further SEM/EDX analyses were conducted to identify sediment composition.

Bushkill Spring

Representative particle morphologies and analyses from Bushkill Spring are presented in Figure 4-6. Most samples from Bushkill Spring contained silica (presumably quartz) as the dominant phase. Although the concentration and flux of sediment varied substantially with stage and discharge in the spring, silica predominated through a variety of hydrologic conditions. Figure 4-6c shows a sample taken during very low stage, when the spring had likely been dry just a few days earlier. Based on examination with an optical microscope, the sediment morphology and composition of low stage samples were not substantially different from storm samples taken March 30, 2003 and October 15, 2003, when the water was quite high in the spring (Rillstone and Toran 2004). Water in the Bushkill Spring was consistently below saturation with respect to calcite (SI_C ranged from 0 to –1.6, with a mean of –0.4), and as expected, calcite was not seen in the samples. The drainage to the spring at Bushkill was probably below saturation throughout its extent making it a substantially different spring from Nolte Spring in spite of its geologic similarity.

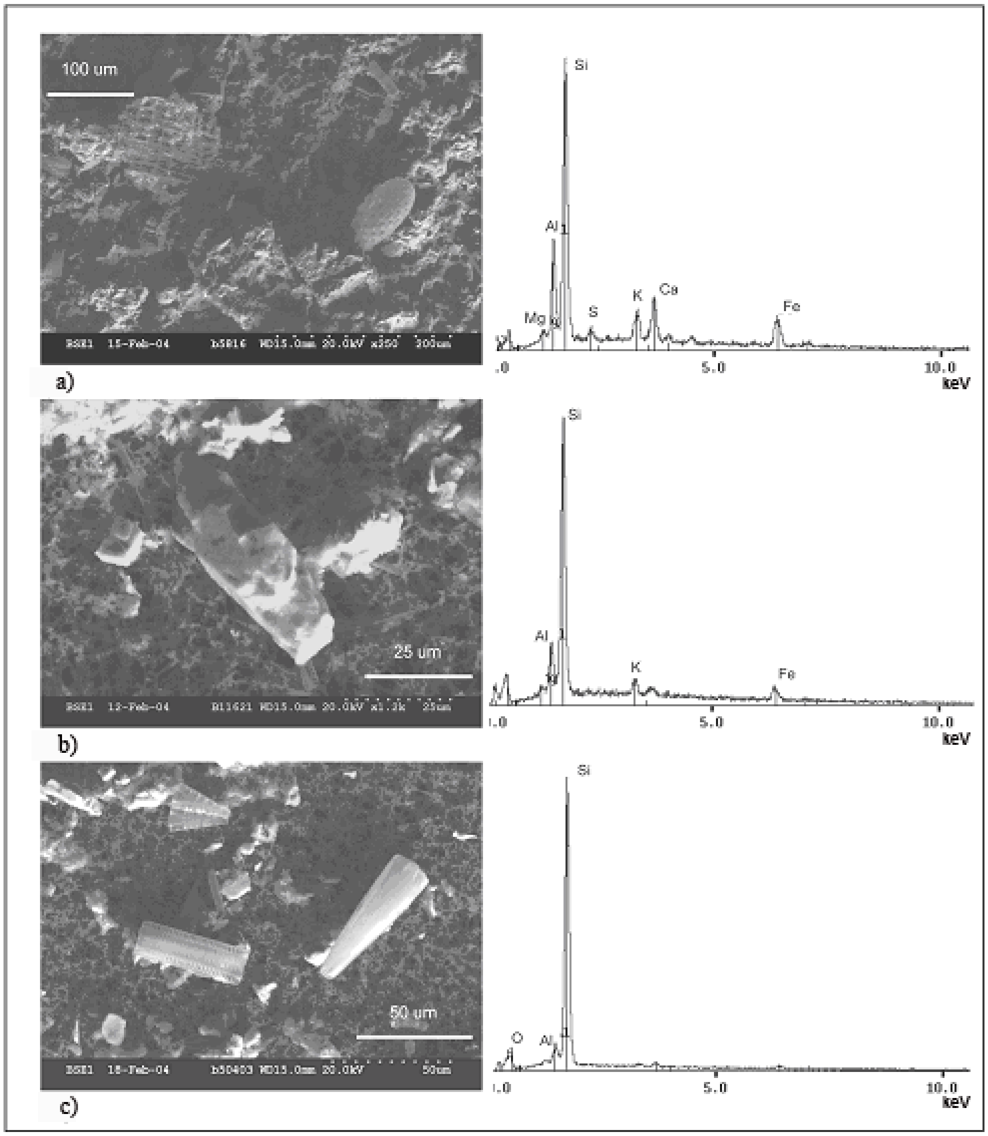


Figure 4-6: **SEM images and EDX spectra from three Bushkill Spring samples.** From top: i) May 8, 2003; ii) November 6, 2002; and iii) May 4, 2003. The samples all showed sliciclastics with silica predominating. Pictured here are fine-grained siliciclastics from the storm sample of 5/8/03 (i), a quartz grain with conchoidal fracture from the 11/6/02 storm sample (ii), and a collection of diatoms from the 5/4/03 monthly sample. Diatoms were very common in the Bushkill Spring samples, but it is possible that their source was Bushkill Creek flowing past the spring rather than the spring itself. It was not possible to rule out stream contributions due to sampling constraints.

Origin of Calcite in the Nolte Samples

Because the discovery of calcite particles in the Nolte Spring suspended sediment was completely unexpected, some additional discussion is required. The SI_C at Nolte generally remained below saturation, with the only values over saturation occurring in the drought of 2002, making the origin of much of the precipitated calcite a puzzle. Chemical conditions in the aquifer must be more complicated than indicated by water chemistry at the spring mouth.

Our samples showed sediment being flushed out the spring in both base flow and high flow conditions. The average flow rate at the spring was 25 L/s, but over the seasons shown in Fig. **4-5**, the flux varied from only 0.1 L/s (September 2002 drought) to slightly over 40 L/s (March 2003). There was no seasonal variation in sediment type or amount. This implies a continuous sediment source or else the system would have been flushed clean over time. The soil and regolith in the epikarst provides the only available continuous source of siliciclastic particles. The bedrock probably does not provide a continuous source of carbonate sediments because calcite, rather than a mix of calcite and dolomite, is the material observed in the spring water, while both are present in the bedrock. This suggests that contemporary precipitation of calcite is occurring in other parts of the spring's feeder system where more saturated conditions prevail.

The variation in calcite morphologies observed in Nolte Spring sediment (Figure **4-4**) point to at least two distinct origins for the particles. The popcorn structures and nodules of calcite observed in some of the samples suggest precipitation from either supersaturated water in a fracture or in the vadose zone. For example, prisms in the sample collected on October 17, 2002 (Figure 4-4e) appear to be joined at the base, as if they had grown together. Although the aspect ratio of these crystals' long and short axes is 3:1 and too low to be termed acicular, the fabric of the calcite prisms is similar to that of needle-like acicular calcite, which forms in the vadose zone of arid or semi-arid climates (Fitzpatrick 1993; Scholle and Ulmer-Scholle 2003). A sample collected on September 18, 2003 (Figure 4-4b) has a popcorn texture, which may indicate precipitation during condensation of water also likely in the vadose zone (Gonzalez et al. 1992).

Other calcite morphologies, such as rhombs with dissolution pits, flakes, and other chipped or etched grains, indicate that these may have been precipitated in a pool or quiet environment. Such sediment grains offer clues not just to their precipitation history, but also to their transport history. A suspended sediment sample collected on July 9, 2003 contained equant crystals and nodules, as well as shell-shaped particles and thin crusts, some of which were chipped or looked like they had been broken off a larger area (Figure 4-4a). A calcite rhomb showed a chipped edge and dissolution pits in a storm sample from June 3, 2003 (Figure 4-4d). Etch pits and other evidence of re-dissolution are consistent with transport to the spring mouth in undersaturated conditions. The variety in calcite grain morphology implies that the chemical saturation state of calcite changes along the flow path. Undersaturated water emerging from the spring mouth does not imply that such conditions exist throughout the aquifer.

The geochemistry at the spring mouth suggests different geochemical and hydrologic conditions during particular times in the sampling period. The P_{CO2} and SI_C conditions at the Nolte Spring mouth fell into three categories: low P_{CO2} with high SI_C, intermediate P_{CO2} and SI_C, and high P_{CO2} with low SI_C as shown in Figure **4-7** . Low P_{CO2} with high SI_C occurred during the drought of 2002 in summer and fall; intermediate P_{CO2} and SI_C occurred from mid-fall 2002 to spring 2003; and high P_{CO2} with low SI_C occurred during the growing season in the summer and early fall of 2003, which was unusually wet for those seasons. Two sets of chemical conditions prevailed when the sediment discharged from the spring was primarily calcite: low P_{CO2} with high SI_C and high P_{CO2} with low SI_C. During periods of intermediate P_{CO2} and SI_C, sediment was mainly clay and other siliciclastics which were expected for such chemical conditions. As such only the low P_{CO2} with high SI_C and high P_{CO2} with low SI_C groups will be discussed in this section.

Calcite During the 2002 Drought (low P_{CO2} with high SI_C)

Precipitation at the spring mouth or in dewatered fractures during the 2002 drought might explain calcite in the spring samples. At Nolte Spring, the low stage during the drought of 2002 may have caused the larger fractures and the conduits that are usually phreatic to drain, allowing dissolved CO_2 in groundwater to escape into air-filled spaces. This would lower the P_{CO2}, which would in turn cause the SI_C to increase (Figure **4-7**). The following reaction for calcite dissolution would be driven to the right allowing for precipitation at the spring:

$$Ca^{2+} + 2\,HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \qquad \textbf{4.1}$$

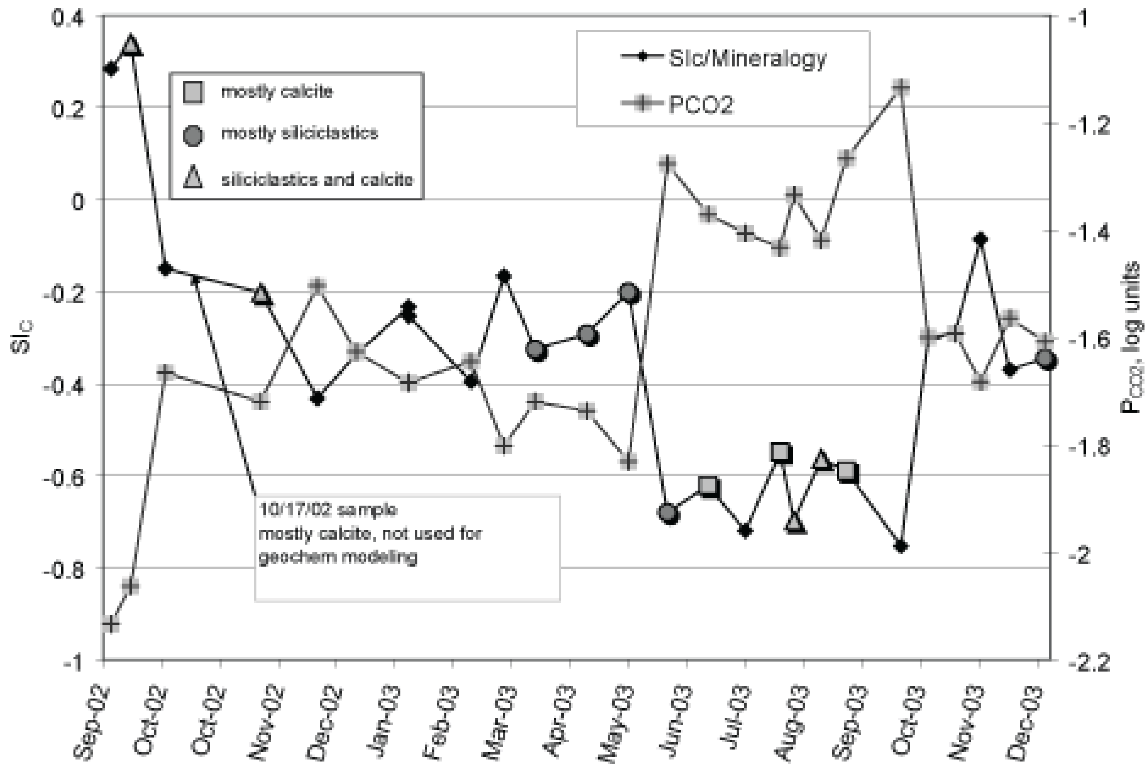


Figure 4-7: **Geochemistry and mineralogy of Nolte Spring for September 2002 through December 2003.** Mineralogy of samples collected concurrent with the geochemistry samples are marked on the SI_C data points, which are below saturation except for fall 2002. Calcite precipitation when P_{CO2} was low may have been driven by CO_2 outgassing. Calcite precipitation when P_{CO2} was high may have occurred under different geochemical conditions elsewhere in the system, followed by rapid transport to the spring. A sample from 10/17/02 also showed mostly calcite, but was not used for geochemical modeling and is not plotted here. After December 2003, sediment concentrations of samples collected were generally less than 5 mg/L, and no further SEM/EDX analyses were conducted to identify sediment composition.

Between site visits (two to four weeks), a calcium carbonate crust sometimes developed on the automatic sampler's water level sensor, indicating that the air-water interface where CO_2 outgassing can occur results in saturated conditions and precipitation at the spring mouth.

Some calcite morphologies observed during the drought suggest that vadose growth at the soil/bedrock interface may also have accounted for the presence of calcite in the spring. Although the overlying soils are generally well-leached, the carbonate at the soil/bedrock interface could have dissolved and re-precipitated. The drought may have caused supersaturated conditions sufficient for calcite to form, become disarticulated, and be transported into the aquifer by storm water.

Calcite in the 2003 Growing Season (high P_{CO2} with low SI_C)

Calcite precipitation at the spring mouth cannot account for the calcite in spring samples from summer and early fall 2003. The SI_C values calculated during this time were the lowest of the entire monitoring period, ranging from -0.75 to -0.52 in the samples from July 9, 2003 to October 15, 2003, compared to values from -0.43 to 0.33 during the remainder of the monitoring period. P_{CO2} values were the highest of the monitoring period, ranging up to an order of magnitude higher than the P_{CO2} measured one year earlier (during the drought). These values indicate that water in the spring would have been aggressive toward calcite. During the 2003 growing season, CO_2 was accumulating in the karst aquifer, instead of out-gassing. This drives equation 2 to the right, which would have decreased the pH and caused calcite dissolution, making precipitation at or near the spring mouth highly unlikely.

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^- \qquad \textbf{4.2}$$

Calcite precipitated at an earlier time seems a much more likely source for this sediment. The calcite grains would have been transported to the spring from elsewhere in the system during the growing season of 2003. The transport time to the spring would have to be faster than the time required for dissolution of these dislodged particles; given the small capture zone of this spring (on the order of several km^2, Tancredi 2004) transport of remnant calcite would be possible. However, the flow rate can only be measured at the spring mouth, so the fast flow rates are only inferred from the presence of calcite during undersaturated conditions. Because the seasonal highs and lows in flow rate do not create a trend in sediment concentration or type (Fig. **4-5**), the flow rate at the mouth cannot be used to predict the presence of sediment or calcite in particular.

Similarly, the geochemical conditions at the spring mouth cannot predict the presence calcite in spring mouth sediments. The growing season sediments were not expected to contain calcite (and note the June 2003 sample does not). Instead, the suspended sediment delivered to the mouth and the morphology of the calcite present provides clues to conditions further back in the system, perhaps all the way back to the recharge area.

Conclusions

The suspended sediments flushed from the three karst springs had distinctly different mineral compositions despite their relatively similar geologic settings. The sediment from Arch Spring, with recharge reflecting a large component of mountain runoff, was mainly fine-grained layer silicates. Nolte Spring, with recharge mainly by dispersed infiltration through thick soils, discharged suspended sediment containing large fractions of calcite but not dolomite. Much of the calcite was recovered from spring water that was undersaturated with respect to calcite. Bushkill spring, also with dispersed recharge on a limestone upland, discharged sediment that was dominantly silica.

These results are consistent with the presented mixing and fractionation model for clastic sediment transport through karst aquifers. Although the sediment mineralogy reflects the available material in the recharge area, these materials are injected and mixed within the aquifer. Moderate storms, such as those that occurred during the present investigation skimmed off only the very fine-grained fraction of the injected sediment load. As confirmed by direct observation of the sediment in the Tytoona Cave conduit in the Arch Spring feeder system, the coarser material remains in storage in the conduit awaiting rare high intensity storms.

Morphological evidence suggests that the anomalous calcite particles in Nolte Spring sediments were precipitated *in situ* somewhere in the active karst drainage system. The chemistry requires CO_2 degassing from water that had previously been brought to near saturation at a high CO_2 partial pressure – likely the soil/bedrock interface at times and a quiescent pool at others. The precipitation was followed by flushing of the particles into the main flow path. The transport of the particles through the karst conduit system must have been sufficiently rapid so as to bring the particles to the spring before they dissolved in the undersaturated water of the main flow system.

This study provides detailed mineralogy of the most readily transported fraction of the clastic sediment load revealing material with composition dependent on source area, on mixing within the aquifer, and on transport mechanisms. A further result is that a clastic carbonate fraction may appear depending on the saturation state of water along the flow path within the aquifer.

References

Amraoui F, Razack M, Bouchaou L (2003) Turbidity dynamics in karstic systems: Example of Ribaa and Bittit springs in the Middle Atlas (Morocco). Hydrologic Sciences Journal 48:971-984

Bosch RF, White WB (2004) Lithofacies and transport of clastic sediments in karstic aquifers. In: Sasowsky ID, Mylroie JE (eds) Studies in cave sediments. Kluwer Academic/Plenum Publishers, New York, pp 1-22

Dogwiler T, Wicks CM (2004) Sediment entrainment and transport in fluviokarst systems. Journal of Hydrology 295:163-172.

Drysdale R, Pierotti L, Piccini L, Baldacci F (2001) Suspended sediments in karst spring waters near Massa (Tuscany), Italy. Environmental Geology 40:1037-1050

Fitzpatrick EA (1993) Soil microscopy and micromorphology, John Wiley, Chichester, England

González LA, Carpenter SJ, Lohmann KC (1992) Inorganic calcite morphology: roles of fluid chemistry and fluid flow. Journal of Sedimentary Petrology 62:382-399

Herman EK, Toran L, White, WB (2005) Hurricane precipitation events reveal threshold behavior in water level and sediment concentration at Arch Spring, PA, USA. Geological Society of American National Meeting, Salt Lake City, Utah, Oct 16-19, 2005.

Lynch FL, Mahler BJ, Hauwert NN (2004) Provenance of suspended sediment discharged from a karst aquifer determined by clay mineralogy. In: Sasowsky ID, Mylroie JE (eds) Studies in cave sediments. Kluwer Academic/Plenum Publishers, New York, pp 83-93

Mahler BJ, Lynch FL (1999) Muddy waters: temporal variation in sediment discharging from a karst spring. Journal of Hydrology 214:165-178

Mahler BJ, Personné JC, Lods GF, Drogue C (2000) Transport of free and particulate-associated bacteria in karst. Journal of Hydrology 238:179-193

Mahler BJ, Personné JC, Lynch FL, Van Mere PC (2004) Sediment and sediment-associated contaminant transport through karst. In: Sasowsky ID, Mylroie JE (eds) Studies in cave sediments. Kluwer Academic/Plenum Publishers, New York, pp 23-46

Massei N, Wang HQ, Dupont JP, Rodet J, Laignel B (2003) Assessment of direct transfer and resuspension of particles during turbid flows at a karstic spring. Journal of Hydrology 275:109-121

Peterson EW, Wicks CM (2003) Characterization of the physical and hydraulic properties of the sediment in karst aquifers of the Springfield Plateau, Central Missouri, USA. Hydrogeology Journal 11:357-367.

Rillstone B, Toran L (2004) Variability of karst spring sediments within and between storm waters. Geological Society of American Northeast-Southeast Regional Meeting, Tysons Corner, VA, March 25-27.

Rones, M. (1969) A lithostratigraphic, petrographic and chemical investigations of the lower Middle Ordovician carbonate rocks in central Pennsylvania. Pennsylvania Geologic Survey General Geology Report 53, 224 p.

Scholle PA, Ulmer-Scholle DS (2003) A color guide to the petrography of carbonate rocks: grains, textures, porosity, diagenesis. American Association of Petroleum Geologists Memoir 77

Schuster ET, White WB (1971) Seasonal fluctuations in the chemistry of limestone springs: a possible means for characterizing carbonate aquifers. Journal of Hydrology 14:93-128

Tancredi JM (2004) Variation in sediment and geochemistry as evidence of changes in flowpaths to a karst spring in Southeastern Pennsylvania. MS, Temple University, USA

Toran L, Tancredi J, Herman EK, White WB (2006) Conductivity and sediment variation during storms as evidence of pathways in karst springs. Geological Society of America Special Paper 404, no 14: 169-176.

Vesper DJ, White WB (2003) Metal transport to karst springs during storm flow: an example from Fort Campbell, Kentucky/Tennessee, USA. Journal of Hydrology 276:20-36

Chapter 5

Threshold events in spring discharge: evidence from sediment and continuous water level measurement

Abstract

In September 2004, three major hurricanes, Frances, Ivan, and Jeanne, traveled up the east coast of the U.S. from the Gulf Coast bringing large amounts of rain to Central Pennsylvania. Monitoring equipment in place at Arch Spring in Blair County, PA captured the effects of these storms on the spring flow. Together these storms revealed that flow at Arch Spring is regulated by the capacity of the upstream cave system, with an upper flow threshold controlled by conduit structure in combination with antecedent conditions. Ivan was a much more devastating storm to the area because rain fell on ground already saturated by Frances, but the net stage increase at the spring was greater during the earlier Frances storm, a 74 cm stage increase versus a 54 cm increase. Storm water not transported through the Arch Spring system was diverted into surface channels during these storms.

Suspended sediment collected by an automatic sampler during Frances reveals another threshold crossed. Concurrent with increasing stage and high conductance water, sediment concentrations (933 mg/L) exceed previous marks by up to an order of magnitude. The timing of the sediment pulse indicates some of the highest sediment concentrations occur not when the storm water reaches the spring, but rather when stored water is being flushed out of the karst system. Sediment previously deposited in the

conduit system is flushed only when adequate flows occur, indicating that sediment transport in karst is marked by thresholds and is a strongly non-linear process.

Introduction

Researchers have long postulated that large storms play an important role in water and sediment transport to karst springs, but few opportunities have presented themselves to document the effects of large storms with intense rainfall. In addition to the relative rarity of these large events, the danger posed by high water levels to automated equipment and the researchers themselves has left quantifying large storm effects mostly in the realm of supposition. Nevertheless, observations of sediments in caves imply that transport during extreme storms is qualitatively different from that in more normal flow regimes.

Strong and frequent September storms in Blair County, Pennsylvania in 2004 permitted us to document the crossing of two thresholds in the Arch Spring–Sinking Run drainage basin and assess the importance of severe storms to sediment transport. Hurricanes Frances made landfall near Stuart, Florida on September 5, 2004, while Hurricane Ivan made landfall west of Gulf Shores, Alabama on September 16, 2004. Both hurricanes weakened to tropical storms and then tropical depressions while traveling northeast. Jeanne made landfall near Stuart, Florida on September 26, 2004. Though its landfall location was closer to that of Frances, its path north matched Ivan more closely. The first two storms, the remnants of Hurricanes Frances and Ivan, yielded precipitation events of 14.7 and 15.3 cm total rainfall in Central Pennsylvania, respectively. The storm associated with Jeanne was much smaller with only 4.5 cm total rain.

Though most of direct damage associated with Ivan's winds and coastal surge occurred on the Gulf Coast of Alabama and Florida, substantial damage occurred well north of landfall when Ivan-associated precipitation fell on areas already saturated by Frances nine days before. The flooding associated with Ivan, the second storm, was devastating to much of Central Pennsylvania. Flood levels in some cases exceeded those associated with Hurricane Agnes in June of 1972. At USGS gauges closest to Arch Spring, including the Little Juniata River (USGS Gauge 01558000) and the Juniata River at Huntingdon (USGS Gauge 01559000), flood stages did not exceed those associated with Agnes, but were the greatest flows observed since that storm (Figure **5-1**) (http://waterdata.usgs.gov/pa/nwis/rt).

Storms such as these may push large fluxes of rain water and allochthonous sediment through karst aquifers at rates close to those of surface water systems, but additional complicating factors are present in karst systems. Stored water and sediment in karst conduits sum with input rain water and allochthonous sediment to generate a composite signal of transport at the spring mouth. The conduits influence how these components sum by exerting flow controls. Large fluxes of sediment attendant to water level rises are frequently observed in surface and karst water systems as are large sediment deposits within karst systems assumed to be deposited following large events (Gillieson, 1986; Mahler and Lynch, 1999; Drysdale et al., 2001; Dussart-Baptista et al., 2003; Massei et al., 2003; Vesper & White, 2003). Bouchaou et al. (2002) and Amraoui et al. (2003) found strong direct correlations between increased turbidity in karst springs (and an implied increase in suspended sediment) and rain events using time series analysis, discovering that turbidity and water level are not clearly related. Ryan and Meiman (1996) also observed a timing difference between peak water and peak sediment discharge at a spring in Kentucky. These point to the complex sum of components that appears at springs during storm events.

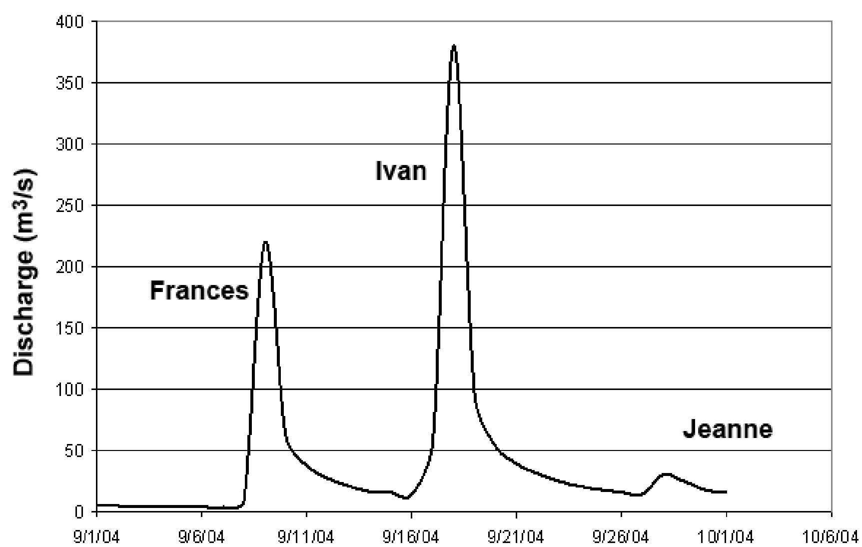


Figure 5-1: **Data from September 2004 from USGS Gauge 1558000 on the Little Juniata River at Spruce Creek.** The Little Juniata at Spruce Creek is the closest USGS Gauge to Arch Spring. The Little Juniata manifested a response similar to most surface water bodies in response to these events. Gauged surface water features in Central Pennsylvania showed a much greater water level rise in response to Ivan than Frances. Attributed to the fact that Frances's rain fell on relatively dry soil and Ivan's fell on saturated soils, this increased effect was not evident at Arch Spring.

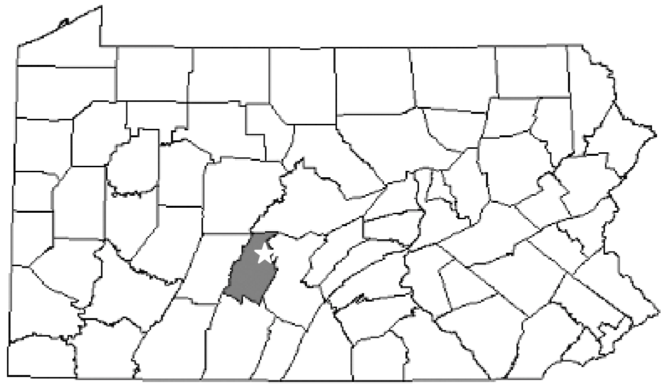
In addition to general changes that result from storm flow supplanting baseflow, we also must consider how aquifer response to large intense storms differs from response to small storms. Researchers have identified limitations imposed on aquifer infiltration in karst systems due to epikarst response to storms (Chandler & Bisogni, 1999; Perrin et al., 2003). Others have identified how frequently storm flows result in bed load transport of cobbles of certain sizes (Dogwiler & Wicks, 2004). The pathways utilized for flow in karst aquifers and the relative contributions of stored and storm water to flow can be alterd by hydrologic conditions such as low flow (Laroque et al., 1998) or recent storms (Martin & Dean, 2001).

Conceptually, it has long been known that karst conduit systems have a finite carrying capacity (e.g., White, 1988). Some drainage basins lose water through the stream channel but a fraction of the flow always remains on the surface. Some basins have distinct swallets that capture all normal flow with only storm flow spilling over into surface channels. In some blind valleys, the underground system has sufficient capacity to carry even the most extreme storms so that the former surface channel is degraded and lost. However, there are very few quantitative measurements of conduit system carrying capacities, perhaps because such measurements would require placing gauges in dry stream channels or long term continuous monitoring with low probability of success. An exception is the work of Bonacci (2001) who found upper limits on the discharge of some karst springs dependent on rainfall intensity, conduit size, and other factors. The September 2004 storms permitted us to separate multiple signals at Arch Spring and assess some thresholds imposed on transport there based on conduit structure.

Site Description

Arch Spring is the downstream outlet of a master conduit system that drains Sinking Valley, Blair County, Pennsylvania (Figure **5-2**). It is the headwater of the lower portion of Sinking Run, which drains into the Little Juniata River, a tributary of the Susquehanna River. The baseflow discharge at Arch Spring is on the order of 250 – 400 L/s. The spring and master conduit are developed in the Grazier member of the Hatter Formation, a lower unit of the Ordovician Black River Group (Rones, 1969). Below this limestone unit, the carbonate sequence consists mainly of dolomite. The recharge reaching the spring is from mountain runoff that sinks where the Reedsville Shale contacts the limestones and from direct infiltration through the limestone soils of the carbonate valley uplands.

The master conduit can be accessed through Tytoona Cave with an entrance in a collapse sink 1.2 km upstream from the spring. The initial swallet of Sinking Run is located an additional 6 km upstream from the cave entrance. Cave divers have explored almost the entire length of conduit between the cave and the spring, and though they have not made the ultimate connection, notes from multiple dives indicate that the conduits from each end are converging (Schweyan, 1986). Additional dives are currently being attempted to connect the cave and spring, and the hydraulic connection has been independently verified by a qualitative dye trace (McCarthy, 2001). Figure **5-3** maps the location of the conduit based on the diver's logs and personal accounts.



a)

b)

Figure 5-2: **Location Map and Digital Elevation Model of the Basin**

a) The map of Pennsylvania shows county outlines with Blair County highlighted and Arch Spring marked with a star (★).

b) This southwest looking 3-meter digital elevation model (DEM) of Sinking Valley shows the breached anticline at 3x vertical exaggeration with a ridge of Cambrian Gatesburg formation splitting the valley. Sinking Run flows to the east of this ridge.

These maps were created with data from the Pennsylvania Geospatial Data Clearinghouse at Penn State, accessible at http://www.pasda.psu.edu/.

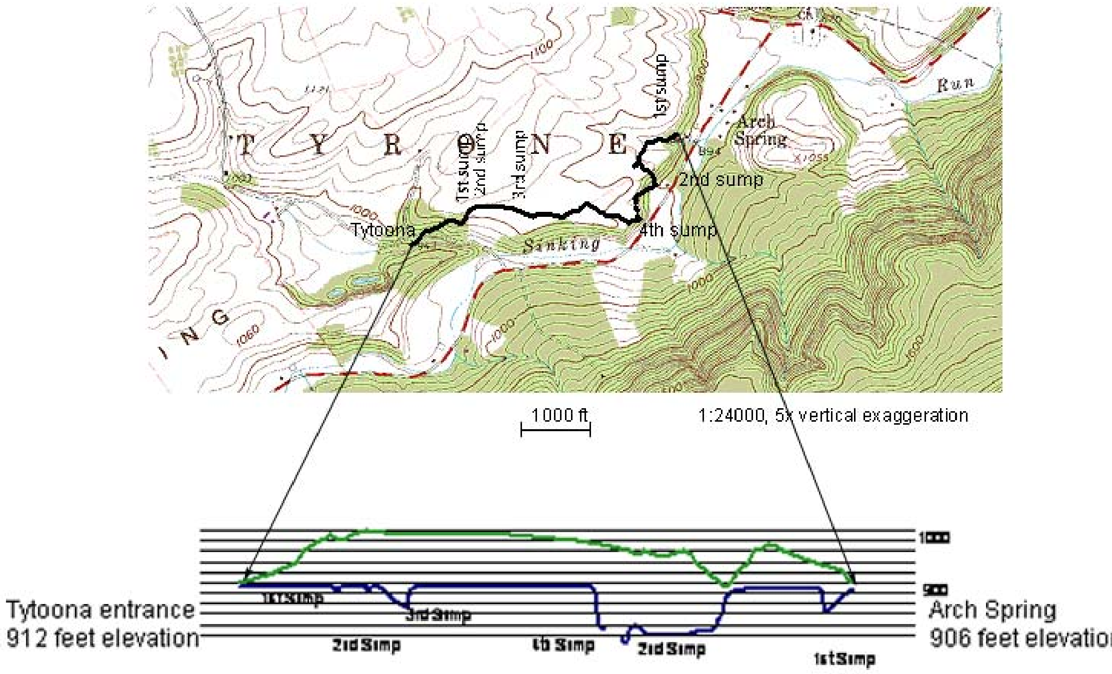


Figure 5-3: **Cross-section of conduit between Tytoona Cave and Arch Spring**

The path of the cave down the valley is based on survey data in the air-filled portion of the cave and divers notes from beyond the sumps on both the Tytoona Cave and Arch Spring sides. The callout is a cross-section of the area with the land surface sketched over the cave elevations, also based on divers' observations. Note English units on map and cross-section.

The conduit system that connects Tytoona Cave and Arch Spring has multiple lengths of air-filled passage interrupted by at least five sumps through continuously water-filled passage. There is evidence from remarkably long soda straw speleothems in an air-filled chamber beyond the first sump that portions of the air-filled conduit system rarely if ever fill with water, indicating that the transition from open channel to closed pipe flow and back again is always present in the cave even during high flows.

For 2.4 km downstream below the initial swallet, the main surface channel of Sinking Run is degraded until it reaches a major tributary. Downstream from this junction the surface channel is well-defined and frequently filled with water from the tributary. The surface channel extends parallel but to the south of Tytoona Cave until it joins Sinking Run after it has just emerged from Arch Spring. Only following large storms and high water events is water visible in this segment of the surface channel. This segment represents a rarely activated alternate pathway for water that would normally flow through Tytoona Cave to Arch Spring. During Frances, a bridge over this segment of the surface channel was washed away. Following Frances, highway workers began to rebuild the bridge, but the new construction and a large dump truck were washed off the bridge during Ivan (G. Czmor, personal communication).

Methods

From December 2002 to April 2005, we maintained automated equipment at Arch Spring. The suite of monitoring equipment included a data logger recording stage, conductivity, and temperature at a fixed point in the spring outflow at 15 to 20-minute intervals and an ISCO™ storm water sampler with an actuator that was triggered by an adequate water level rise. The storm water sampler, once triggered, collected 24 water samples from the spring at a programmed interval. In addition to the automated equipment, we made site visits at bi-weekly to monthly intervals to take two grab samples of water and record pH, temperature, conductivity, and water level. With the exception of the winter months when the storm water sampler wasn't operating, site visits were also used to collect and replace the bottles in the automated sampler.

The storm samples from the ISCO and one of the grab samples were sequentially filtered through 5 μm and 0.45 μm cellulose nitrate membranes to collect suspended sediment. Membranes were then weighed to determine the concentration of total suspended solids. Selected sediment samples were examined using a scanning electron microscope (SEM) in low-vacuum mode with accompanying energy dispersive x-ray analysis (EDX). The second grab sample was field filtered and used for major ion analysis, including alkalinity by titration. Those results are not reported here.

Rainfall data were taken from the NOAA gauge at the Altoona Blair County Airport (AOO). Data are available from the National Climatic Data Center on-line at http://www.ncdc.noaa.gov/oa/ncdc.html. The gauge at AOO is located 36 km from the spring and records data hourly. There is a closer NOAA weather station at Tyrone, PA, but as that station records daily precipitation rather than hourly, it was used only to verify that portions of Pennsylvania received similar amounts of rainfall during the periods studied.

Results: Water Level Threshold

This study examines events related to three successive hurricane-related storm events during September 2004. Each storm resulted in water level rises, but the increases were not directly related to the size of the storm event (Figure **5-4**a).

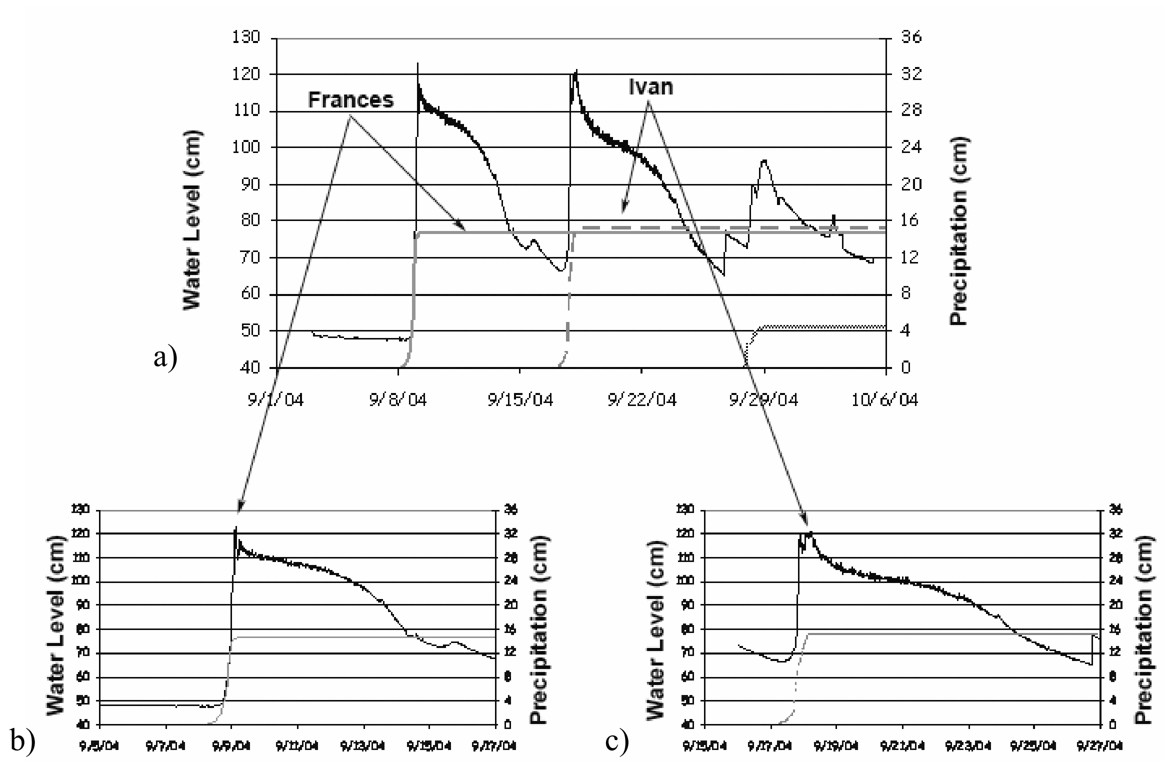


Figure 5-4: **Water level data recorded at Arch Spring and cumulative precipitation data recorded at the Blair County – Altoona Airport in September of 2004**

a) Remnants of hurricanes Frances, Ivan, and Jeanne arrived in Central Pennsylvania in September of 2004. The associated cumulative rainfall for each storm is shown with the water level in Arch Spring.

b) The cumulative rain and Arch Spring water level associated with Hurricane Frances.

c) The cumulative rain and Arch Spring water level associated with Hurricane Ivan.

The water level rises for Frances and Ivan were 74 cm and 54 cm above background, respectively (Figures **5-4b** & **5-4c**), even though slightly more precipitation fell during Ivan. Jeanne had the smallest associated precipitation (only 4.5 cm) but still caused a 25 cm rise in water level. Both Frances and Ivan caused the water level to rise to the same level, 120 cm, which was the maximum water level observed over the 2.5 years of observation The ~120-cm level at Arch Spring measured represents a plateau in discharge at which the conduit system is operating at full capacity. Once the spring rises to this level, excess storm-flow is diverted into the normally dry surface channel. The morphology of the conduit appears to play a role in controlling the maximum discharge levels as there are portions of the conduit system that never flood regardless of the input.

Results: Sediment Threshold

The automatic sampler was deployed at the spring during the first hurricane, Frances. Samples were collected every 2 hours from 12:19am on September 9, 2004 until 10:19pm on September 10, 2004 (Figure 5-5). The sampler triggered 20 hours following the onset of rain associated with Frances at the AOO rain gauge and two hours after the most intense periods of Frances rainfall.

Several samples had much higher sediment concentrations than previously observed. The first very high concentration of sediment (sample of 9/9/04, 2:19a.m.) arrived at the spring coincident with high conductivity stored water, while the second high concentration sample was taken just as the low conductivity storm water began to arrive at the spring (Figure 5-5). The piston flow of stored water through the spring prior to the arrival of storm water is well-documented in karst systems (Dreiss, 1989; Desmarais & Rojstaczer, 2002; Ryan and Meiman, 1996). Arch Spring manifests this flushing with water of increased conductivity reaching the spring followed by the lower conductivity rainfall-associated water. The concurrent arrival of stored water and sediment-laden water indicates that at least a portion of the sediment pulse was stored sediment rather than sediment flushed into the aquifer by surface runoff.

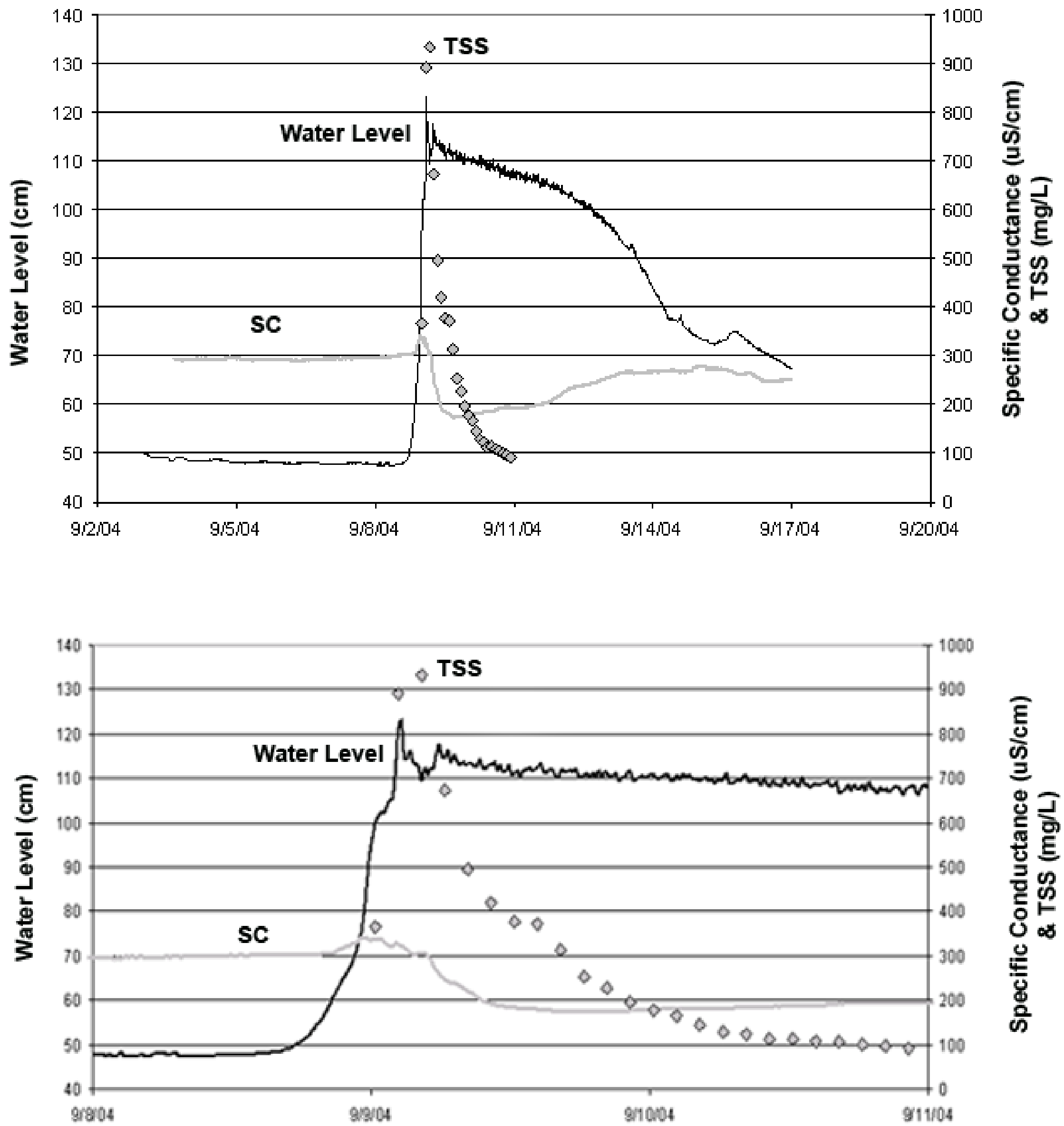


Figure 5-5: **Arch Spring water level, specific conductance, and total suspended solids associated with Hurricane Frances. Lower graph shows magnified scale for the Frances event.**

The gross appearance of these samples was distinct from prior samples with a darker color and with much more sediment than in prior storms, particularly early in the storm sequence. The Frances samples contained up to an order of magnitude greater sediment concentration than the majority of samples collected during storms at Arch Spring in 2004 (Figure **5-6**). Though sediment concentration increased during the hurricanes and appeared darker during filtering, sediment composition itself appeared very similar to that of other storms at Arch Spring (Figure **5-7**). Arch Spring discharges primarily siliciclastic particles during baseflow and storm flow (Herman et al., in press). Sediment mass increased but sediment mineralogy wasn't substantially changed during this very high flow event. The sample bottles were not replaced prior to Ivan's and Jeanne's rainfall, and no samples were collected during these storms.

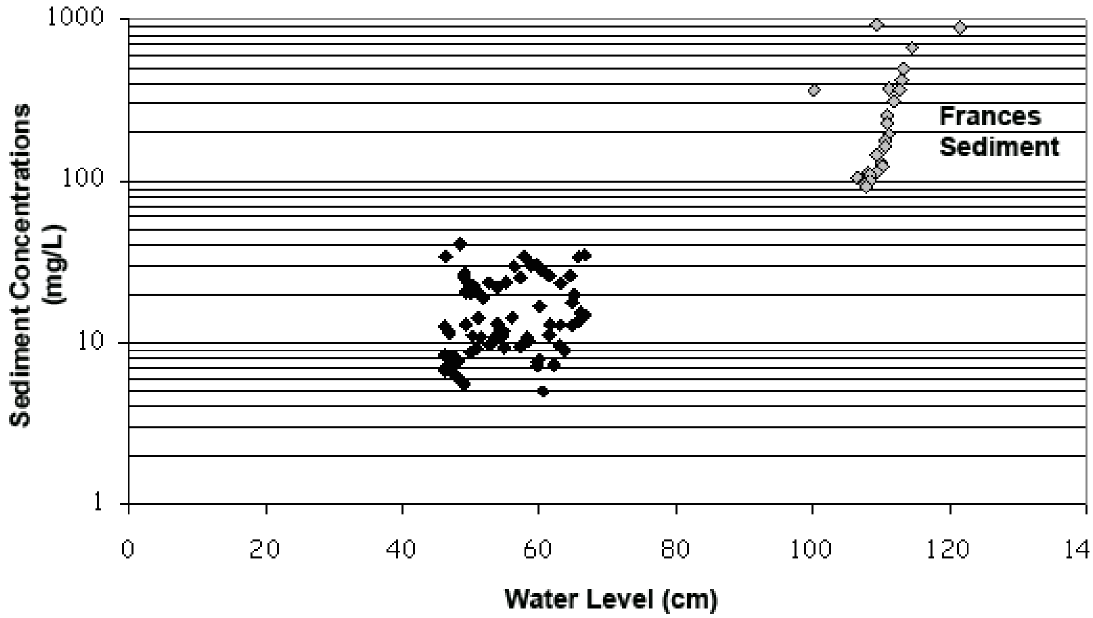


Figure 5-6: **Sediment concentrations associated with 2004 samples storms at Arch Spring**

The sediment concentrations through the Frances-associated storm are much higher than the other storm concentrations in 2004. Samples collected during other times in the monitoring period occasionally approached 100 mg/L, but in general were much less concentrated.

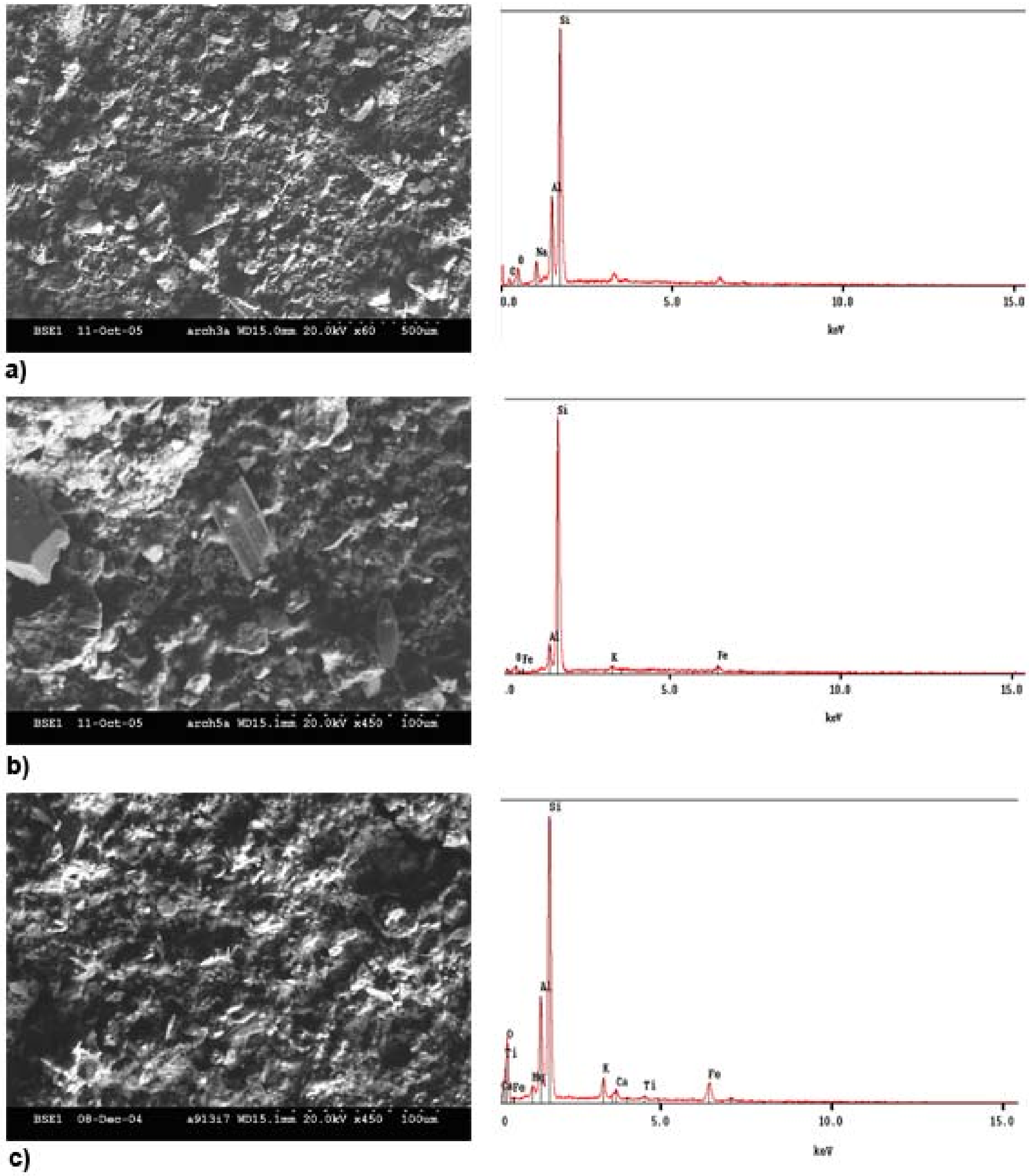


Figure 5-7: **SEM images of Arch Spring sediment across a range of conditions including Hurricane Frances.** a) This sample was collected by the sampler at 4:19am on 9/9/04 and is the most concentrated sediment collected at the site. b) This sample was collected by the sampler on 9/9/04 at 8:19am. c) This sample was collected by the sampler on 9/1/03 at the peak sediment concentration associated with a small storm event.

Discussion

The limitation imposed on flow at Arch Spring at a stage of ~120-cm was only revealed because of the serendipitous succession of the Frances and Ivan storms. The spring had reached this water level previously during the monitoring period on January 1, 2004 when a heavy rain of 3.5-cm fell on a sizeable snow pack in the drainage basin. This event melted much of the snow pack and flushed it, along with the precipitation, through the spring. There was spillover into the surface channel, but because there was no following event of equal or greater magnitude, the rise appeared to be simply the appropriate level for that amount of precipitation and snowmelt added to the system. The maximum level at Arch Spring during the snowmelt event reached the limit of the underground system, but there was not adequate information from the single event to determine that the spring level indeed could go no higher.

Once the remnant hurricanes passed through in 2004, it became clear that large storms are instead shifting the excess flow into the surface channel once the upper limit of the Arch Spring system is reached. Our monitoring revealed that the size of the storm is not the only control on water level increases. Instead, the conduit system itself is limiting the flow and setting a threshold level. This regulation may be enforced by channel constrictions such as the collapses upstream from the Tytoona Cave entrance or by the conduit undulations and shifts from open channel to pipe flow in the underground system. Evidence for constrictions comes from long soda straw speleothems which show water never fills the chamber past the first sump. Modeling by Halihan et al. (1998) investigated the importance of cave constrictions in regulating flow. They characterized constrictions as the most important feature in limiting flow in Devil's Ice Box Cave in Missouri, but did not investigate the role of permanently air-filled chambers in the conduit. Based on our observations, we cannot discount the role of the air-filled chambers in favor of the constrictions without further investigation.

Karst systems act as mixing and storage chambers for sediment, accumulating stored sediment in fractures and conduits. These storage areas may either be dry where sediment accumulated was left behind after higher flows, or water may remain but be moving slowly enough for finer sediment to settle. This storage is evident in Tytoona Cave where cobbles line the stream bed and finer sediments have accumulated on the banks and in areas where the flow slows. Cave divers exploring the system also report transient sediment storage in the form of an easily mobilized, fine-grained slurry that coats walls and ceilings within the sumps. This loosely deposited sediment is easily mobilized during minor storm flows and is likely the material observed at the spring during minor storm flows (Figure 5-6).

The increased sediment concentrations that resulted from Frances appear to be in large part from the stored sediment. One of the more intense sediment pulses at Arch Spring arrived coincident with the high conductivity stored water rather than the low-conductivity storm water indicating the sediment too was from the stored component. The exact source of this sediment in the conduit is difficult to determine. The sediment might represent a flush of the slurry-like sediment accumulations in the conduits that the divers have observed. More likely the increased shear stress generated by the piston flow may have mobilized compacted fine-grained sediment in the water-filled conduits or along the banks of the air-filled chambers, compounding the nature of the non-linear relationship between discharge and sediment concentration. There are no discernible differences in composition between the storm-related sediment at Arch Spring and baseflow sediment. Given the very high concentrations of sediment compared with more ordinary storms in the system, it is likely that the sediment mobilized by the Frances storm represents a rarely tapped release of sediment. This has implications for the persistence of sediment-associated contaminants in the system (Loop & White, 2001; Dussart-Baptista et al., 2003).

Conclusion

Observations of the Arch Spring karst drainage system during exceptional runoff from Hurricanes Frances and Ivan revealed quantitatively the magnitude of discharge necessary to override the karst drainage system and spill excess discharge into the surface channel. In terms of suspended solids, our data indicate that extraordinary quantities of sediment were dislodged from storage and moved through the system during threshold-exceeding events. Our observations document the strongly non-linear behavior of karst discharge following large rain events and illustrate the necessity of event-based monitoring in these systems.

References

Amraoui, F., Razack, M., and Bouchaou, L., 2003. Turbidity dynamics in karstic systems. Example of Ribaa and Bittit springs in the Middle Atlas (Morocco). Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 48: 971-984.

Bonacci, O., 2001. Analysis of the maximum discharge of karst springs. Hydrogeology Journal, 9: 328-338.

Bouchaou, L., Mangin, A., and Chauve, P., 2002. Turbidity mechanism of water from a karstic spring: example of the Ain Asserdoune spring (Beni Mellal Atlas, Morocco). Journal of Hydrology, 265: 34-42.

Chandler, D. G. and Bisogni, J. J. 1999. The use of alkalinity as a conservative tracer in a study of near-surface hydrologic change in tropical karst. Journal of Hydrology, 216: 172-182.

Desmarais, K. and Rojstaczer, S., 2002. Inferring source waters from measurements of carbonate spring response to storms. Journal of Hydrology, 260: 118-134.

Dogwiler, T. and Wicks, C.M., 2004. Sediment entrainment and transport in fluviokarst systems. Journal of Hydrology, 295: 163-172.

Dreiss, S. J., 1989. Regional scale transport in a karst aquifer; 1, Component separation of spring flow hydrographs. Water Resources Research, 25: 117-125.

Drysdale, R., Pierotti, L., Piccini, L., and Baldacci, F., 2001. Suspended sediments in karst spring waters near Massa (Tuscany), Italy. Environmental Geology, 40: 1037-1050.

Dussart-Baptista, L., Massei, N., Dupont, J. P., and Jouenne, T., 2003. Transfer of bacteria-contaminated particles in a karst aquifer: evolution of contaminated materials from a sinkhole to a spring. Journal of Hydrology, 284(1-4): 285-295.

Gillieson, D., 1986. Cave sedimentation in the New Guinea Highlands. Earth Surface Processes and Landforms, 11: 533-543.

Halihan, T., Wicks, C.M., and Engeln, J.F., 1998. Physical response of a karst drainage basin to flood pulses: Example of the Devil's Icebox cave system (Missouri, USA). Journal of Hydrology, 204: 24-36.

Herman, E.K., Tancredi, J.H., Toran, L., and White, W.B., in press. Mineralogy of suspended sediment in three karst springs. Hydrogeology Journal, XX: XXX-XXX.

Larocque, M., Mangin, A., Razack, M., and Banton, O., 1998. Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). Journal of Hydrology, 205: 217-231.

Loop, C. M. and White, W.B., 2001. A conceptual model for DNAPL transport in karst ground water basins. Ground Water, 39: 119-127.

Mahler, B. J. and Lynch, F.L., 1999. Muddy waters: temporal variation in sediment discharging from a karst spring. Journal of Hydrology, 214: 165-178.

Martin, J. B. and Dean, R.W., 2001. Exchange of water between conduits and matrix in the Floridan aquifer. Chemical Geology, 179: 145-165.

Massei, N., Wang, H.Q., Dupont, J. P., Rodet, J., and Laignel, B., 2003. Assessment of direct transfer and resuspension of particles during turbid floods at a karstic spring. Journal of Hydrology, 275: 109-121.

McCarthy, S.C, 2001. Using dye tracers to delineate flow patterns through two karst basins : Kooken Cave, Huntingdon County and Tytoona Cave, Blair County, PA. B.S. thesis, The Pennsylvania State University.

Perrin, K., Jeannin, P. Y., and Zwahlen, F., 2003. Epikarst storage in a karst aquifer: a conceptual model based on isotopic data, Milandre test site, Switzerland. Journal of Hydrology, 279(1-4): 106-124.

Rones, M., 1969. A lithostratigraphic, petrographic and chemical investigations of the lower Middle Ordovician carbonate rocks in central Pennsylvania. Pennsylvania Geologic Survey General Geology Report 53, 224 pp.

Ryan, M. and Meiman, J. 1996. An examination of short-term variations in water quality at a karst spring in Kentucky. Ground Water, 34: 23-30.

Schweyan, J., 1986. Tytoona Cave / Arch Spring, Blair County. Speleo Digest, 21: 205-207.

Vesper, D. J. and White, W.B., 2003. Metal transport to karst springs during storm flow: an example from Fort Campbell, Kentucky/Tennessee, USA. Journal of Hydrology, 276: 20-36.

White, W.B., 1988. Geomorphology and hydrology of karst terrains. Oxford University Press: New York, 464 pp.

Chapter 6

Conclusions

Though the effects of storms on karst water chemistry have been actively investigated for decades, sediment transport and the effects of storm events on sediment have received less attention from karst researchers. Yet, sediment fluxing through and being stored in the aquifer is essential to the understanding of karst function and to predicting contaminant transport behavior. Deductions from cave and spring data must form the basis for our descriptions of the processes transporting sediment through karst systems, but observation points in karst are sparse.

Relating conduit morphology, water flux and sediment transport behavior is one of the fundamental problems in karst. Ultimately, the goal is deducing past flows based on sediment deposits and predicting future sediment transport events based on flow conditions. The facies classification system presented for karst sediment deposits enable comparison to well-studied surface deposits and application of the basic equations governing sediment transport. The conceptual models presented here are intended to stimulate research.

Collecting long-term data sets is the first step toward improving our understanding of these systems, but the variability inherent in the data requires tools such as time series analysis for accurate interpretation of trends and characteristics. Time series analysis of data sets from springs, streams, and wells indicates that karst springs exhibit different temporal behavior than either surface water or groundwater in porous media. Karst aquifers must be treated as a complex combination of both. The combination will be dependent on the structure of the karst system (for example the conduit structure of Arch Spring), the input storms to the system, and the basin size. This study also demonstrates the need for caution when using short data sets on the order of one year for time series analysis of springs.

The variety and quantity of sediment discharged from springs can be useful in deducing flow patterns, particularly when shifting flow patterns result in sediment of different composition. The calcite sediment at Nolte Spring enabled us to deduce some processes occurring in the spring system that were counter-intuitive based on water chemistry at the outlet alone. This study in particular demonstrates the usefulness of incorporating sediment questions into any basic analysis of karst systems. While researchers have quite long records of water chemistry in karst resources, very few long-term records of sediment transport exist, limiting the usefulness of these data sets.

While the data collected are particularly useful at pointing out the complexities of interpreting karst aquifer systems based on spring output, data from the outlet alone are unlikely to allow us to identify the source of the behaviors we observe. Because conduit data are not typically available or data are discontinuous, interpretations based on spring output are non-unique. The next logical step is generating a computer model that will allow examination of how various channel and conduit attributes affect karst system behavior, particularly with regard to the generation of shear stresses necessary to transport sediment. The data collected in the course of this study clearly indicate that conduit morphology plays an essential role in regulating discharge and shear stress, but specification beyond this general statement is difficult without the kind of shear stress distributions that can be generated with a computational fluid dynamics code. This model is in the planning stages and combined with further field monitoring will form the basis of future research.

In this study, results from individual large scale storms were perhaps the most revealing events in the karst system, offering insight into the relationship (or lack thereof) between spring flow and sediment mobilization. The storm observations in this study permitted us to determine that sediment transport in karst is a strongly non-linear function of spring discharge and shear stresses, where sediment storage in karst aquifers results in thresholds for entrainment that are activated only by very large storms. This study points toward the importance of individual large storm events and storm events in general to the understanding of karst system functioning.

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Toran, L., Herman, E.K., and White, W.B., *submitted 2006*, Variation in flow paths to a well and spring in a poorly integrated karst system. *Groundwater*.

Herman, E.K., Tancredi, J., Toran, L., and White, W.B., *in press*, Mineralogy of suspended sediment in karst springs in relation to spring water chemistry. *Hydrogeology Journal*.

Toran, L., Tancredi, J.H., Herman, E.K., and White, W.B., *2006,* Conductivity and sediment variation during storms as evidence of pathways in karst springs, *in* Harmon, R.S., and Wicks, C., eds., *Perspectives on karst geomorphology, hydrology, and geochemistry – A tribute volume to Derek C. Ford and William B. White*. Geological Society of America Special Paper 404, 169-176.

Herman, E.K. and Kump, L.R., *2005*, Response of microbial mats to Precambrian environmental conditions: a modeling study. *Geobiology* 3, 77-92.