

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

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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 for springs ranged from 5 to 9 days, while streams ranged from 1 to 6 days and wells from 6 to 10 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 appear due to data collection differences rather than system characteristics.

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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; however, 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:

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

where k is a point in the series, r_k is the autocorrelation coefficient at any 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 auto-correlation function drops off quickly indicating that precipitation has low inertia. Nonetheless, a karst spring with high storage would be expected to manifest an auto-correlation 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:

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

$$D_k = \frac{1}{2} \left(1 + \cos \pi \frac{k}{m} \right) \quad (3)$$

where f is a given frequency and D_k is the Tukey filter (LaRocque et al. 1998; Amraoui et al., 2003). The regulation time of the system determines the impulse response or the length of time the input signal persists in the system:

$$T_{reg} = \frac{S(f=0)}{2} \quad (4)$$

where $S(f=0)$ is the intensity of the spectral density function at a frequency of zero (Larocque et al., 1998). The regulation time is half of the maximum spectral intensity as the frequency goes to zero and the period goes toward infinity. The regulation time is a way of comparing systems and can be thought of as the time at which half of the system signal has been exhausted or a passing band in signal treatment (Larocque et al., 1998). 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.

Autocorrelation coefficients (r_k) and regulation times (T_{reg}) in different spring, surface water, and groundwater systems allow determination of system inertia regardless of system size or physical manifestation.

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 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 m³/s) and drainage areas (from 3 to 25 km²). Key characteristics of each site including drainage basin area, baseflow, periods analyzed, and recording intervals are presented in Table 1a. 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.

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 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).

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 1 presents their location; Figure 2 illustrates a sample stream data set; and Table 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 2). Figure 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 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 2 outlines how calculated system lag time is affected by several variations in data set length.

Figure 3 presents results from Blair County for 2003 (Figure 3a & 3b) and 2004 (Figure 3c & 3d). Table 3 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.

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.

Figures 4 and 5 and table 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 short regulation times to match. The Huntingdon County well showed a much longer characteristic lag and regulation time. 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. Although the Susquehanna, with the highest flow in the system, has a longer response time, the shape of the autocorrelation function is similar to the faster responding streams.

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 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 likely 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 by no means 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 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 long 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 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 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 evapotranspiration.

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.

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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 corrélatrice 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* XX, XXX-XXX.
- 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.

Tables

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Figure 3:

a) Plot of 2003 auto-correlation 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.

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Figure 4:

a) Plot of auto-correlation 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.

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Figure 5:

a) Plot of 2003 auto-correlation 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.

Table 1
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 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

¹ From Hull 1980

Table 2

Name	Water Resource Type	Period	Characteristic Lag (days)
Arch Spring	Spring	01/2003 to 12/2003	25.04
		01/2003 to 12/2004	28.46
Bald Eagle Creek at Tyrone	Stream	01/2003 to 12/2003	3.13
		08/2002 to 05/2005	3.17
Juniata River at Mapleton Depot, PA	Stream	01/2003 to 12/2003	7.08
		08/2002 to 05/2005	9.46
Susquehanna River at Marietta, PA	Stream	01/2003 to 12/2003	8.79
		08/2002 to 05/2005	9.88
Blair County Observation Well USGS BA-74	Well	01/2003 to 12/2003	26.21
		08/2002 to 05/2005	35
Huntingdon County Observation Well USGS HU-301	Well	01/2003 to 12/2003	23.13
		08/2002 to 05/2005	30.58
Lancaster County Observation Well USGS LN-1351	Well	01/2003 to 12/2003	23.79
		08/2002 to 05/2005	36.21

Table 3

Name	Period	Characteristic Lag (days)	T_{reg} (days)
Arch Spring	01/2003 to 12/2003	25.04	22.5
	01/2004 to 12/2004	12.51	15.42
Near Tippery Spring	08/2004 to 05/2005	6.74	18.91
Tippery Spring	08/2004 to 05/2005	5.55	20.15
Nolte Spring	02/2003 to 12/2003	15.13	22.85
Bald Eagle Creek at Tyrone	01/2003 to 12/2003	3.13	1.82
	01/2004 to 12/2004	2.04	1.76
	08/2004 to 05/2005	2.25	3.07
Frankstown Branch, Juniata River at Williamsburg, PA	01/2003 to 12/2003	5.04	3.07
	01/2004 to 12/2004	1.92	2.93
	08/2004 to 05/2005	1.58	3.02
Juniata River at Huntingdon, PA	01/2003 to 12/2003	6.08	3.67
	01/2004 to 12/2004	2.46	3.13
	08/2004 to 05/2005	2.04	3.24
Juniata River at Mapleton Depot, PA	01/2003 to 12/2003	7.08	3.88
	01/2004 to 12/2004	10.04	4.61
	08/2004 to 05/2005	9.38	4.98
Little Juniata River at Spruce Creek, PA	01/2004 to 12/2004	1.88	2.50
	08/2004 to 05/2005	1.67	2.65
Conestoga River at Conestoga, PA	01/2003 to 12/2003	1.99	3.02
	01/2004 to 12/2004	1.29	1.28
	08/2004 to 05/2005	1.88	2.10
Little Conestoga Creek near Millersville, PA	01/2003 to 12/2003	1.00	1.80
	01/2004 to 12/2004	0.67	0.82
	08/2004 to 05/2005	1.00	1.77
Susquehanna River at Marietta, PA	01/2003 to 12/2003	8.79	5.43
	01/2004 to 12/2004	5.33	4.63
	08/2004 to 05/2005	9.13	5.56
Blair County Observation Well USGS BA-74	01/2003 to 12/2003	26.21	9.62
	01/2004 to 12/2004	19.13	9.02
	08/2004 to 05/2005	11.21	6.28
Huntingdon County Observation Well USGS HU-301	01/2003 to 12/2003	23.13	7.99
	01/2004 to 12/2004	21.25	9.43
	08/2004 to 05/2005	11.88	8.43
Lancaster County Observation Well USGS LN-1351	01/2003 to 12/2003	23.79	9.41
	01/2004 to 12/2004	14.50	7.96
	08/2004 to 05/2005	11.25	6.01

Figures

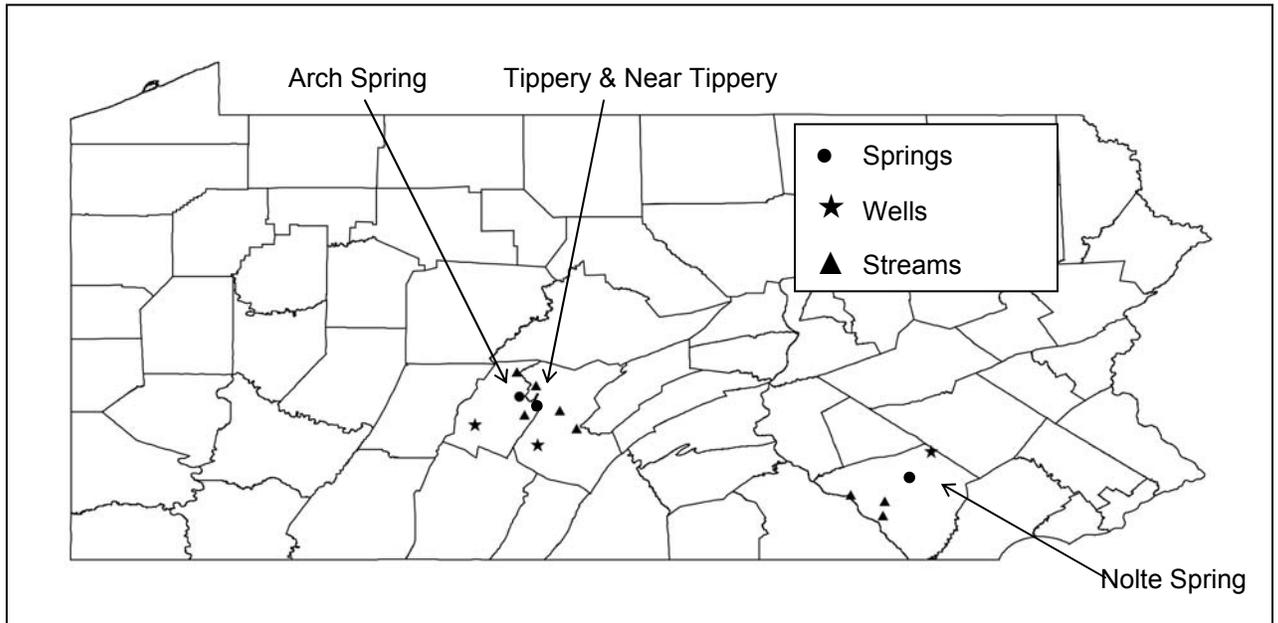
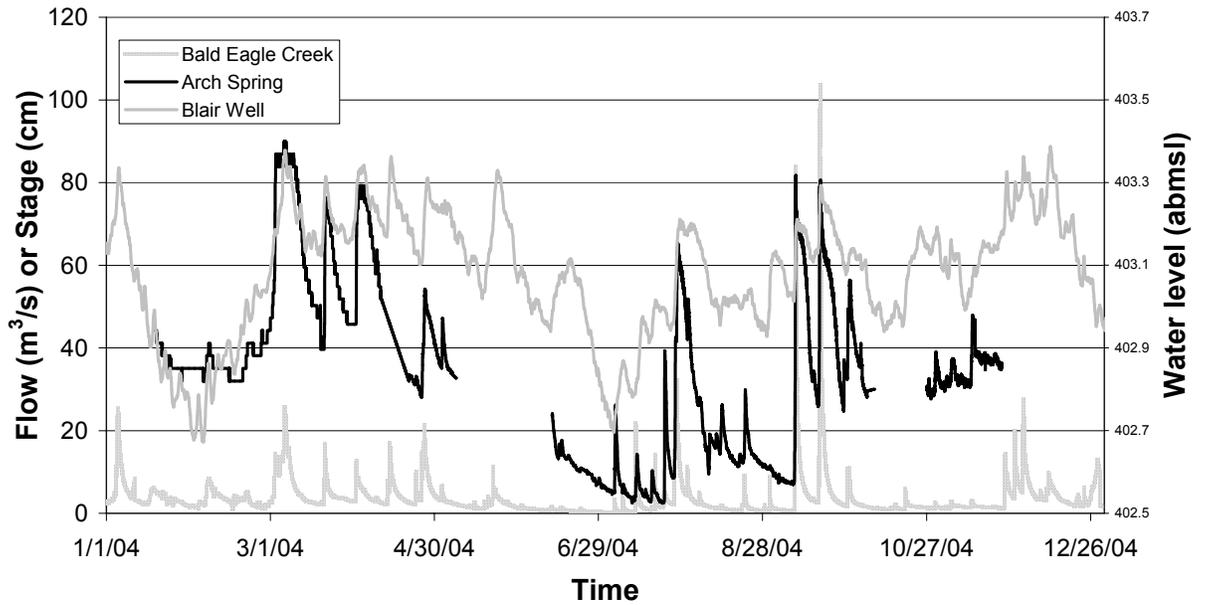


Figure 1: Location map of Pennsylvania with four springs, three wells, and eight gauging stations, county outlines

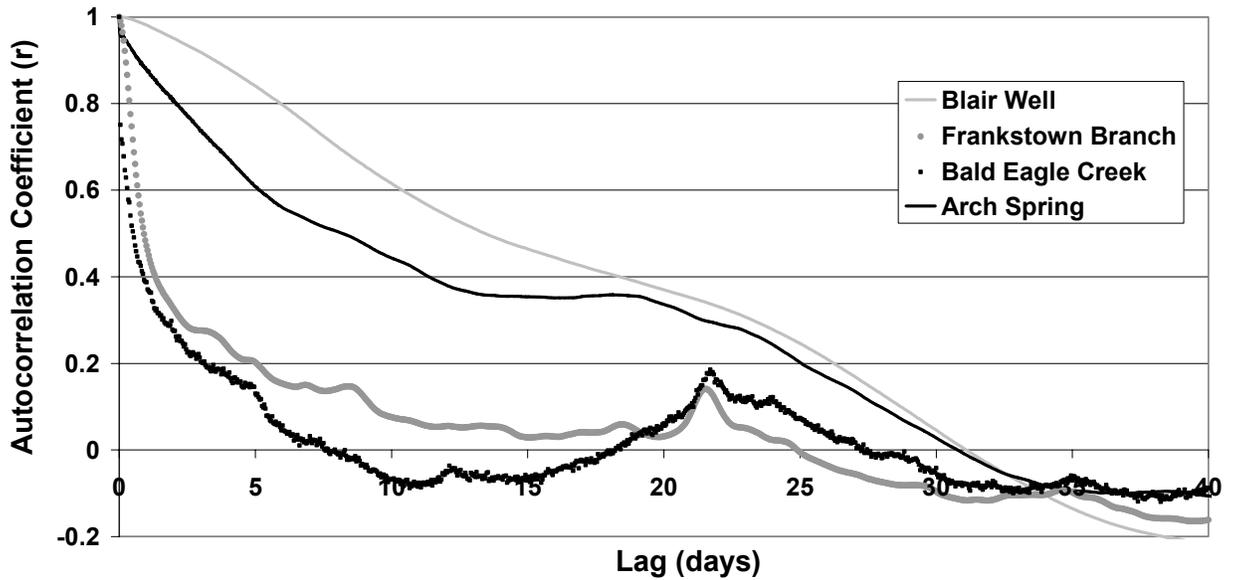
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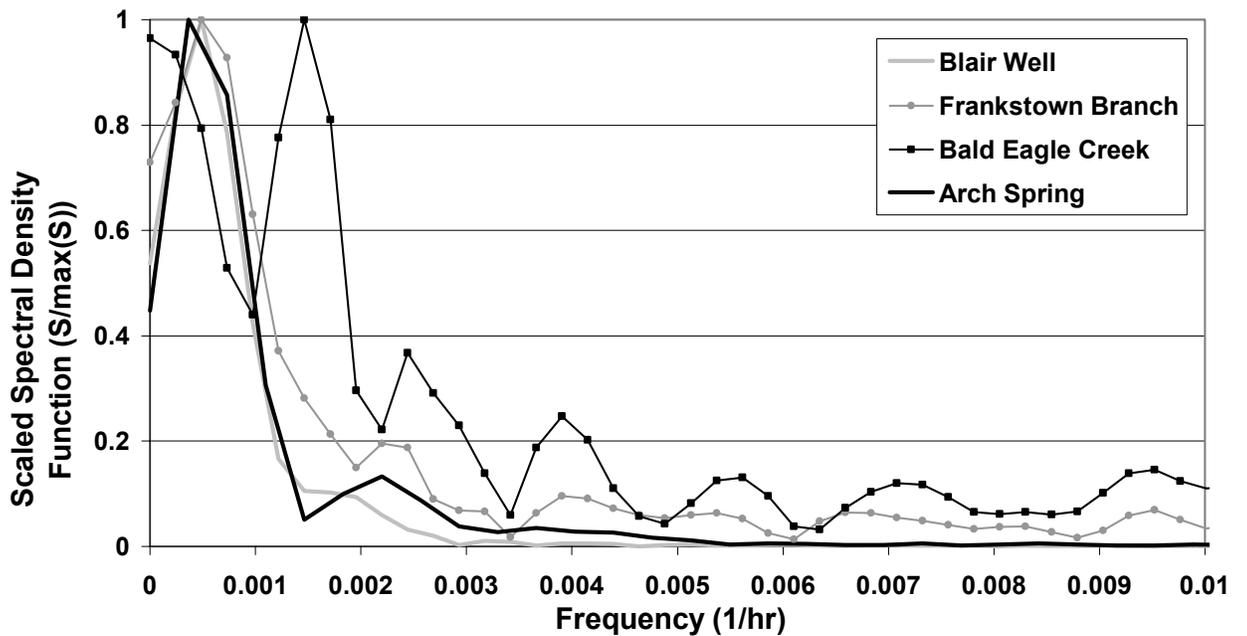
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a)



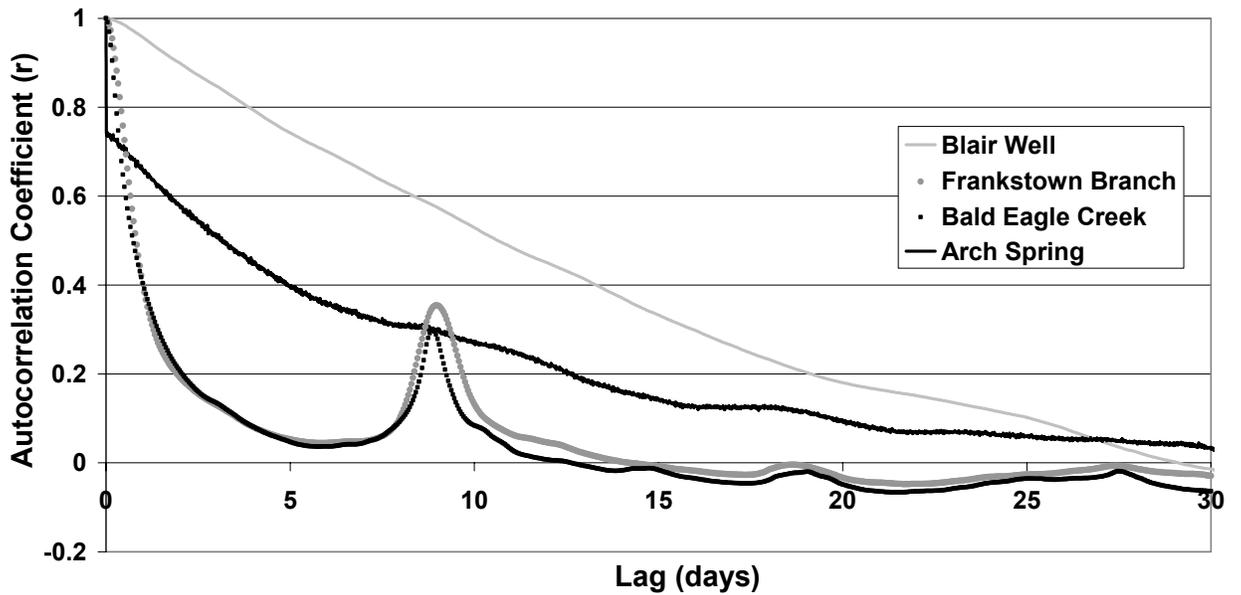
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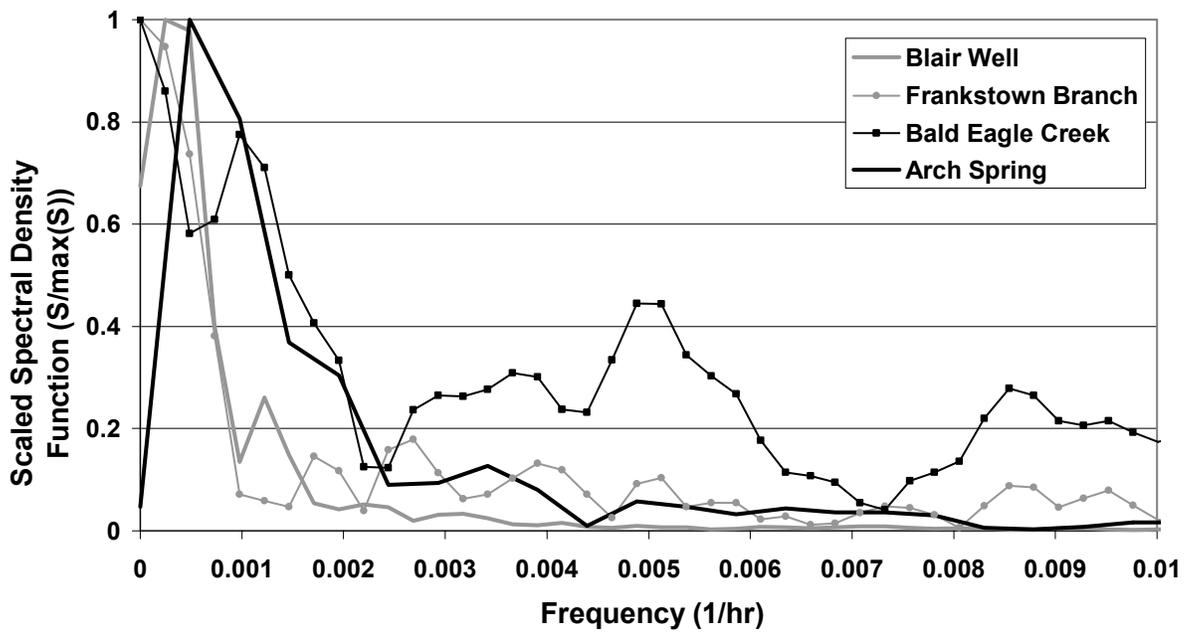
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c)



d)

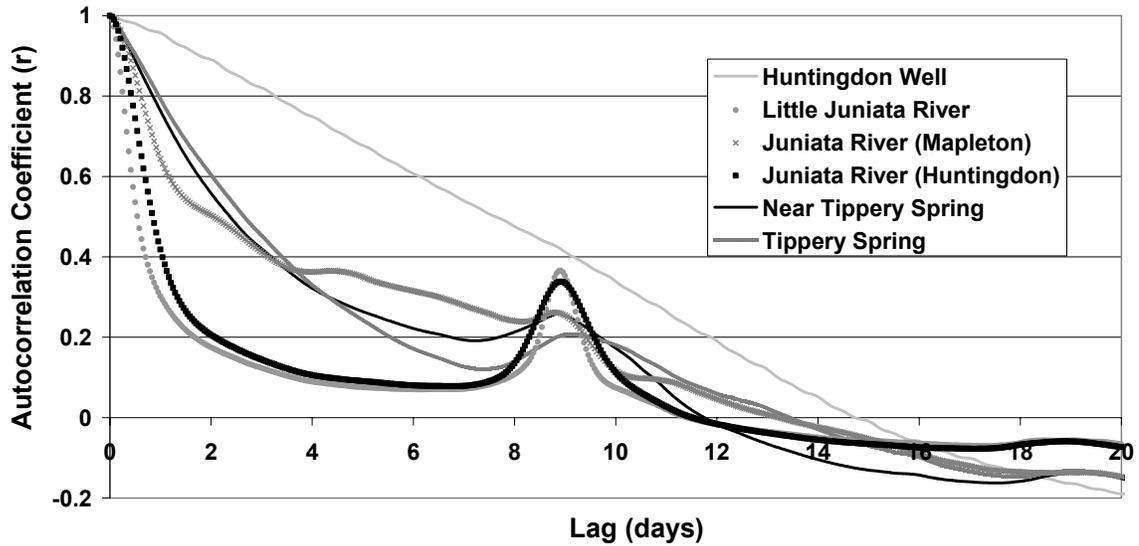


c) Plot of 2004 auto-correlation functions for water resources in Blair County: Arch Spring; Bald Eagle Creek at Tyrone; Frankstown Branch of the Juniata River at Williamsburg; and the Blair County drought monitoring well.

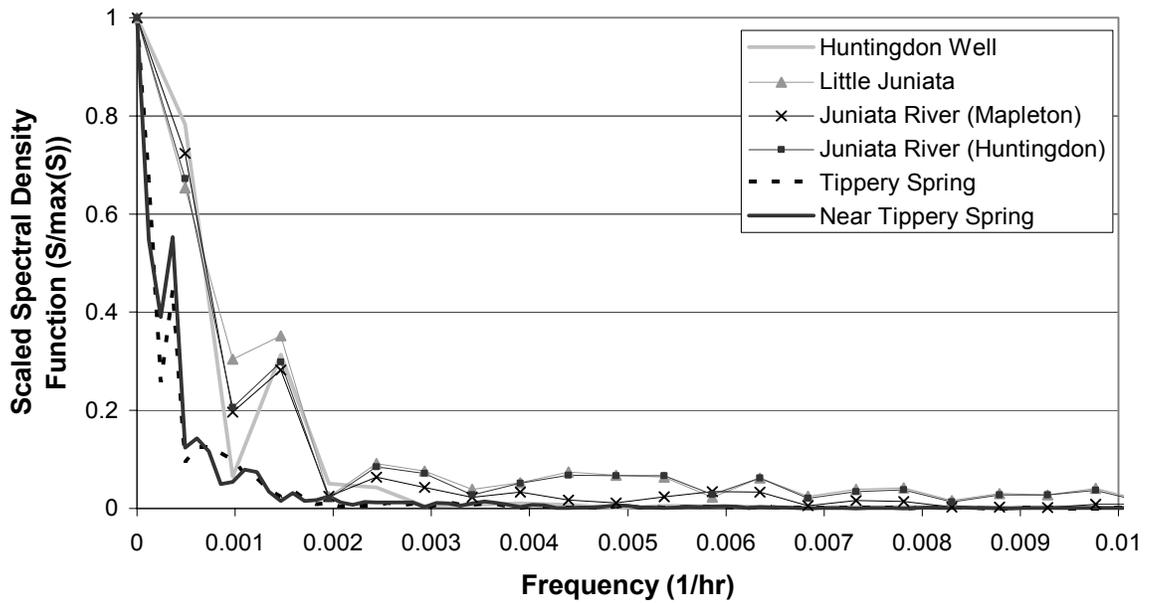
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Figure 4:

a)



b)

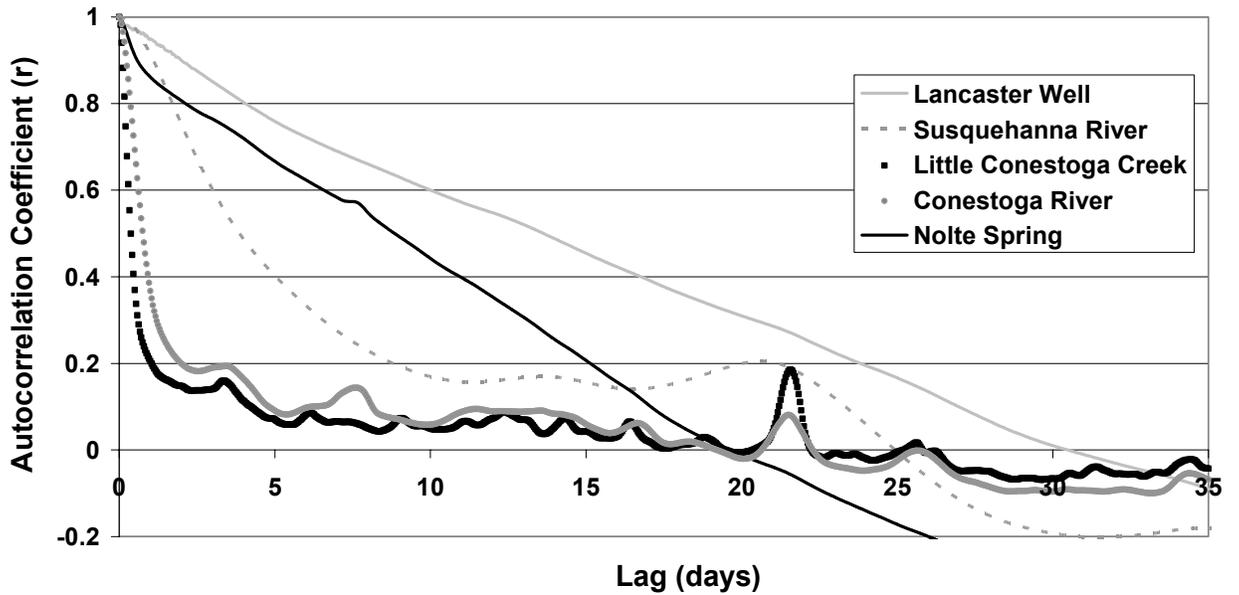


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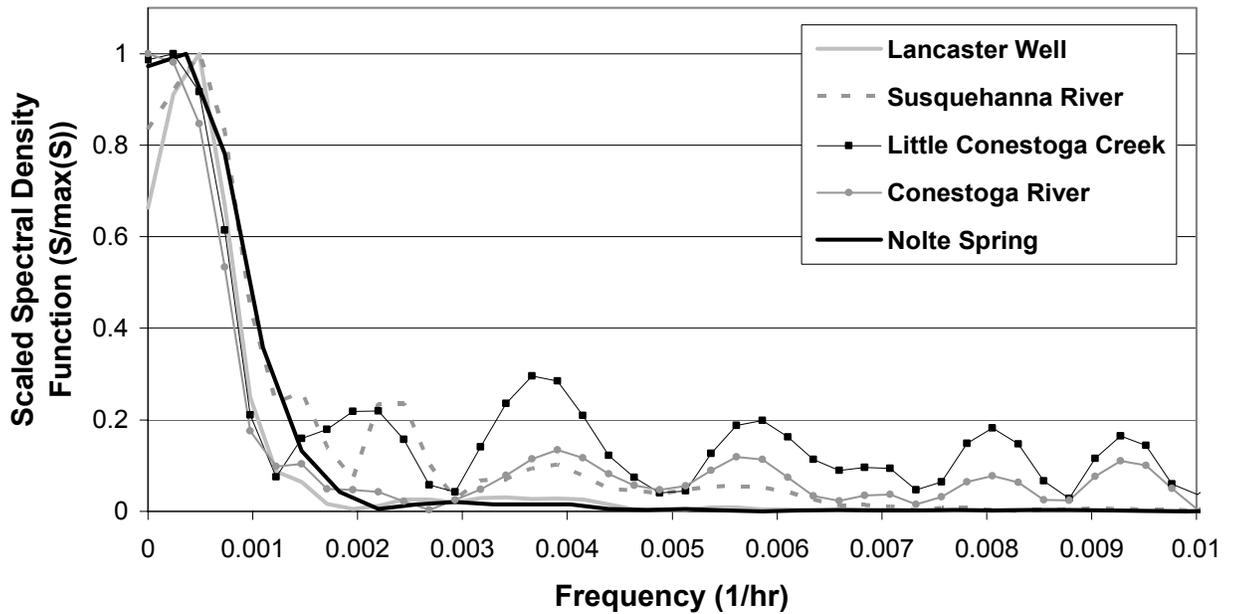
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Figure 5:

a)



b)



a) Plot of 2003 auto-correlation 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.