Effects of restricted recharge in an urban karst system

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ABSTRACT

Urban karst systems are typically considered more vulnerable to contamination and excess storm discharge because of potential sources areas, increased sediment loading, and focusing of water from impervious surfaces. However, urban hydrology can lead to unexpected patterns, such as pirating of recharge into man-made storm systems. Valley Creek Basin located in southeastern Pennsylvania, presents such an urban karst system. Four springs were monitored for suspended sediment, water chemistry, and storm response for an eighteen month period. The suspended sediment concentrations were low, less than 4.0 mg/L. Furthermore, trace metal analysis of baseflow water samples and spring mouth sediment showed only low concentrations.

The response to storms within the system was rapid, on the order of 1-3 hours. The maximum water stage increases at the urban springs were typically less than 15 centimeters, with springs from more commercialized areas showing < 2 cm increase. A nearby retention basin, in contrast, had water level rises of 100 cm, suggesting pirating of recharge into stormwater systems occurs.

Thus, the concept of an urban karst system as a contaminant conduit is not the only one that applies. In Valley Creek basin reduced infiltration led to smaller storm response and less contaminant input, and the smaller capture area led to rapid storm response. Although contaminant levels have not increased due to urbanization, the springs may be at risk for future contamination. The lack of flushing means that the

system will not cleanse itself if contamination occurs, and the short flow paths make the karst system vulnerable to spills and leaks.

BACKGROUND

The vulnerability of karst aquifers is well-known – fast flow paths and unexpected flow direction can move contaminants and threaten water supplies. Karst conduits make these aquifers more susceptible to contamination because of diminished filtration. This problem becomes more severe during storms because of the larger volume of water entering the aquifer (Hess and White, 1988; Stephenson *et al*., 1999). Conduits can also provide storage chambers for contaminants that can be mobilized when storms provide a flushing event (Loop and White, 2001). Urban karst aquifers have been studied less and their particular vulnerabilities are not well understood. Case studies have suggested that urbanization can uncover sinkholes and dolines (Green, 2000; Bencic, 2006) and increase exposure to contaminants such as organics (Hoetzl, 1999).

Sediment transport occurs in both urban and non-urban karst systems because of enlarged fractures and conduits in karst, but sources of sediment may increase during urban construction. Sediment transport is an issue for several reasons. The sediments themselves can affect water use and aquatic habitats. In addition, metals adsorb onto sediment surfaces, so sediment transport and storage are related to metal cycling (Vesper and White, 2003).   Furthermore, sediments provide an analogue for understanding bacteria and virus transport (Mahler et al., 1999). Bedload sediments can incorporate metal contaminants over time and so may be able to give a better long-term picture of urbanization effects than water samples alone (Gutierrez et al. 2004). The urban spring in Missouri studied by Gutierrez et al. had high levels of Cr, Zn, Pb and As.

One of the most-studied urban karst springs is Barton Spring in Austin, Texas. This spring is a major discharge point for the Edwards Aquifer, and the northern third of the 390 km^2 recharge area has been experiencing urbanization (Mahler et al., 2007). Pesticides, volatile organic carbons, nutrients, and sediments have been observed in spring chemographs (Mahler and Lynch, 1999; Mahler et al., 2005; Mahler et al., 2007). An analysis of 80 years of discharge data from Barton Spring and two others in the Edwards aquifer showed that as urbanization increased, both increases and descreases in discharge can be observed (Llado, 2007).

This variation points out the complexity of identifying recharge areas in both urban and karst systems – there is both spatial and temporal variability. Lack of basic infrastructure data (i.e., maps of stormpipes or karst conduits) creates high uncertainty. Furthermore, changes in recharge and discharge can occur rapidly in uban systems (Sharp et al., 2003).

STUDY SITE

The study area is in the Valley Creek Watershed in Chester County, southeastern Pennsylvania (Figure 1). The drainage basin for Valley Creek Watershed covers about 64 square kilometers. The watershed is experiencing high rates of both residential and commercial developmentand has an estimated 18 – 24 % impervious surface (Chester County Water Resource Authority, 2004).

Valley Creek Basin contains a sequence of carbonate rocks of Cambrian and Ordovician age dipping 30 to 50 degree to the south. Igneous and metamorphic rocks found in the topographic highs form the northern and southern boundaries of the watershed (Sloto, 1990). The carbonate unit from which springs were sampled is the

Elbrook Formation, composed of a gray fine crystalline dolomite with laminar partings and a siliceous dolomite interbedded with phyllitic shale. Most of the groundwater flow in Valley Creek basin is local with discharge to close by streams. Although sink holes, caverns, and pinnacles (Kochanov, xxxx) provide evidence of karstification, an outcrop near one spring shows the groundwater flow is through enlarged fractured rock.

There are more than 120 springs in the Valley Creek Watershed (McGinty, 2003; Dr. Claire Welty, University of Maryland-Baltimore County, personal communication, December 2004). Spring discharge occurs mostly along fractures within bedrock and contacts between different rock units. For example, there are several springs along the contacts of the crystalline rock units and the carbonate rocks.

The four of the springs selected for this study, named Gunkle, Park, Lawson, and Lebout, are located at springhouses in the Elbrook Formation (Figure 1). Gunkle and Park have obvious discharge points at 5-10 cm openings within outcrops. Lawson and Lebout's spring mouths are more diffuse and bubble up through sediment rather than at an outcrop. Both of these springs were monitored outside the springhouse. At Lawson, the spring house roof had collapsed and was missing. At Lebout, because of the lack of a focus point for discharge, monitoring was set up where the spring discharged outside the springhouse. The springs had baseflow discharge > 0.5 L/s (Table 1). In addition to the four springs, a constructed retention basin adjacent to Park spring was monitored briefly for water level data.

There is some variability of land use in the areas surrounding the springs. Most of the springs are on small sections of preserved land but with development nearby. There is both residential and commercial land use surrounding Gunkle. Park is located near the intersection of a highway and a major artery through the county, and to the south, east, and west of the spring are commercial office parks. At the top of the ridge about 0.8 kilometer north, outside of the recharge area is the Cedar Hollow Mine. Currently the mine is not operational; however, the groundwater in the water-filled quarry is discharged to maintain trout fishing streams. Lawson is located on a major artery in a residential area. The spring on Leboutillier Road (abbreviated as Lebout) is surrounded by old farmhouses and fields that are no longer used for agriculture. These fields are now filled with grass, but new houses are being built. Thus, Lebout represents an area in transition from agriculture to residential land use.

METHODS

Data loggers provided high resolution data on storms and long term monitoring of baseflow. The parameters monitored using continuous data logging included conductivity, water level, and temperature collected at 15 minute intervals. Instruments were placed close to the discharge point of each spring. Precipitation data were downloaded from the USGS water data website (http://waterdata.usgs.gov) for the Valley Creek station (Hydrologic Unit: 02040202). The springs were monitored for 18 months; the retention basin was monitored for water level for only 4 months.

In addition to continuous monitoring, monthly field visits during baseflow were made to measure pH, water level, conductivity and temperature. The following samples were collected for geochemical analysis: a 500 ml unfiltered suspended sediment sample, a filtered 60 ml ion sample, a filtered 125 ml alkalinity sample, and (for seven months) a 60 ml filtered and acidified trace metal sample. These samples were kept cool until they were brought back to the lab and stored in a refrigerator. A Dionex GP40 DX ion chromatograph was used to analyze Na, Ca, Mg, K, Cl, F, NO_3, and SO_4. Titration within 24 hours was used to measure alkalinity. SI values were calculated using the PHREEQC Interactive 2.8 software (Parkhurst and Appelo, 1999). In addition, PHREEQC was used to calculate the partial pressure of carbon dioxide in equilibrium with each water sample.

Based on the Ca^{2+} and Mg^{2+} concentrations analyzed in a geochemistry study of the springs, we calculated the coefficient of variation using the ratios of standard deviation (std.) to the mean normalize the variation of the major cations (Ca^{2+} and Mg^{2+}):

$$CV\% = 100x\frac{Std(2.5Ca^{2+} + 4.1Mg^{2+})}{Mean(2.5Ca^{2+} + 4.1Mg^{2+})}$$

Ca^{2+} and Mg^{2+}were measured in mg/L, therefore the coefficients provide molar proportions. CV has been used to classify springs into matrix, conduit, or mixed flow type, with values of 10 to 24% considered conduit dominated and values below 5% considered matrix flow dominated (Shuster and White, 1971). The use of CV may omit information about multimodal behavior that can better be observed by plotting frequency distributions (Massei et al., 2007). Frequency distributions of conductance over a year were plotted to look for multimodal populations.

Suspended sediment samples were filtered in the lab through two separate filters using a Millipore vacuum system. The first filter was a 5.0 µm pore size to remove most of the sediment, then a 0.45 µm filter was used to separate the remaining suspended sediment from the dissolved solids. The weight of the filtered sediment on the 5.0 and 0.45 µm filters were added together for each sample. A one time set of bedload sediment samples was collected both inside and outside the spring house (only inside at Gunkle). A layer of approximately 10 cm thick sediment was present in the spring houses and there was a more diffuse sediment layer in the stream bed outside the spring house. After the sediment samples were collected, they were dried and then shaken through a 1/256 inch plastic sieve to separate the clay size particles. The clay-size particles were then digested using hydrogen peroxide (H_2O_2) and nitric acid (HNO_3) to remove metals. The digestion removed metals from adsorbed matter such as carbonates, organics, hydrous ferric oxides, and if present, sulfides. The digested sediment samples, along with water samples collected for trace metals, were analyzed using an inductively coupled plasma – optical emissions spectrometer (ICP-OES). The metals that were analyzed were Cr, Co, Ni, Cu, Zn, As, Cd, Sn, and Pb.

To help interpret whether sediment concentration data indicated anthropogenic contamination, sediment quality guidelines (SQGs) were used. MacDonald et al. (2000) developed the consensus-based SQGs by calculating the geometric mean of 347 sediment samples, which were collected at fourteen fresh water locations in the United States. MacDonald et al. identified threshold effect concentrations (TEC) where sediments are considered clean or only slightly polluted and below which no adverse affects are expected for most sediment dwelling organisms. Probable effect concentrations (PEC) are values expected to cause adverse effects on sediment dwelling organisms in freshwater ecosystems. EPA safe drinking water guidelines were used to interpret potential anthropogenic impact in dissolved metal concentrations.

RESULTS

Geochemistry

The geochemical data provide evidence for both conduit and matrix flow paths to these springs. The CVs of these urban springs varied from 9.3 to 14.5%, within the range typically considered dominated by conduit flow (Table 2). Lawson and Lebout, the springs with more diffuse discharge, had the lowest values, slightly below the 10% value typically considered conduit-dominated, but above the typical matrix-dominated value given as 5%. The CDF technique was applied to the data from Gunkle spring and shows a trimodal distribution, also suggesting a mixture of conduit and matrix flow paths occur (Figure 2). The trimodal distribution could be due to baseflow conductivity, plus both conductivity increases and decreases observed during storm events.

The log PCO_2 values averaged -2.1 for Lawson and -1.9 for the other three springs Table 2). These values are slightly higher than atmospheric but not as high as predicted for closed system evolution (Freeze and Cherry, 1976, Fig 7.11) This suggests that the urban system has shallow, conduit flow paths possibly in contact with soil gas.

All of the springs are undersaturated with respect to both calcite and dolomite (Table 2), although Park is nearly at saturation with average SIs of -0.01 and -0.05 for calcite and dolomite, respectively. Most of the year, the springs were understaturated (Gross, 2007). The lack of time to equilibrate with the surrounding carbonate rock suggests fast flow paths.

There was very little nitrate in the water and little variation in concentrations. All of the concentrations were below 5 mg/L. The concentrations at Gunkle and Lebout's were between 3 and 5 mg/L; at Park and Lawson concentrations were between 1 and 2 mg/L. These low concentrations are evidence of a lack of agricultural land use in the area.

Year round high concentrations of chloride were observed at the springs (Figure 3). Park spring had the highest concentrations of chloride and the greatest variability.

The average was 218 mg/L for Park, with minimum of 154 mg/L and maximum of 278 mg/L. There is a major highway next to the spring as well as paved parking lots. Road salt is the likely source of chloride. Lebout spring showed the lowest concentrations and the least variation in chloride, with an average of 19 mg/L. Gunkle spring had the next lowest concentrations with an average of 48 mg/L. Lawson spring had concentrations that were slightly higher, an average of 65 mg/L. There was a greater variation of chloride concentration for the Lawson spring with a minimum of 39 mg/L and a maximum of 86 mg/L. Panno *et al.* (2006) have suggested groundwater at or below 15 mg/L of chloride may be from naturally occurring sources. The chloride concentrations measured at the Lebout spring were very close to that of background level. The other springs are above background, in particular Park spring with over 100 mg/L year round. The persistent, high concentrations of chloride suggest a long term anthropogenic source. Road salt may have accumulated in the epikarst, where it can inflitrate the groundwater flow path during storm events. The higher concentration of Cl close to a major highway is consistent with a surface water study conducted by the USGS in the region, which showed chloride concentrations at 28 urban streams correlated to road density (Fischer et al., 2004). In aquifers, the highest concentrations they observed were around 160 mg/L, at sites with the highest percentage of urbanization.

The karst springs each have nearly constant temperature ranging from 12 to 13.5^{o}C for the four springs. Only one or two storms per season were large enough to cause a short term temperature pulse, typically at Lawson or Lebout spring which may receive some overland flow or for storms larger than 5 cm. In contrast, surface water at Valley Creek has been impacted by temperature variations which stress the fish (e.g., brown trout) population. Steffy and Kilham (2006) found reduced diversity and patchiness from 1993 to 2001 as urbanization increased. Locations with a large number of springs discharging had higher diversity, suggesting that the constant water temperature of springs provided more habitat stability.

Sediment in karst systems can provide evidence of source areas, and in urban systems a potential source area is construction sites. However, the urban spring sampled here had very low suspended sediment concentrations (Figure 4). The concentrations were generally lower than 4 mg/L and almost all were about 2 mg/L or less. The small amount of variation seen was usually within 1 to 2 mg/L, within the sensitivity range for the suspended sediment analyses. Sometimes higher concentrations were seen at Park spring, such as 20 mg/L on 1/12/06. However, the conduit opening at Park created turbulent water at the spring mouth. The turbulent water may have mobilized bed sediments and is the most likely cause of the occasional higher urban sediment concentrations. Most of the suspended sediment consisted of silt-size silicate grains. The silicates included angular quartz grains and weathered mica flakes. There was also some organic matter, which generally composed 5 to 15% of the total sample. Only a few samples showed evidence of carbonate minerals.

The concentrations of metals in the water are very low, less than 15 ppb (Gross, 2007). Slightly less than half the water analyses were considered above detection (larger than 0.1 ppb). None of the metals had concentrations above available EPA drinking water standards.

The metal concentrations in the bedload sediment were higher than those in the water samples, as expected since metals can accumulate there (Table 3). Even so, two-thirds of the sites had no metal concentrations over the consensus-based TEC values. However there were some instances in which sediment metal concentrations exceeded TEC or PEC recommendations: the Cu concentration at Gunkle, the Zn concentration and at Lebout, the Pb concentration at Gunkle and outside at Lebout. Although there are high metal concentrations found at some sites, other sites were found to have all low metal concentrations. Samples from Park, outside Lawson's springhouse, and inside at Lebout, had no metal concentrations over the consensus-based TEC values. Analysis of sediments in urban stream beds throughout the Delaware River Basin found metal TEC exceedances ranging from 48% and 100% (Fischer et al. 2004). The low concentration of metals in the Valley Creek sediment suggests that urbanization in Valley Creek Basin has not exposed the karst system to metal contamination.

Storm response

The chemical and physical responses of the springs to storm events were also influenced by land-use in their capture areas. Fast storm responses in both conductivity and water level were observed (Figure 5). The water level rose and conductivity shifted on the order of 1-3 hours after storm onset. Recovery to baseflow conditions for both conductivity and water level was also rapid, generally within 6-12 hours. Gunkle had longer recovery times (3 to 6 days), suggesting more contribution from matrix flow (Figure 5). Storms could result in either an increase or decrease in conductivity, probably depending on contribution of rainwater from epikarst containing road salt or not. The maximum water level increase at the urban springs were typically less than 15 centimeters (Figure 6). There was no relation between storm size or storm intensity and water level rise, so other factors influenced response (such as antecedent conditions).

However, springs from more commercialized areas (Gunkle and Park) showed < 2 cm increase in water level (Figure 6). This difference in spring response could have two causes. The springs from more commercialized areas had a smaller capture area (Table 1, Yang, 2006). In addition, these two springs had covered spring houses. Lawson and Lebout had higher water level for some storms, up to 70 cm, but they could be receiving water from overland flow because they were monitored in the open. A temporary monitoring station was set up both inside and outside the spring house at Lebout and showed that conductivity response indicated more dilute water incorporated in storms outside the spring house (Figure 7). More dilute water would be expected from overland flow contribution.

There was little variation from storm to storm, other than the different water level response at Lebout and Lawson which receive overland flow. Variation from storm to storm can indicate alternate flow paths in a karst system (Toran et al., 2006). The lack of variation suggests shorter, more consistent flow paths here. Lawson and Lebout had occasional high water level response, but they could capture water from both the spring and overland flow. Even for these high stage events, the recovery time was very rapid and varied little from storm to storm.

Since urbanization increases impervious surfaces, it might have been expected that the storm response would be large in an urban karst system, with the water focusing on karst recharge areas. Alternately, the water could be diverted to storm drains and end up going directly to surface water and by passing the groundwater system. To test this hypothesis, a water level logger was placed in a retention basin adjacent to Park spring. For a pair of storms on July 2007, the Park spring showed a water level increase of 0 and

3 cm, while the water level in the retention basin rose 71 cm for the first storm and 76 cm for the second storm (Figure 8). Of 25 storm events in the 4 months monitored, Park spring showed a water level increase three times (up to 3 cm) while the retention basin typically rose 70 to 100 cm for each storm. These data support the notion that water is being pirated from the karst groundwater system.

DISCUSSION

The data in this study point out that the concept of an urban karst system as a contaminant conduit is not the only one that applies. In contrast to some previously studied urban karst systems, the main impact of urbanization in Valley Creek Basin seems to have been to restrict the recharge area and thus the potential flux of sediment and contaminants. It is difficult to directly observe recharge in karst or other systems, so indirect evidence is needed for restriction of the recharge area. In particular, long term continuous monitoring of storm response is needed to understand these systems. The urban springs' response to storm events was minimal, especially when compared to non-urban karst and to overland flow observed in the study area in an adjacent retention basin. The rapid storm response in conductivity and water level also indicated the effects of urbanization. When impervious surfaces decrease the recharge area by limiting infiltration, the water that does enter the aquifer has shorter flow paths. The lack of variability from storm to storm further suggests short flow paths rather than alternate flow paths that can occur in complex karst systems that switch from matrix to conduit dominant flow depending on recharge area. Although historic data on spring flow rates were not available, the current discharge rates are low and suggest small capture areas.

In addition to continuous monitoring, it is important to collect samples for geochemical analysis to further understand the behavior of an urban karst system. The year round high concentrations of chloride at theses springs provided further evidence of shallow flow paths. Road salts likely accumulated in the epikarst where they can continuously recharge.

The CV of hardness and SI of the baseflow samples indicate that water can travel rapidly through this urban karst system. This rapid transport makes the springs vulnerable to contamination. However, diversion of recharge water to storm systems and surface water has reduced the amount of sediment and other contaminants washing into the groundwater system. Thus, metal concentrations at the springs are low because metal infiltration has been reduced. Likewise, only low levels of sediment are being discharged at the springs, because only low levels are washing into the system.

Although contaminant levels have not increased due to urbanization, the springs may be at risk for future contamination. The lack of flushing means that the system will not cleanse itself if contamination occurs, and the short flow paths make the karst system vulnerable to spills and leaks. Thus, it is important to design monitoring systems that specifically address issues applicable to urban karst. Although the concepts of traditional monitoring apply, there are additional considerations for urban karst.

What are the important features of an urban karst monitoring system? Don't assume that there will be contaminants present in karst springs, but do look for them. Nutrients should be included since they can be present in both urban and agricultural systems. Both suspended sediment and bedload sediment should be examined; the bedload sediment can be influenced by both baseflow and storm events so they integrate over time. In addition to monitoring springs, storm water discharge points should be identified and monitored. Although infrastructure is not always clearly mapped, where possible the stormwater component of the urban water budget should be quantified. Furthermore, open karst springs (those not inside a spring house) may be influenced by overland flow in addition to spring discharge. The potential for overland flow should be considered when interpreting water level and geochemical data. Find historical data when possible to evaluate the changes in spring discharge over time. As in most karst systems, long term continuous monitoring of water level, conductivity, and temperature in addition to baseflow samples for more detailed water chemistry is helpful in sorting out flow paths and responses to stresses in an urban karst system.

ACKNOWLEDGMENTS

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Table 1: Baseflow spring discharge rates and estimated capture area based on regional recharge rate (Yang, 2006).

	Spring Discharge (L/sec)	**Spring capture area (km^2)**
Gunkle Spring	0.59	0.054
Park Spring	1.07	0.098
Lawson Spring	14.98	1.35
Lebout Spring	5.10	0.47

Table 2: Summary of geochemical data from baseflow samples of the four springs.

	Gunkle	**Park**	**Lawson**	**Lebout**
CV of Hardness	14.5	10.7	9.8	9.3
Average log PCO_2	-1.9	-1.9	-1.9	-2.1
Average SI_{Ca}	-0.3	-0.01	-0.05	-0.1
Average SI_{dol}	-0.6	-0.05	-0.1	-0.2

Table 3. Sediment metal concentration table (mg/kg). The sediment metal concentrations were compared with MacDonald et al. consensus-based SQGs values. Two-thirds of the springs had no metal concentrations over the TEC values, and 96% of the metal concentrations were below the PEC values.
Blank = below detection
X = not available in reference article

Sediment Conc. mg/kg	Cr	Co	Ni	Cu	Zn	As	Cd	Sn	Pb
TEC	43.4	X	22.7	31.6	121	9.79	0.99	X	35.8
PEC	111	X	48.6	149	459	33	4.98	X	128
GUNKLE	19	82.8	20	54.8	190.7		0.5	2.6	114.9
PARK SPRING MOUTH	12.3	64.5	13.3	9.5	27.4			2.7	2.9
PARK TROUGH	9.2	61.6	11.6	17.8	19		0.1		
LAWSONS SPRING OUTSIDE	5.1	49.6	7.6	7.9	33.4		0.1		
LAWSONS SPRING INSIDE	8.5	59.4	16.1	34.8	45.9		0.6		
LEBOUT OUTSIDE	17.8	95.6	12.6	15.5	127.7				260.5
LEBOUT INSIDE	9.1	68.1	10.4	9.9	17.4				

Above TEC values	
Above PEC values	

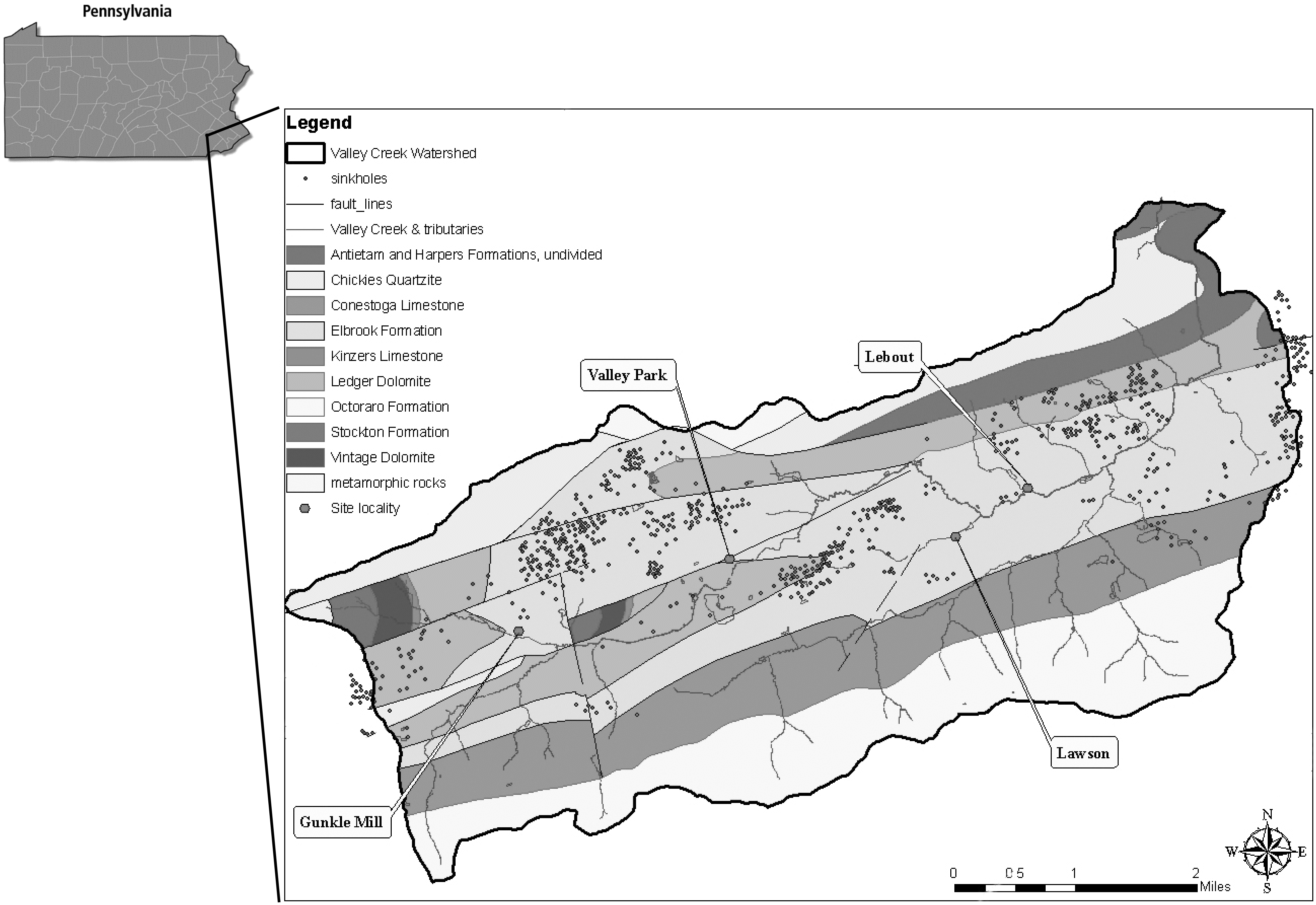


Figure 1.Location of studied springs within Valley Creek Basin in Chester County, Southeastern Pennsylvania. Geologic map from Chester Country GIS Database, sinkholes from Kochonav, 19xx (also in Chester County GIS Database).

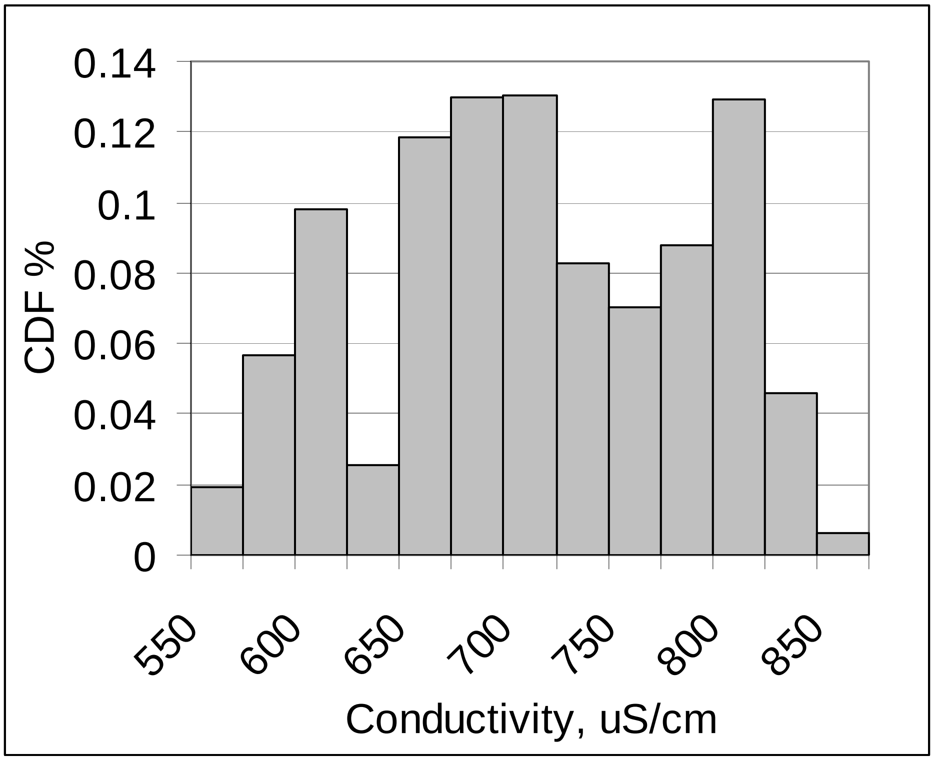


Figure 2: Cummulative distribution function (CDF) of conductivity at Gunkle spring, showing trimodal distribution.

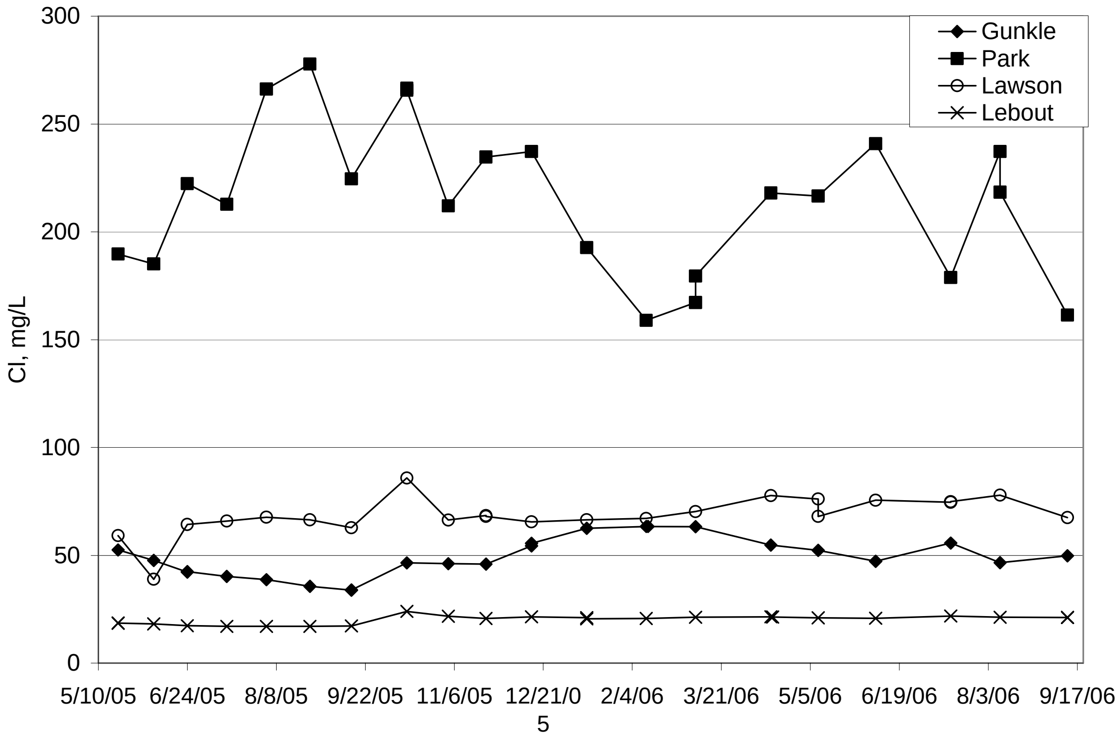


Figure 3: Concentration of chloride through time at the four springs. Park spring had persistent, high chloride.

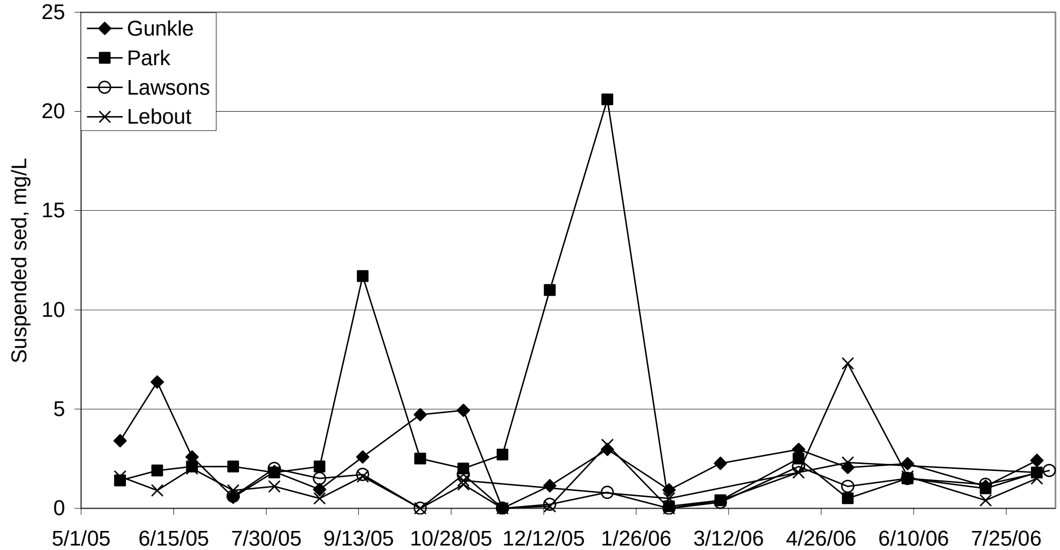
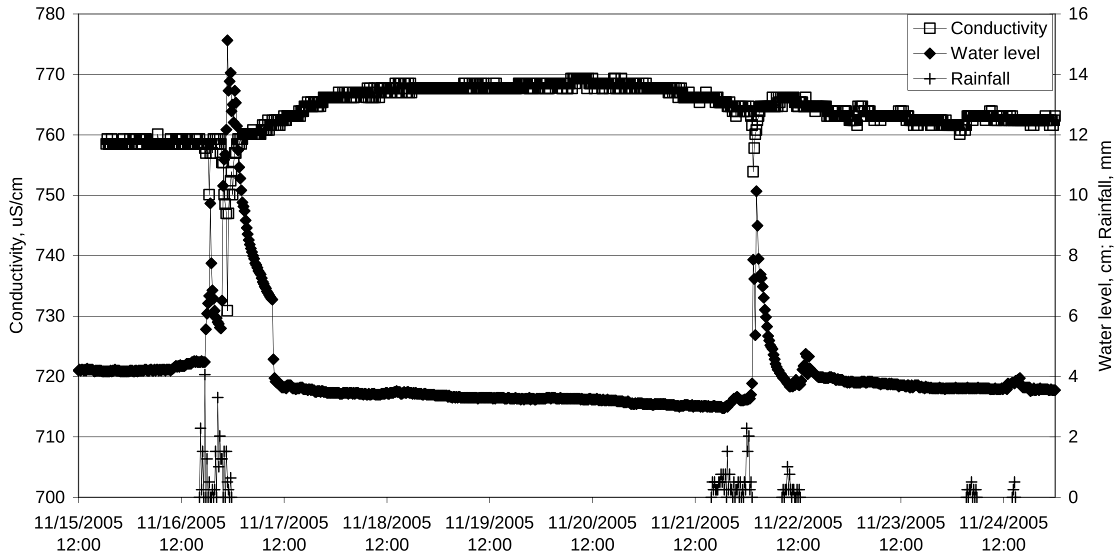


Figure 4: Suspended sediment concentration at the four springs through time. Concentrations were generally low.



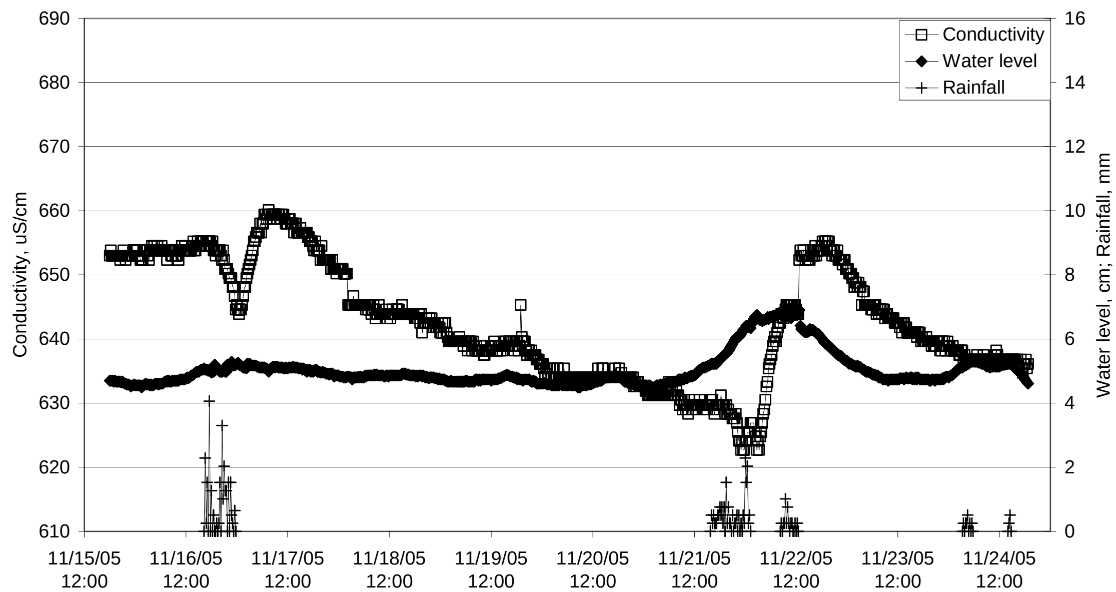


Figure 5: Storm response for a storm at Lawson (top) and Gunkle (bottom) springs, plotted at the same range in scale. Response and recovery were rapid.

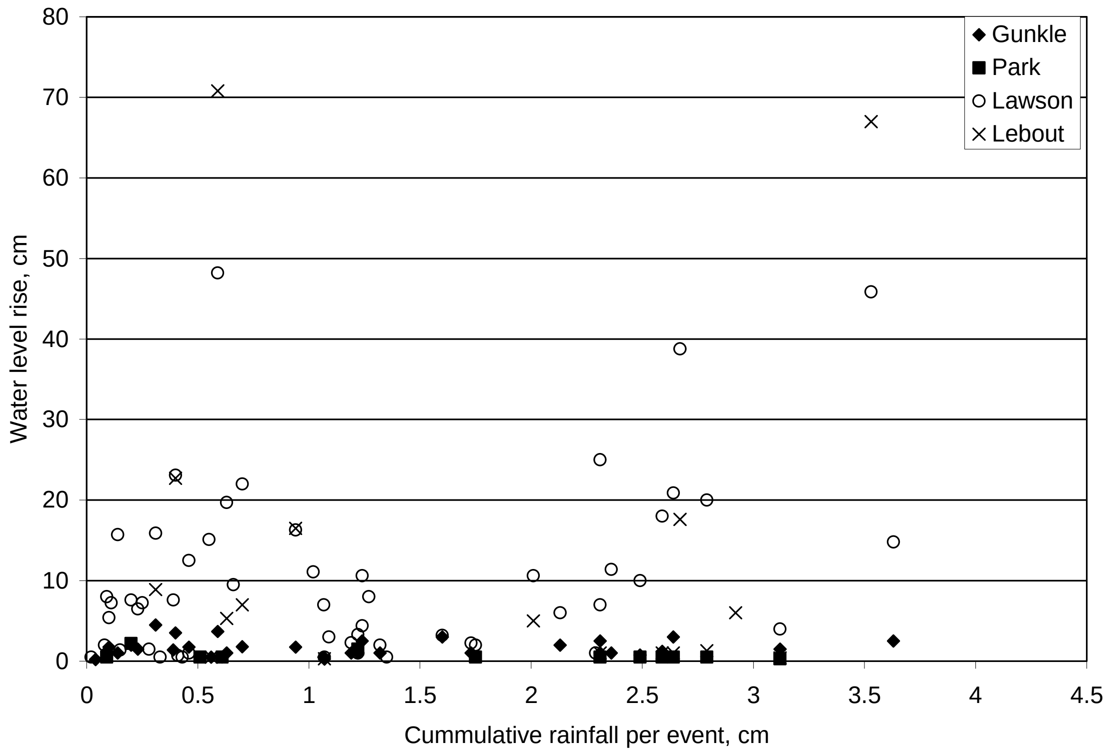


Figure 6: Water level rise versus cumulative rainfall at the four springs. The springs monitored in covered springhouses (Gunkle and Park) had very small increases in water level. Springs monitored outside were more variable, suggesting contributions from overland flow.

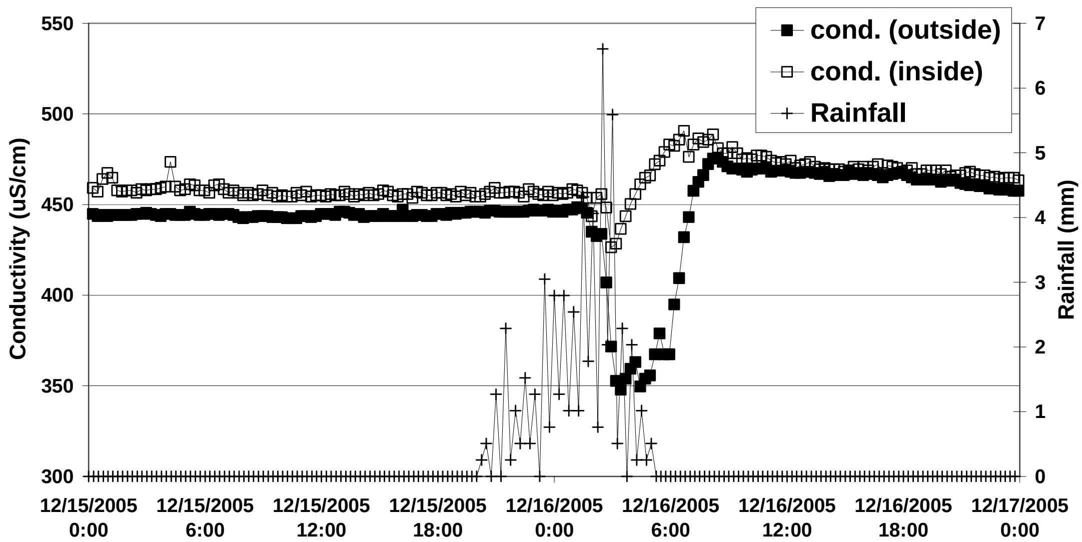


Figure 7: Conductivity response for a storm at Lebout spring. There was more dilute water outside the springhouse than inside the spring house, suggesting contributions from overland flow.

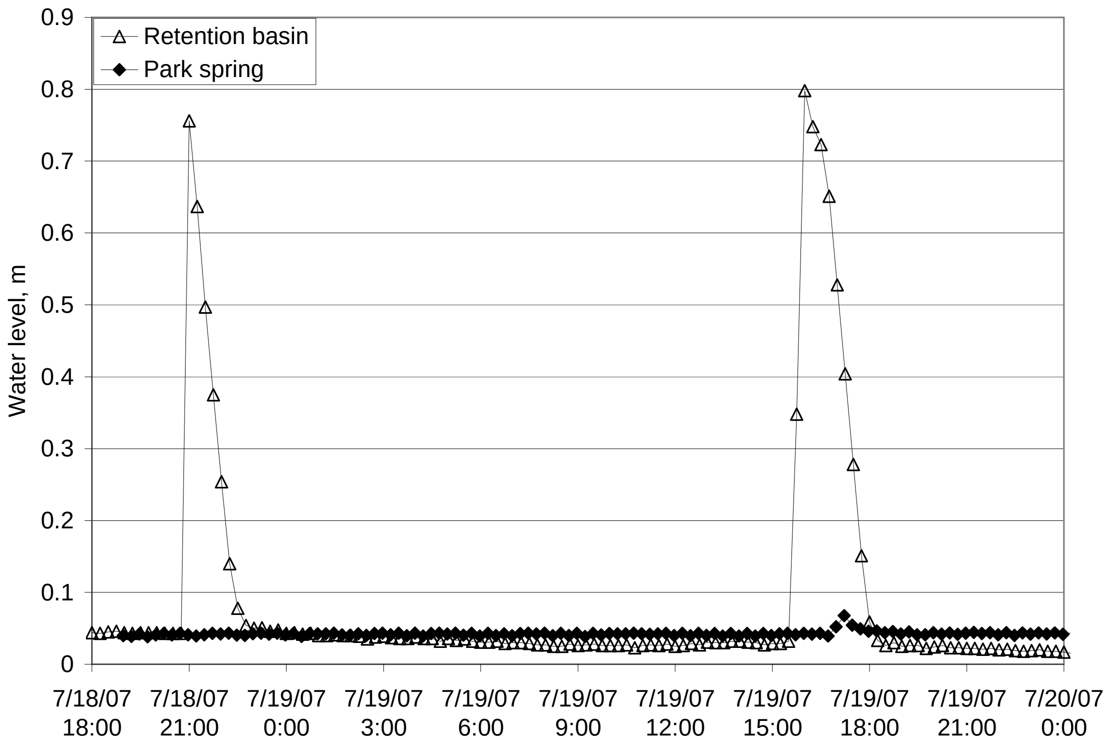


Figure 8: Water level response at Park spring compared to retention basin in the park. Large response was recorded in the retention basin in contrast to the spring.