COMPLEX EPIKARST HYDROLOGEOLOGY AND CONTAMINANT TRANSPORT IN A SOUTH-CENTRAL KENTUCKY KARST LANDSCAPE

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The movement of autogenic recharge through the shallow epikarstic zone in soil-mantled karst aquifers is important in understanding recharge areas and rates, storage, and contaminant transport processes. The groundwater in agricultural karst areas, such as Kentucky's Pennyroyal Plateau, which is characterized by shallow epikarst and deeper conduits flow, is susceptible to contamination from organic soil amendments and pesticides. To understand the storage and flow of autogenic recharge and its effects on contaminant transport on water flowing to a single epikarst drain in Crump's Cave on Kentucky's Mississippian Plateau, we employed several techniques to characterize the nature and hydrogeology of the system. During 2010–2012, water samples and geochemical data were collected every four hours before, during, and between storm events from a waterfall in Crumps Cave to track the transport and residence time of epikarst water and organic soil amendments during variable flow conditions. Geochemical data consisting of pH, specific conductivity, temperature, and discharge were collected continuously at 10-minute intervals, along with rainfall amounts. In addition, stable isotope data from rainfall, soil water, and epikarst water were collected weekly and during storm events to examine storage and recharge behavior of the system. The changes in geochemistry indicate simultaneous storage and transport of meteoric water through epikarst pathways into the cave, with rapid transport of bacteria occurring through the conduits that bypass storage. The isotopic data indicate that recharge is rapidly homogenized in the epikarst, with storage varying throughout the year based on meteorological conditions. Results indicate current best management practices in agricultural karst areas need to be revisited to incorporate areas that do not have surface runoff, but where contaminants are transported by seepage into local aquifers.

1. Introduction

Kentucky's subtropical climate and fertile soil provide extensive agricultural lands for row crops. A common agricultural practice in the area is to apply animal waste as an organic soil amendment for soil nutrient enhancement. If these amendments are not completely exhausted through crop utilization, they can become pollutants and enter the groundwater system. In Kentucky, 55 % of the land area is characterized by highly soluble carbonate rocks within which karst landscapes form (Currens 2002). The resulting karst landscape/aquifer systems, typically with high permeability, are characterized by the development of features such as sinkholes, caves, and large springs. Because much of the recharge entering these systems moves rapidly under turbulent flow, and in many cases as sinking streams with little physical filtration, groundwater in these karst aquifers is often highly susceptible to contamination from agricultural practices, among other sources of pollution (White 1988; Drew and Holtzl 1999).

This research was designed to better understand the fate and transport of agricultural contaminants in the well-developed karst aquifer/landscape systems of south-central Kentucky by conducting field experiments associated with actual field-scale agriculture at the Crumps Cave Educational Preserve, and aimed to answer the following research questions: (1) if aquifer recharge influences manure transport at this representative site, is there significant retardation of flow and storage of water and/or fecal bacteria in the soil/epikarst zone before it enters the main part of the aquifer?; and, if so 2) what is the timing of flow through this shallow part of the epikarst flow system?; 3) how does that effect the introduction of fecal bacteria into the main part of the aquifer?; and 4) where is the primary storage for contaminants and bacteria in the soil-epikarst setting?

2. Study Area

Crumps Cave is located beneath a portion of the extensive sinkhole plain of the Pennyroyal Plateau within the Mississippian Plateaus Section of the Interior Low Plateaus Physiographic Province in Waren County, KY, USA (Figure 1) (Groves et al. 2005). There is about two km of horizontal cave passages beneath several agricultural fields, with the cave floor averaging 25 m below the surface. The recharge area lays within the Graham Springs groundwater basin (Ray and Currens 1998, 2000) which discharges at Wilkins Bluehole on the Barren River, 18 km southwest. It is the second largest spring in Kentucky (Ray and Blair 2005). The site is underlain by Crider silt loam, Pembroke silt loam and Baxter gravelly silt loam soils (Soil Survey Staff NRCS 2011). These soils are moderately permeable, well-drained soils, reddish in color with chert fragments in their lower portions. The thickness of the soils varies throughout the study area. Auger hole tests show the thickness before encountering chert fragments ranges from 0.3–4 meters.

The entrance to Crumps Cave is a collapse sinkhole that has partially collapsed. The cave passages have formed within the highest part of the Mississippian-aged St. Louis limestone, with a local dip of 1–2° to the west (Richards 1964). The bedded Lost River Chert lies between the ground surface and the cave below, and locally appears to operate as a leaky perching layer. Water tends to reach the cave at distinct locations, mainly at perennial or intermittent waterfalls emerging from the cave ceiling through fractures, draining the epikarstic zone to the east of the cave and flowing westward down the dip of the rock (Bolster et al. 2005). Six perennial in-cave waterfalls are located within the entrance area of the cave. These waterfalls are focused on the east side of the cave, but some flow from different parts of the ceiling. Waterfall One (WF1) is approximately 4.5 m tall and is located 40 m from the entrance. It is the closest waterfall to the entrance and has perennial flow (Figure 2). It is the focus of the monitoring and research described herein.

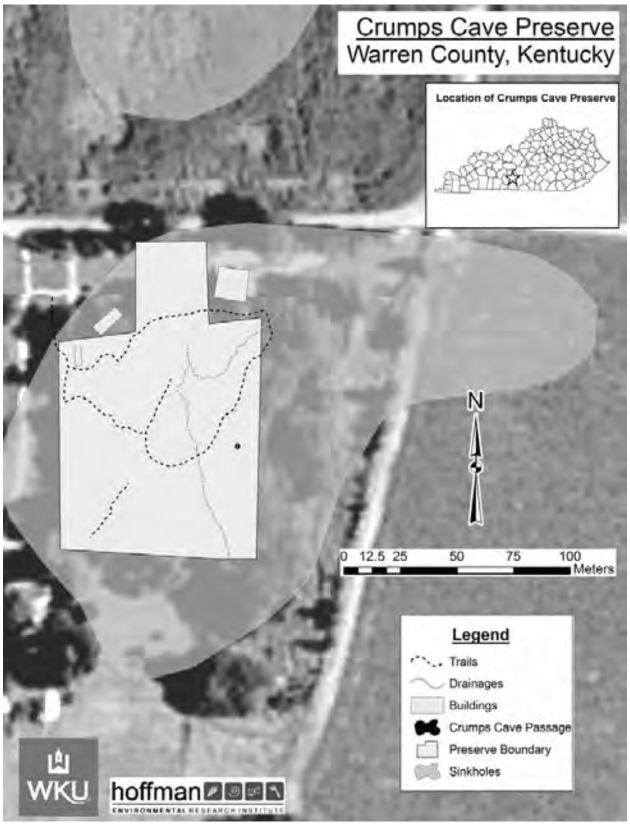

Figure 1. Location of Crumps Cave, Warren County, KY, USA.

The climate of Warren County is classified as a humid subtropical climate on the Köppen climate classification scale (*Cfa*). Its humid summers reach an average high temperature of 31 °C and its mild to cool winters average a high of 7 °C (NOAA 2011). The average annual total precipitation is around 1,294 millimeters. Of this, about 721 millimeters, or 56 percent, usually falls in April through October. May has the highest average rainfall with 136 millimeters (NOAA 2011). The growing season for most crops falls in the April through October range. Hess (1974) estimated that mean-annual potential evaporation is 800 mm, varying from near zero to over 100 mm/mo.

Land use above and surrounding Crumps Cave is dominated by agriculture (Figure 1). Row cropping, which usually rotates between corn, soy, and wheat, surrounds the Crumps Cave property to the east and north. West of the property is a residential property at which a bed and breakfast operation is run. Northeast of the property land is currently being used for cattle grazing.

3. Methods

The movement of autogenic recharge through the shallow epikarstic zone in soil-mantled karst aquifers is important in understanding recharge areas and rates, storage, and contaminant transport processes. To understand the storage and flow of autogenic recharge flowing to a single epikarst drain in Crump's Cave on Kentucky's Mississippian Plateau, we employed several methods to characterize the nature of the system.

3.1. Storm Event Contaminant Sampling

From 2010–2012, on the surface at Crumps Cave, 110 meters from the sink entrance, a HOBO U-30^{tm} weather station was used to collect weather data. A rain gauge tipping bucket collected rainfall amounts every ten minutes. The weather station also collected temperature, dew point, solar radiation, relative humidity, wind speed and direction, and soil moisture content with ten-minute resolution.

Inside the cave, a 208 liter barrel with circular holes drilled into its side to measure discharge was placed under WF1 and a conical tarp directs virtually all flow of the epikarst drain into the barrel (Figure 3). A procedure based on Bernoulli's law relates the WF1 discharge rate (L/s) to the water level (stage height) in the barrel (White 1988). The water level is measured by a pressure transducer inside a stilling well at ten-minute resolution. At WF1, two Campbell Scientific CR10x data loggers were used to collect geochemical and discharge data for the waterfall. Data Logger One (DL1) recorded data from one pH probe, one dual specific conductance and temperature probe, and a pressure transducer probe placed in the discharge barrel at WF1. Data Logger Two (DL2) recorded data from two pH probes and a duel specific conductivity probe. Both data loggers collected data every two minutes and recorded the average every ten minutes for temperature, specific conductance (SpC), and pH. Stage height from the pressure transducer was also recorded every ten minutes.

During the farming season of late winter through spring, three fluorescent dye traces (sulphorhodamine B, fluorescein, and eosine, respectively) took place to track transport and residence time of water from storm events and epikarstic waters. The dyes were chosen for their spectrum wavelength so as to be able to recognize each individual dye as it came through WF1 from the surface. The traces were performed in a location on the edge of the property in an area that has previously been established as having a hydrological surface connection to WF1.

ISCO 3700 portable water samplers were placed in the cave at WF1 to collect water samples to analyze for dye, bacteria, cations and anions. Samples were collected in 1000 mL polypropylene bottles every four hours during storm events occurring within the study period. During a portion of the winter and spring sampling period weekly samples of fecal coliform bacteria (FC) were taken. Samples were also collected weekly for the analysis of dye and collected within 24 hours of analysis time for total coliform, *E. coli*, cations and anions.

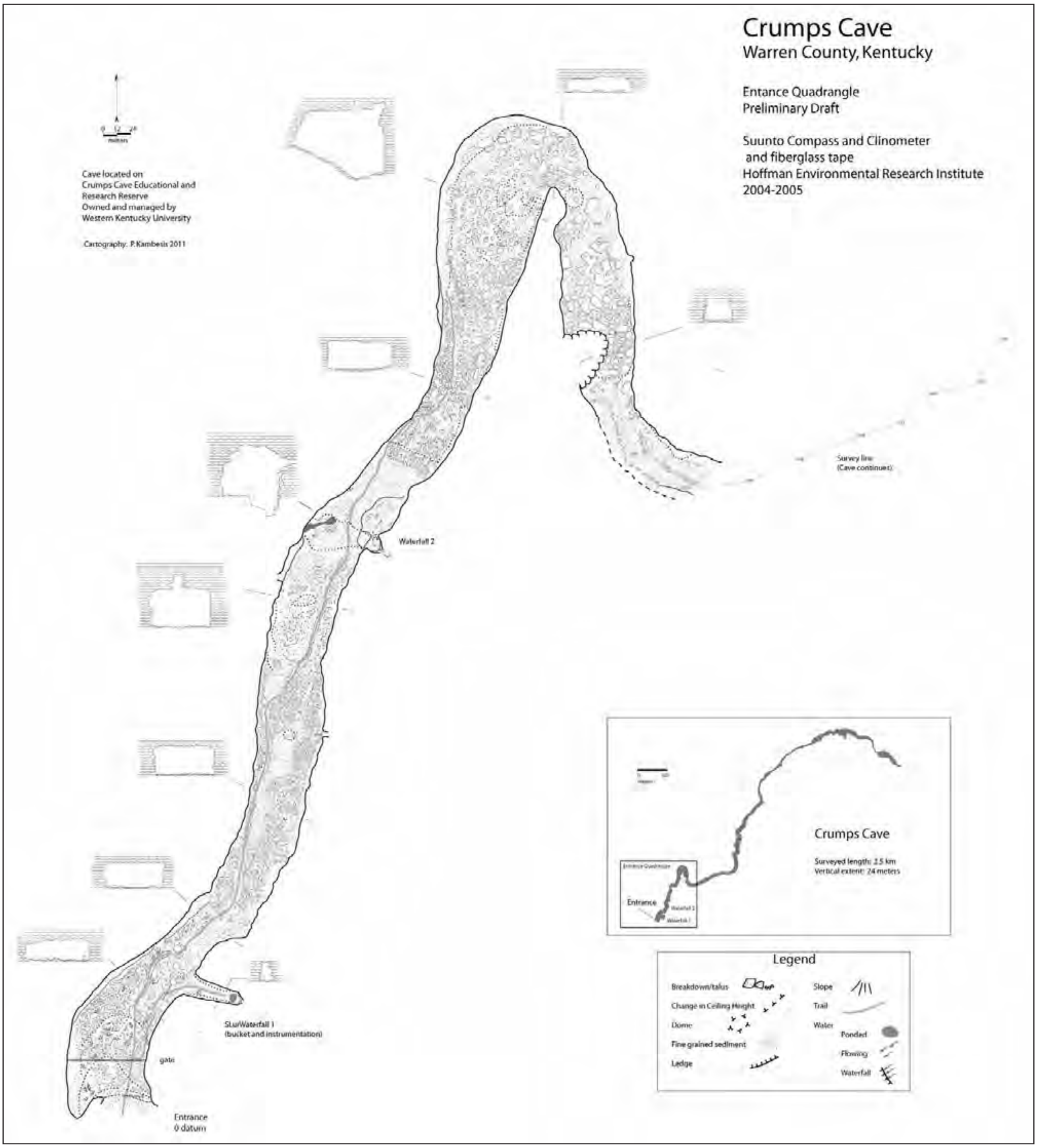

Figure 2. Map of Crumps Cave in south-central Kentucky.

3.2. Epikarst Storage and Recharge

First, we performed base flow separation of several discrete storms, where stormflow was integrated to measure individual storm volumes, and a nominal recharge area parameter, ζ, was calculated for each storm event by determining the measured amount of rainfall (thickness) and setting the drainage volume from the in-cave waterfall during the event to be equal to this recharge amount, and then dividing the resulting recharge volume by the presumably uniform measured rainfall depth. In this manner, we are taking the volume of discharge at the waterfall and dividing it by the amount of rainfall during the event (volume/thickness) to calculate an estimated area over which the rainfall presumably fell during the event, or in this case an average recharge area on the surface that contributes to the water flowing from the waterfall.

A second independent proxy of recharge and epikarst storage conditions from isotopic analysis of precipitation and epikarst water supports this finding. Rainfall amounts above the cave and discharge of the water flowing from the drain below were measured every ten minutes in 2010–12. Weekly precipitation and cave waterfall samples were collected for stable isotope (O and H) analysis, with higher resolution sampling of the waterfall during storm events.

A third measure of the character and response of the epikarst was the three dye-traces performed during the study period, which resulted in a breakthrough curve for each storm event that caused the dye to move through WF1, which provided an estimated threshold for epikarst storage to be flushed out and the travel time of surface water to WF1 under various antecedent storage conditions (Figure 4).

Figure 3. Discharge barrel and data logger setup at WF1 during storm event.

4. Results and Discussion

Identifying the hydrological characteristics of the soil-epikarst zone in response to storm events is an important task for understanding the fate of agricultural contaminants. Recognizing the mechanisms of movement and storage is central for determining the fate of these pollutants. The movement of fecal coliform bacteria through the soil-epikarst is dictated by the amount and intensity of storm events. During the study period, the majority of storm events provoked a response at WF1 indicated by the increased discharge. The data show contaminants that move through the epikarstic system correlate with significant rainfall events and rainfall amount. The dye traces and SpC data support this statement and further the understanding of soil-epikarst hydrology and contaminant transport.

The various storm event data and dye traces combined with fecal coliform analysis indicate rapid response of the epikarst drain to precipitation events (Figures 5, 6). High levels of contaminants, including *E. Coli*, were found during the peak of each storm event, with maximum numbers (greater than 200 colonies/100mL) being reached shortly after surface application, but lasting for many months.

For the epikarst storage data, values of ζ range from 843 m^2 to 11,200 m^2, with lower values likely resulting from water entering epikarst storage that does not reach the drain during that storm response. Values of ζ may thus provide way to quantify varying epikarst storage input. Data also suggest that the actual recharge area is on the order of 100 × 100 m. Using between-storm baseflow discharges and individual values of ζ for storm events, we calculated unit-baseflow (UBF – baseflow discharge per unit recharge area, calculated from dividing total discharge during baseflow conditions by calculated area from ζ), and show that calculated values for the epikarst drain are 2–3 orders of magnitude higher than published UBF values for regional springs (Worthington 2007). This gives quantitative evidence that storage is more concentrated in the epikarst than the regional aquifer as a whole.

Precipitation isotope $\delta^{18}O$ values ranged from -5.7 to -16‰, while the cave waterfall $\delta^{18}O$ values averaged -6.3‰ (ranging between -5.2 to -7.3‰), indicating that despite intense storm events with highly variable $\delta^{18}O$ values, a rapid homogenization of meteoric recharge water with epikarst storage water occurs in the system, further supporting that substantial storage occurs in the epikarst zone through diffuse flowpaths.

From the seasonal data, there are two conditions that occur in the soil that dictate the transport of fecal coliform and *E. coli*. First, there is a threshold for rain intensity and rain amount that push the bacteria (Pasquarell and Boyer 1995) and dye through the soil-epikarst system (Figure 6). Additionally, diffuse flow through conduits adds to the movement of bacteria through the soil-epikarst system. Significant storm events infiltrate the soils and create a high hydraulic head that rapidly pushes the bacteria through main conduits of the epikarst (WF1). This causes a quick drop in SpC and a rise in discharge simultaneously. After the head is lowered, discharge decreases, SpC will slowly rise back toward pre-storm levels and FC counts will decrease. Often, the SpC does not return to previous base flow levels, likely due to the dilution of storage water by rainfall. However, during periods of higher storage, it appears as though continuing recharge and hydraulic pressure pushes out additional storage waters after storm event recovery, and there is a rise in SpC during the falling limb of the discharge curve. During time in-between storms, waters percolate through diffuse conduits as evident by the lower fecal coliform and *E. coli* counts and steady rise of SpC, which indicates water that is in contact with the bedrock for a longer duration, thus dissolving more carbonate rock.

This information is vital to understanding and improving best management practices in agriculture on karst terrains, particularly with regard to water quality degredation from the application of organic soil amendments. The results indicate that rapid, continuous contamination can occur from the use of manure and fertilizers in karst areas, and this must be addressed through better policy creation.

Acknowledgments

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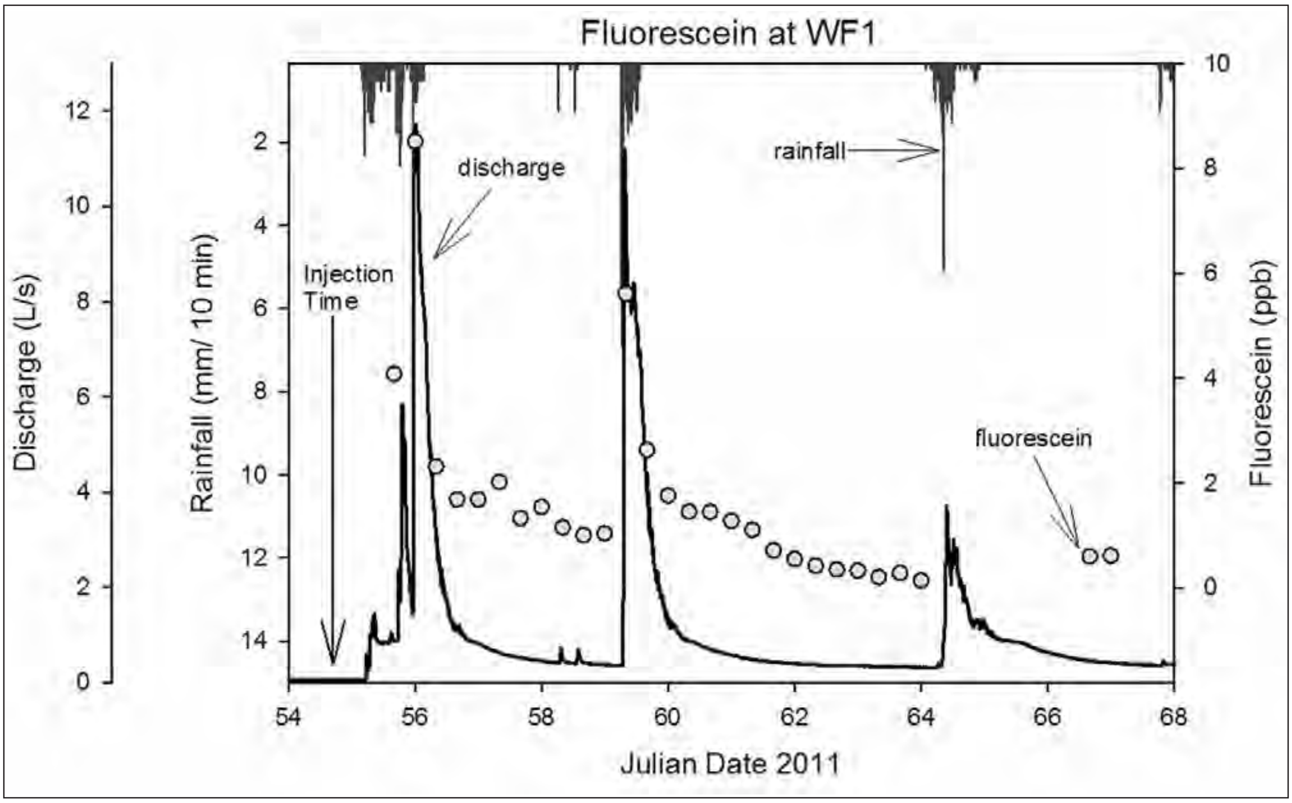

Figure 4. Dye trace 2 during the study period (dots), indicating the WF1 response to a storm event as shown by how the dye moved through with the storm pulses.

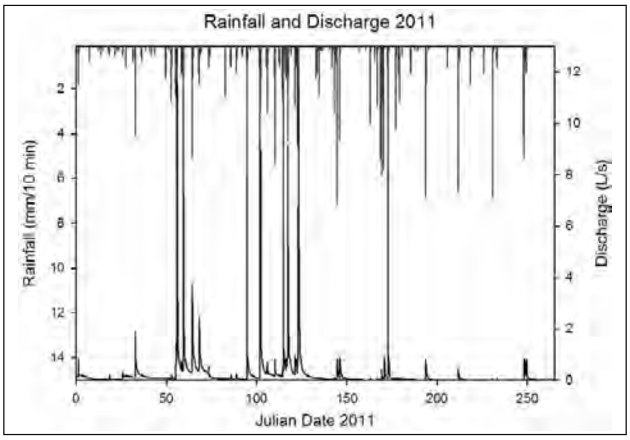

Figure 5. Example of discharge response in WF1 during storm events from 2011.

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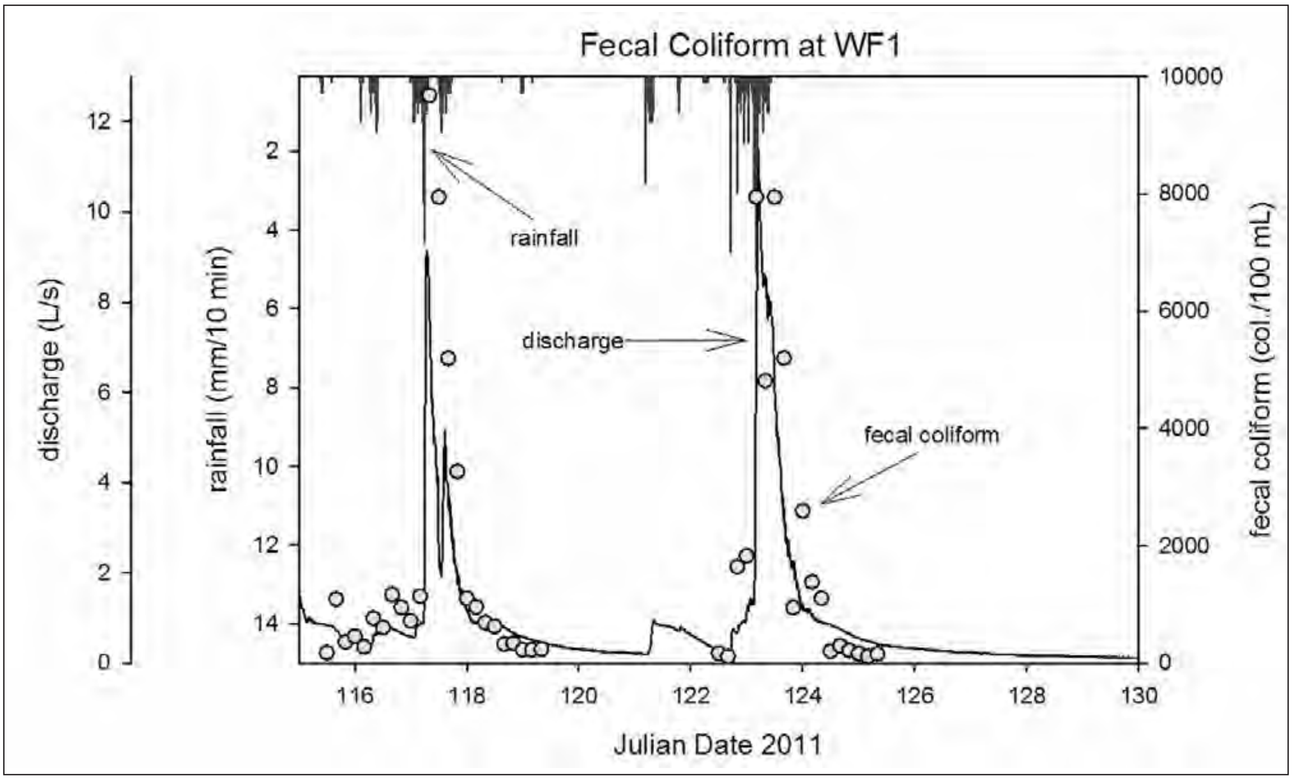

Figure 6. Fecal coliform (dots) counts at WF1 during a storm event from April 25 – May 10, 2011.

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