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ORIGINAL ARTICLE

Characterization of the karst hydrogeology of the Boone Formation in Big Creek Valley near Mt. Judea, Arkansas—documenting the close relation of groundwater and surface water

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Abstract The Boone Formation has been generalized as a karst aquifer throughout northern Arkansas, although it is an impure limestone. Because the formation contains from 50 to 70 % insoluble chert, it is typically covered with a mantle of regolith, rocky clay, and soil which infills and masks its internal fast-flow pathways within the limestone facies. This paper describes continuous monitoring of precipitation, water levels in wells, and water levels in streams (stream stage) in Big Creek Valley upstream from its confluence with the Buffalo National River to characterize the nearly identical timing response of relevant components of the hydrologic budget and to clearly establish the karstic nature of this formation. Although the complete hydrographs of streams and wells are not identical in the study area, lag time between precipitation onset and water-level response in wells and streams is rapid and essentially indistinguishable from one another. The spikey nature of the stream hydrographs reflects low storage, high transmissivity, and rapid draining of the upper zones of the karst aquifer, whereas the longer-term, plateau-like draining in the lower zones reflects groundwater perching on chert layers that feed low-yield springs and seeps through lower storage and lower permeability flow paths. Groundwater drainage to thin terrace and alluvial deposits with intermediate hydraulic attributes overlying the Boone Formation also shows rapid drainage to Big Creek, consistent with karst hydrogeology, but with high precipitation peaks retarded by slower recession in the alluvial and terrace deposits as the stream peaks move downstream.

Keywords Mantled karst · Concentrated animal feeding operations · Buffalo National River · Ozarks · Lag time · Hydrologic budget

Introduction

The Boone Formation (hereafter referred to as the Boone) occurs throughout northern Arkansas with a physiographic range approximating that of the Springfield Plateau (Fig. 1). Although this geologic unit encompasses about 35 % of the land area of the northern two tiers of Arkansas counties, site-specific details of its hydrogeology are only generally understood, and its water-transmitting capacity and its ability to attenuate contamination have not been well documented other than to reference the entire area as a mantled karst (Aley 1988; Aley and Aley 1989; Imes and Emmett 1994; Adamski et al. 1995; Funkhouser et al. 1999; Braden and Ausbrooks 2003; Mott 2003; Hobza et al. 2005; Leh et al. 2008; Gouzie et al. 2010; Brahana 2011; Kosic et al. 2015). Given this general consensus, there exists a claim by some that lack of obvious karst topography at air-photo scales and map resolutions is evidence that karst in the outcrop of the Boone does not exist.

The Boone is a relatively thick unit (about 110 m) with variable lithology, including limestone, chert, and thin shaley limestone layers. The soluble limestone of the Boone contrasts with the highly insoluble, brittle chert,

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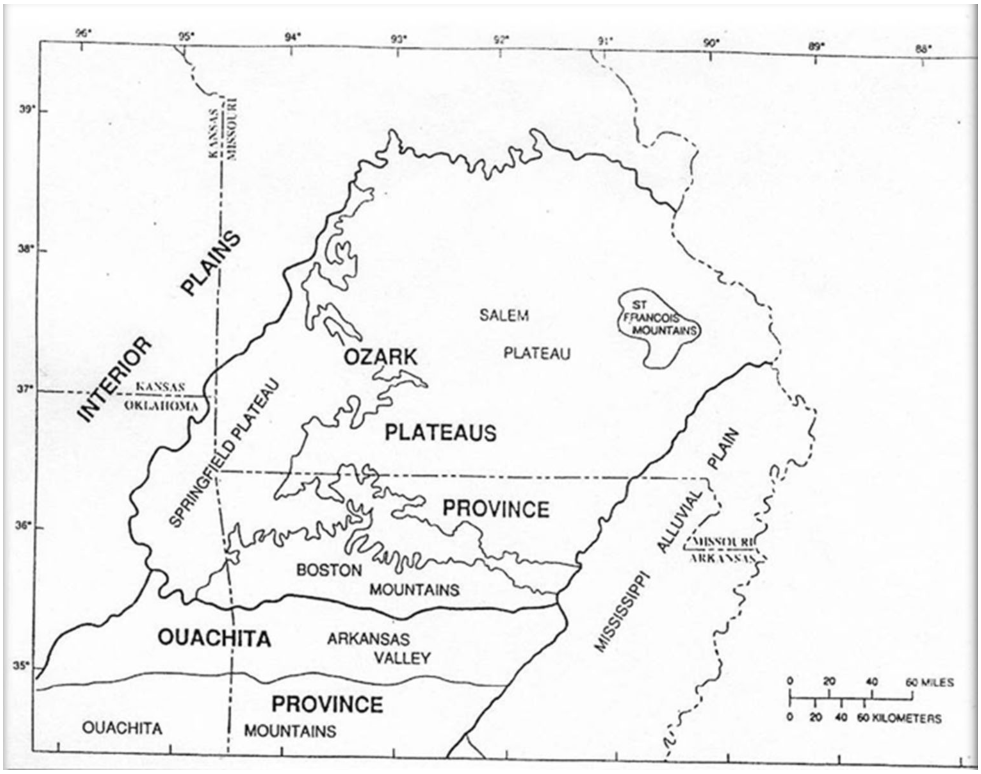


Fig. 1 Location of the Springfield Plateau physiographic province on the southern and northwestern margins of the Ozark Plateaus, midcontinent USA

which can occupy as much as 70 % of the entire thickness of this formation. For the most part, the Boone contains no less than 50 % chert, except in its upper and lower pure limestone measures (Liner 1979). The Boone is nearly flat-lying, and has numerous, interbedded limestone layers forming couplets with thin, areally continuous chert layers through much of its middle and lower sections (Fig. 2). Brittle fracturing, a result of about 200 m of total uplift in the distal, far-field of the Ouachita orogeny has allowed groundwater to chemically weather and karstify the formation (Liner 1978; Hudson 2000; Brahana 2012).

The physical attributes of the chert at a regional scale provide near-uniform thickness (Fig. 3), but in the field under close, non-magnified inspection, contact boundaries between the chert and limestone reflect thickening and thinning that one would expect in soft, non-indurated sediment, typically on the order of several centimeters, whereas individual chert layers typically extend continuously for kilometers with approximately similar thickness; different layers can be thinner than 5 cm, and as thick as 30 cm. The low permeability of the chert results in segregation and vertical isolation of parts of the groundwater flow system, which typically has been developed only in the limestone layers where the rock has been dissolved and karstified. The systematic orthogonal jointing resulting from the uplift and the long duration of weathering near the land surface are responsible for introduction of aggressive recharge and dissolution.

A significant land-use change occurred in 2013 that involved the permitting and construction of a concentrated animal feeding operation (CAFO) near Big Creek, slightly more than 10 km upstream from the Buffalo National River near the town of Mt. Judea, Arkansas. The CAFO, a 6500-head facility for farrowing sows and piglets, was permitted to be constructed on the Boone Formation. In addition to the large structures housing the swine, two lagoons approximately one acre each were included as temporary holding facilities for urine, feces, wash water from the operation, and about 600 acres of pasture land for spreading the waste were also approved; all on land underlain by the Boone Formation, or in the valleys with thin alluvial deposits directly overlying the Boone (Fig. 4; Braden and Ausbrooks 2003).

The CAFO permitting process, approved by the Arkansas Department of Environmental Quality (ADEQ), did not include any study of groundwater or study of karst, and many landowners living in Big Creek Valley and many more who use the shallow Boone aquifer for stock and domestic water supply and the Buffalo National River to canoe, kayak, fish and to swim were concerned about the risk for similar environmental and water-quality problems occurring on this river that had occurred elsewhere (Funkhouser et al. 1999; Varnell and Brahana 2003; Palmer 2007; Gurian-Sherman 2008; Brahana et al. 2014; Kosic et al. 2015). The waste generated from 6500 hogs at a facility of this size exceeds more than 2 million gallons per

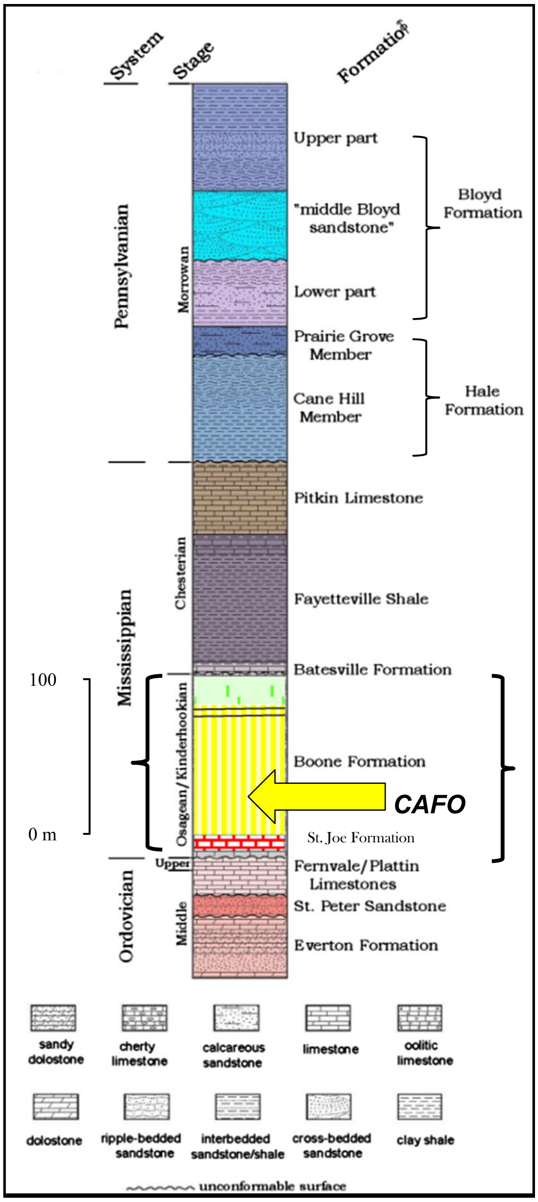


Fig. 2 Stratigraphy in the vicinity of Big Creek and Mt. Judea, in Newton County, Arkansas, showing geologic formations exposed in Big Creek Valley, a major tributary to the Buffalo National River. Emphasis in this research is on the Boone Formation, and particularly the chert-rich interval bracketed and highlighted in *yellow* directly beneath the relatively pure limestone and oolitic facies (Short Creek Oolite) highlighted in *green*, and directly overlying the relatively pure limestone of the lowermost 10 m (St. Joe Formation) shown in *red*. The CAFO and its waste-spreading fields mostly lie within the lower half of the Boone Formation, which in Big Creek Valley may be overlain directly by creek alluvium and terrace deposits

year, requiring that the waste be continually removed to avoid overfilling the waste lagoons (Pesta 2012). Pig feces and urine spread on pasture land overlying karst has generated significant concern that the CAFO will create health problems for the many tourists who utilize the river, as well as many of the downstream landowners who use the groundwater for domestic and stock water supplies. Canoeists are particularly concerned because much of the drainage area of Big Creek has been karstified, which means that contaminated water with concentrated pig waste can move rapidly underground with little or no attenuation, and resurface in Big Creek or springs that drain the spreading fields that lie along the Buffalo. Insofar as the swimmers, fishermen, and canoeists cannot escape primary contact with this river, which has been classified as an Extraordinary Resource Waters (ERW), this research was undertaken as part of a sequence of karst hydrogeologic studies to fill in the gaps that were not addressed in the original permitting and approval process.

Purpose and scope

The objective of this report is to investigate the relation of the groundwater and surface water in Big Creek and Left Fork of Big Creek drainages by comparing continuous, long-term responses of water levels in wells and in Big Creek and Left Fork of Big Creek in response to precipitation in the study area. The underlying justification is to determine the time difference (lag time) between precipitation on the land surface and the rise of hydraulic head in wells and the rise in stream stage. Fast flow and coincidence of lag time in wells and surface water in response to precipitation events are key indicators of underlying karst hydrogeology and document the justification that the wells shown represent useful sites for the introduction of fluorescent dyes to trace groundwater movement and document groundwater velocity in the Boone aquifer in the study area. The geographic scope of this paper is limited to the area atop a 6500-head factory pig CAFO, including the waste-storage lagoons, the structures housing the pigs, and the spreading fields where waste from the lagoons is applied on the land surface (Fig. 4).

Study area

The south and north boundaries of this study extend from an east–west line slightly upstream (south) of the spreading fields to downstream where an east–west line intersects the confluence of Left Fork of Big Creek and Big Creek (Fig. 4). The eastern boundary of the study area is the upper contact of the Batesville Sandstone with the Fayetteville Shale on the eastern side of Big Creek Valley, and the western boundary is the upper contact of the Batesville Sandstone with the Fayetteville Shale on the western side of Big Creek Valley (Fig. 4).

Geologic setting

The rock formations exposed at land surface in Big Creek basin are Paleozoic sedimentary rocks, with lithologies that

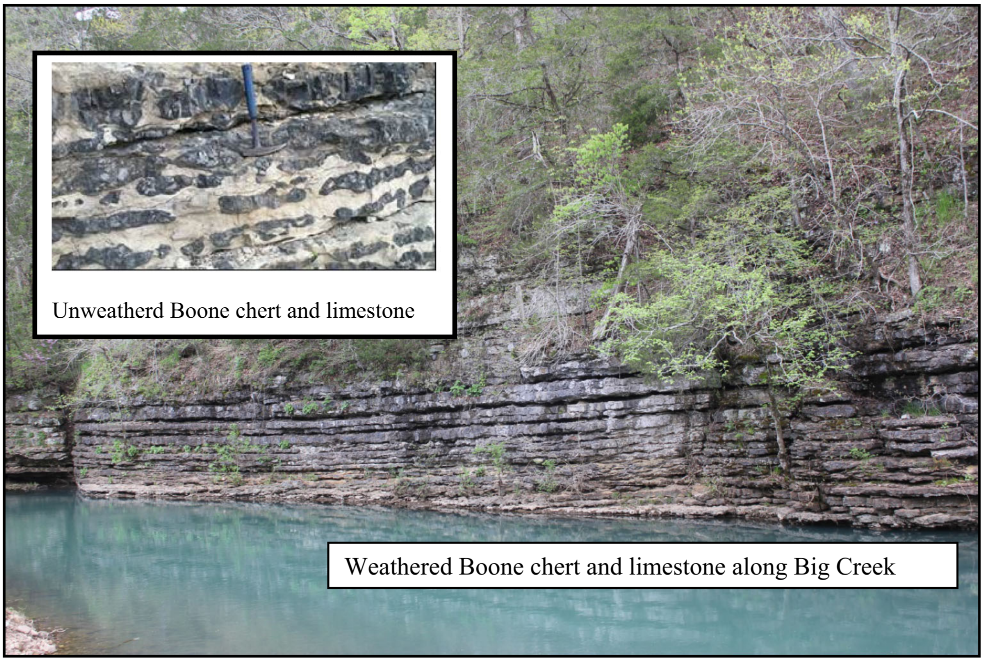
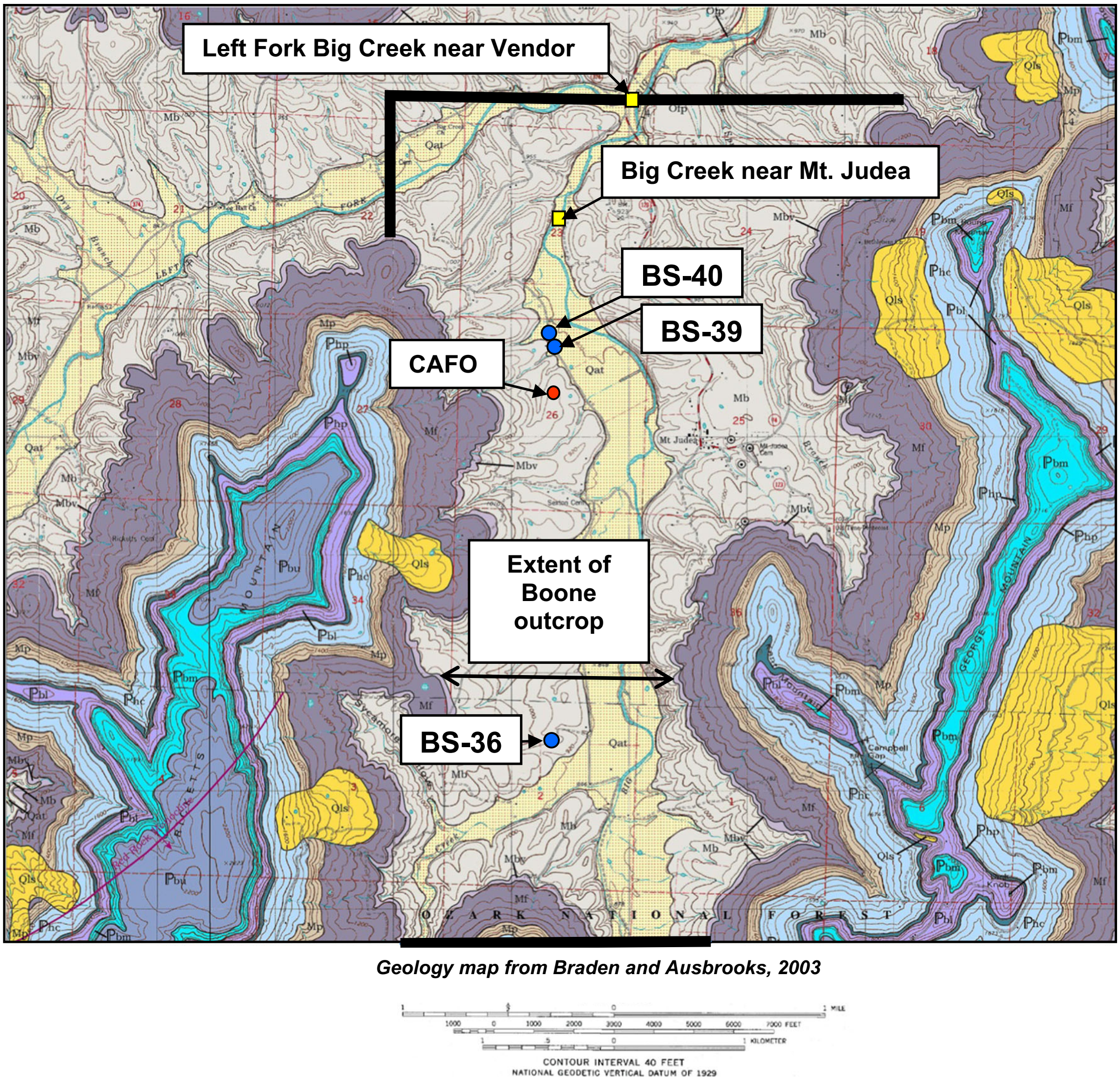


Fig. 3 Dissolution within limestone layers of the chert/limestone couplets creates an effective mantled karst in the middle to lower part of the Boone Formation in Big Creek and throughout northern Arkansas. Groundwater moving along these bedding planes has been measured by dye tracing to travel about 500–800 m per day under natural hydraulic gradients, with little or no attenuation of contaminants. The photo *inset* in the *upper left corner* shows unweathered *light gray* limestone separated between *dark gray* chert layers

range from terrigenous shales and sandstones that cap the hills and ridges in the upper part of the valley near the topographic divides to relatively pure carbonates near the confluence of Big Creek with the Buffalo National River (Fig. 2). Stratigraphically, these rocks encompass slightly less than 600 m, from the Upper Bloyd sandstones of Pennsylvanian age to the Everton Formation of Ordovician age (Braden and Ausbrooks 2003). These rocks were deposited in a range of different environments. For the Boone Formation, the interval of greatest interest to this study, the environments of deposition were mostly very shallow to deep water marine, for the St. Joe Formation. The recurring sequence of limestone and chert as couplets is thought to be derived from periodic expulsion of volcanic ash that was deposited on a very shallow marine carbonate-rock forming platform. Volcanoes are thought to have expelled the ash from south of the exposed core of the Ouachita Mountains, where the northern part of the South American plate subducted beneath the North American plate. When volcanism and ash production were intense, areal deposition of ash over broad regions of a shallow ocean overwhelmed carbonate production (which never ceased), generating the siliceous material that formed the chert. When the volcanoes were quiescent, carbonate production proceeded unimpeded, and limestone sediments were produced. Lithification, induration, and diagenesis produced rocks from the sediment, and uplift, fracturing, and weathering eroded the rocks into the landscape we see today, leaving the rock record seen now in the stratigraphic column (Fig. 2).

Oblique plate closure of the Ouachita orogeny from east to west resulted in approximately 200 m of uplift in the study area (Hudson 2000), reflected in the higher elevations occurrence of stratigraphic intervals in Newton County (Fanning 1994), and the requirement for rappeling into caves overlying some of the deep basement faults in the region that would otherwise be horizontal entrances further east or west (Fanning 1994; Tennyson et al. 2008). Most of the tectonic grain of the region is nearly flat-lying, with large-scale structures such as monoclines grading into faults being the only common feature, and brittle fractures, joints, and faults being the most common deformation types. Dips throughout most of this part of the region are less than 3°, except near major faults, where dips as large as 7°–10° may be found (Hudson 2000).

Physiographically, the chert in the Boone facilitates the formation of an undulating plateau surface, which extends across northern Arkansas from east to west. The outcrop pattern widens and curves back toward the northeast to form a prominent plateau (Fig. 1) named for Springfield, Missouri. Although the geologic nomenclature changes as one crosses the state line from Arkansas into Missouri (Boone becomes Burlington, Keokuk, and Elsie Formations), the lithologies remain the same. Whole-rock percentage of chert declines from south to north, and the continuity of the thin chert layers ceases, with the



Geology map from Braden and Ausbrooks, 2003

Fig. 4 Areal geology of the study area, showing wells (*blue* and *red circles*), stream gaging stations (*red squares*), and boundaries of the area under discussion (*black bars* on the north, northwest, and south margins). Precipitation gages were installed at BS-36 and Big Creek near Mt. Judea. The Boone Formation is shown on the map in gray with Mb symbols. This study was not granted access to the CAFO “House Wells”. *Notes* [Qat, Alluvium and terrace deposits along Big Creek and Left Fork of Big Creek; Mf, Fayetteville Shale; Mbv, Batesville Formation; Mb, Boone Formation; Other geologic units (labeled M and P as first letter are younger geologic units beyond the scope of this study). Qat directly overlies the Boone Formation in the valleys and is in direct hydrogeologic connection with the Boone.]

dominance of discontinuous chert nodules along bedding planes being more prevalent in Missouri rather than continuous chert layers, which are dominant in Arkansas.

Methodology

The approach to measuring and documenting the precise timing of water-level response of groundwater and stream levels in response to precipitation follows the hydrologic methodology of the U.S. Geological Survey (Straub and Parmar 1998; Sauer and Turnipseed 2010). Water level in surface water is called stream stage, which is a measure of the depth of the stream at a resistant rock layer, a “control” that lies within the stream bed and is difficult to erode. Typically, the physical determination for a wide range of variable flow conditions of a stream is measured using Doppler flow methods, and these are compared with stage to create a stage–discharge relation. For this study, the interest is strictly in the water level in the stream, and its timing as compared to hydraulic-head response and timing in the wells.

Stream stage in this study is drawn from two surface-water stations measured by the U.S. Geological Survey, Site 07055790, Big Creek near Mt. Judea, Arkansas, and Site 07055792, Left Fork of Big Creek near Vendor,

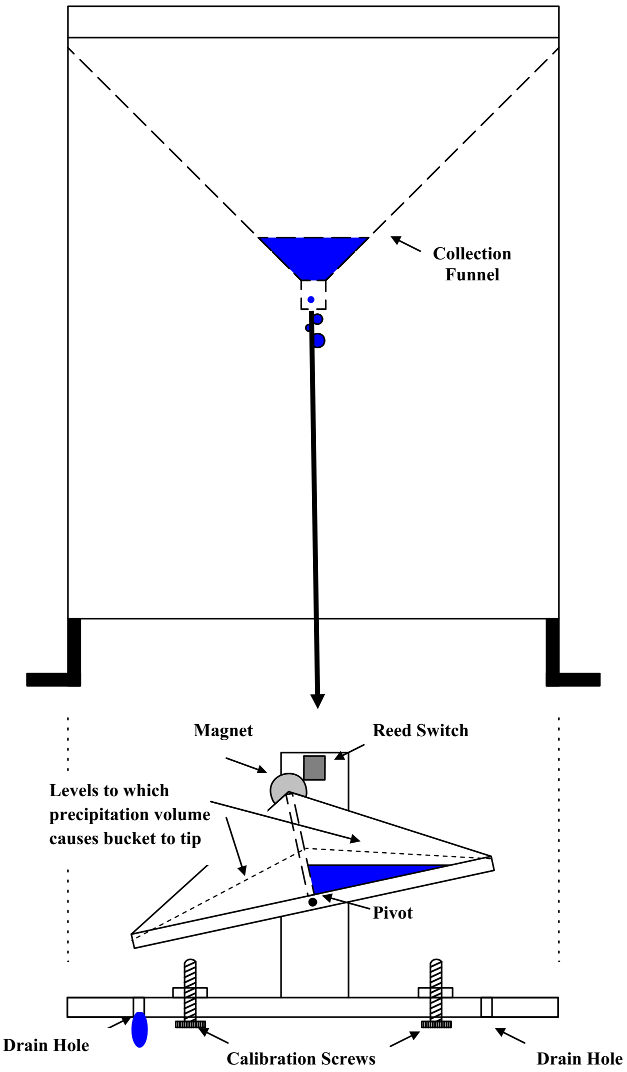


Fig. 5 Internal schematic showing the operation of the tipping-bucket portion of the rain gage, which is centered beneath a narrow funnel (beneath *blue* water drop at the *top of the figure*). When the rainfall reaches 0.04 mm (0.01 inch) of rain, the weight causes the rocker arm to pivot, moving the magnet past the reed switch, which is recorded to the nearest second by cable to the Campbell CR 10× data recorder (Fig. 6). A summation of the number of tips provides the magnitude of the precipitation event, and the time interval provides the duration of the event from start to finish. Data are downloaded from the data recorder to a laptop computer in the field, and processed with data downloaded from transducers which are installed below the water level in wells, and the stream-stage records, which are measured in time increments of every 5 min

Arkansas. In the case of surface-water station Site 07055790, Big Creek near Mt. Judea (Fig. 4), the control is composed of chert in the lower Boone. In the case of surface-water station Site 07055792, Left Fork of Big Creek near Vendor (Fig. 4), the control is the St. Joe Formation (Fig. 2), a relatively pure limestone (Big Creek Research and Extension Team 2015).

Precipitation, which in the study area is dominantly rainfall, was measured at well BS-36 using a tipping-bucket rain gage (Texas Electronics Model TE 525), an electronic weather station with a very accurate clock and a fulcrum-balanced seesaw arrangement of two small buckets on either side of the pivot (Fig. 5). The two buckets are manufactured within accurate tolerances to ensure that they hold an exact amount of precipitation, typically 0.24 mm. The tipping-bucket assembly is located underneath the rain collector, which funnels the precipitation vertically downward to the buckets. As rainfall fills one bucket, it becomes unbalanced and tips down, emptying itself as the other bucket pivots into place for the next filling. The action of each tipping event moves a magnet past a switch, activating the electronic circuitry to transmit the count of the number of tips to a digital datalogger (Campbell CR 10×),

Fig. 6 Pressure transducer, which measures the height of the water column above the pressure sensor, shown by the *red arrow* on the left side of the figure above. This field instrument is also equipped with a temperature thermistor, which measures the temperature of the groundwater. Under most conditions, the transducer is hung vertically in the well by a cable through the cap, identified by the *green arrow*. Water level and temperature data are stored internally in the instrument at a predetermined time interval, typically every 5 min. Data are downloaded periodically by removing the instrument from the well, unscrewing the water-tight cap and connecting it to an optical reader interface attached to a field laptop. Once downloading is complete, the instrument is reset, reinstalled in the well, and the water level is measured with an electric tape to verify the exact water level. The entire process is documented in a field notebook to facilitate data interpretation

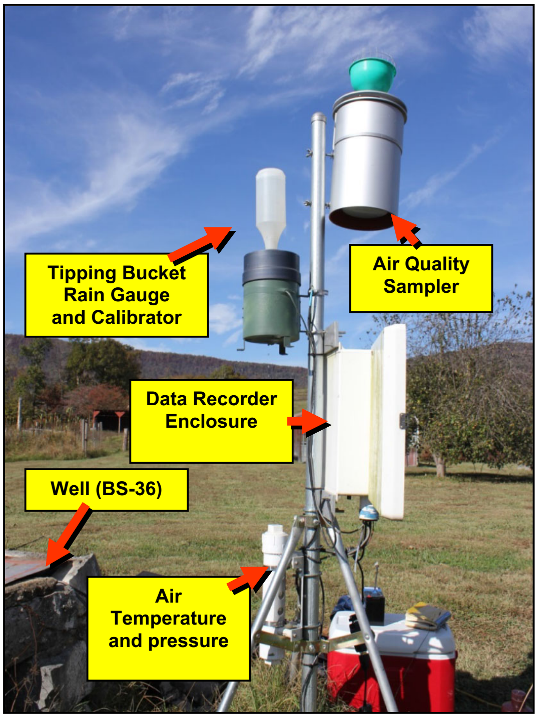


Fig. 7 Data collection equipment at BS-36, a site that is surrounded on three sides by spreading fields that receive waste from the hog CAFO. The instruments used in this research measure rainfall intensity and duration (tipping-bucket rain gage), and air temperature and pressure, which is used to calibrate the transducer which measures changes in the water level in well BS-36 in response to rainfall. The transducer is not shown in this image, but the data it collects are electronically transmitted to the data recorder every 15 min, and these data are plotted with the exact timing and amount of the rain. Data are stored digitally in the recorder, which is locked inside the enclosure which is shown. The air quality sampler is part of another experiment, and those data are not discussed in this research. Connections to the transducer are made by cable down the inside of the well. Figure 6 shows the view down the well

Fig. 8 View looking down well BS-36, which shows the groundwater reflected as a bright spot of light at a depth of 10.15 m below the top of the well. Cables and wires allow data to be communicated from below the water surface to the data recorder (Fig. 7). Hand-dug wells are not uncommon in the Big Creek area, and provide a glimpse into a bygone era when they were created by pick and shovel as the well digger was lowered by rope and pulley down to a level where he encountered water. Dug wells have to be wide enough to allow the well digger to fit inside the borehole, and this one is 0.46 m in diameter. When the well digger has reached the level where water moves into the well to a depth that hopefully does not dry up during droughts, his digging is completed. The walls of the borehole are often lined with sandstone or chert rock slabs that keep soil and other debris from falling into the well. Dug wells are an excellent means for hydrogeologists to gain direct measurement into the water that is flowing underground

recording each event as 0.25 mm of rainfall with an accurate time. Rainfall data from the datalogger were totaled for the same 15-min interval as stream stage and hydraulic-head data from the transducers.

The design and accurate functioning requires that the rain gage be level, accomplished by centering a bubble level. Calibration of the rain gage to 0.24 mm per bucket tip was accomplished using the Novalynx Corporation model 260-2595 Rain Gage Calibrator following the Texas Electronics field calibration method. Replication of precipitation accuracy involved utilizing two rain gages in the basin reported by the U.S. Geological Survey (http://waterdata.usgs.gov/ar/nwis/rt).

Hydraulic head (groundwater level) and temperature were measured using transducers (Fig. 6) at the three groundwater sites within the study area (Fig. 4), but temperature data were not available for the streamflow or precipitation sites. Although temperature data can be very important in groundwater and spring characterization studies, the missing temperature records from the stream and precipitation data were considered to be ancillary to this study and are thus not discussed. Site details for the wells, BS-36 (Figs. 7, 8, 9), BS-39 (Fig. 10), and BS-40 (Fig. 11), reflect well construction, well dimensions, and equipment placement within each well. Transducers record the pressure exerted by the weight of the water above their sensor, using a non-vented water-level logger encapsulated in a polypropylene housing and placed below the water surface in wells. The logger, a HOBO U20L-004 is a research-grade instrument manufactured by Onset Computer Corporation and was used to continuously measure and record water level and temperature with a 0.1 % measurement accuracy. A second identical device was secured at land surface (Fig. 7) to measure air pressure and temperature; parameters necessary for correcting the effect of air pressure changes to compute the precise hydraulic head of the groundwater in the well. Post-processing of the groundwater data allowed for matching the hydraulic head of the groundwater with the precipitation data, which in turn were time synchronized with the USGS stream-stage data.

Verification of transducer accuracy in each well followed standard USGS procedures (Shuter and Teasdale

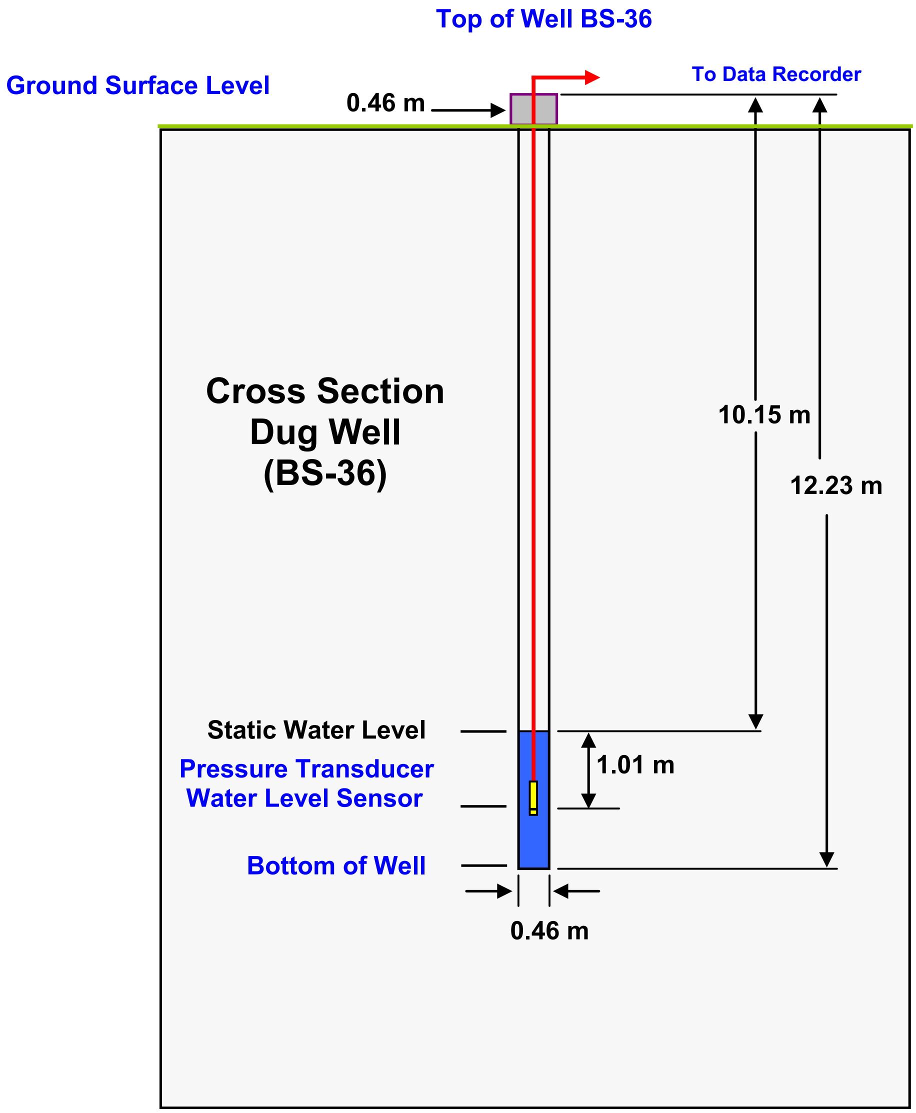


Fig. 9 Cross section showing a geologically prepared view of well BS-36 with distances carefully measured using a steel tape accurate to 1 mm. The pressure transduce, shown as the *yellow cylinder* at the bottom of the *red* cable, accurately measures water level in the water at the bottom of the well in response to rainfall. The transducer actually measures the height of the water above it, which is accurate to a fraction of a mm. The transducer also has a thermistor (temperature), and a very accurate clock built into it, so that data collected can be compared to the accurate clock of the rain gage. The resulting hydrograph (plot of water level vs. time) of the well can be compared to the timing of the rainfall to assess how long it takes the water on the surface to infiltrate into the well, which is an excellent indicator of how well developed and open the karst is in this area. Well BS-36 was chosen because it represents groundwater that occurs in the limestone/chert couplets that are shown in Fig. 3. The diagram is not drawn to scale

1989; Taylor and Alley 2001; Freeman et al. 2004) and was measured using both steel and electric water-level tapes during site visits, approximately every 3 weeks. As a further quality assurance/quality control determination, hydraulic-head data in BS-36 were replicated using a Druck (Model PDCR 1830 (mv) 5 psi) pressure transducer connected to a Campbell Scientific CR 10× Datalogger. The datalogger sampled every 5 min, and data were post-processed to convert to hydraulic head averaged over a 15-minute interval.

Results

Hydrographs of two surface-water gaging stations for the month of May 2015 are shown in Fig. 12. The hydrographs show the stage (stream level rise and fall) on the *vertical axis* plotted against time on the *horizontal axis*. Precipitation is shown by the vertical lines that are plotted along the bottom axis of the graph based on the duration and intensity of precipitation events. The scale for the stream responses is shown on the *left side* of the *y*-axis, and the scale for the precipitation is shown on the *right side* of the *y*-axis. Time is shown on the *x*-axis of the plot, along the bottom of the graph. The timing of the causes (precipitation) and effects (stream-stage response) on the graph allows for a rapid visual assessment of the difference between precipitation initiation and stream-stage increase, a difference called the lag time. In Fig. 12, the lag time was less than an hour in all cases, indicating that the stream levels started rising essentially no later than an hour after the precipitation started.

Hydrographs of three groundwater wells for the month of May 2015 are shown in Fig. 13. The hydrographs show the hydraulic head on the vertical axis plotted against time

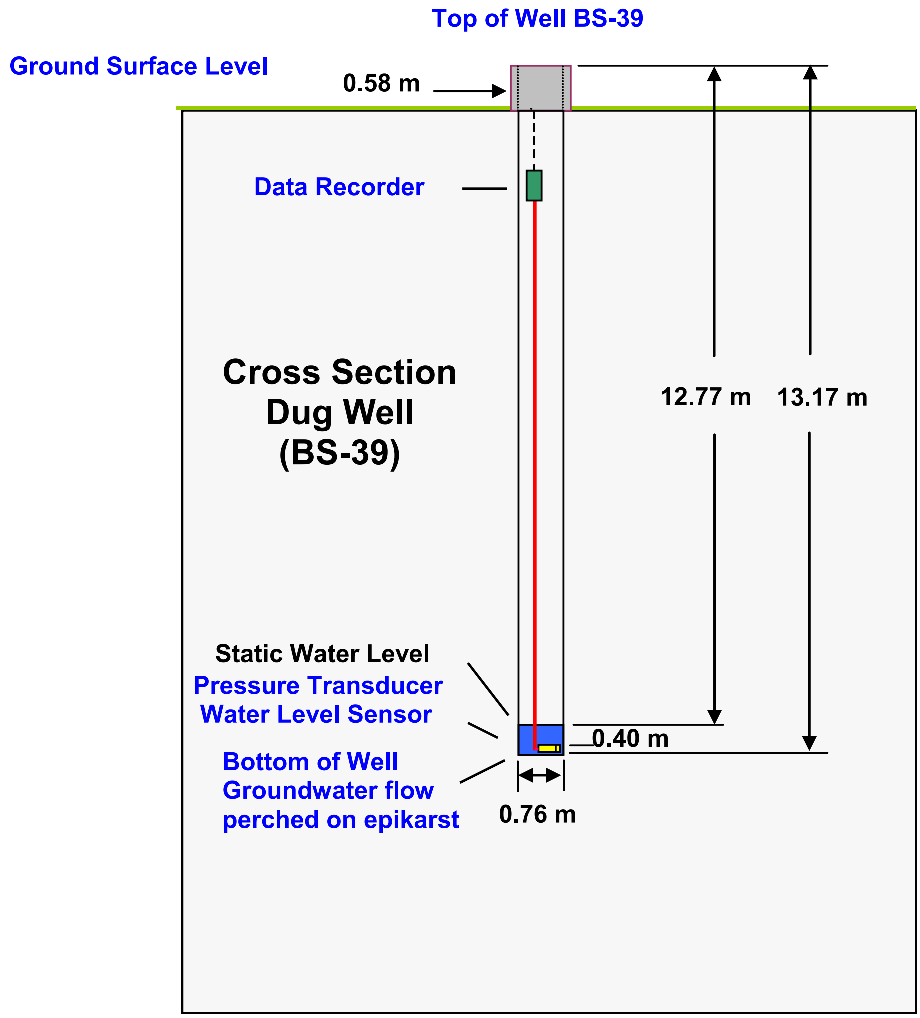


Fig. 10 Cross section showing a second type of hand-dug well, BS-39, which is located on the top of the epikarst, the weathered zone of karst rock that lies directly below the regolith and alluvium in the valley across the county road from the CAFO property. Well-completion methods are similar to those used in BS-36, with the borehole stacked with sandstone and chert rock slabs to protect the completed well from collapse, just as BS-36 was. The diagram is not drawn to scale

on the horizontal axis. As in Fig. 12, precipitation is shown by the vertical lines along the bottom axis of the graph, and the scale of hydraulic head is presented as it was the surface-water graphs. For the three groundwater wells, time lag was essentially identical to the time lag of the surface-water stage, indicating that groundwater levels started rising no later than an hour after precipitation started.

Rapid response of the groundwater level is an indicator that karst conditions facilitate rapid flow of precipitation into the ground. The magnitude of the water-level increases can be caused by several factors including: variation of permeability or porosity of the aquifer materials; variation in storage as the groundwater moves downgradient; variation in karstification in the limestone/chert couplet interval of the Boone (BS-36); variations in the epikarst (upper eroded zone) at the top of the Boone (BS-39); and variations in Big Creek alluvium and terrace deposits (BS-40) that directly overlie the Boone in Big Creek Valley (Braden and Ausbrooks 2003).

Figure 14 provides a compilation of Figs. 12 and 13 in the study area, showing the nearly identical lag times of all water-level responses of wells and streams for the time interval from May 1, 2015, through June 2, 2015.

For the period of record, from May 1, 2015, through early June, 2015, 10 storms of varying intensity were recorded. Hydrograph records of the wells and streams indicate that water level rises rapidly after the onset of precipitation in Big Creek and contiguous basins, with little delay (less than an hour) between the wells and the streams (Figs. 13, 14, 15). This coincidence of the start of water-level rise in the hydrographs reflects the close relation of surface and ground water. The time to maximum crest of each hydrograph, however, indicates the duration the water takes to move laterally below ground through aquifers to the hydrologic drains. Variations in time-to-crest of each of the hydrographs indicate details of the rainfall intensity and variations in the underground flow system, including permeability, prestorm water levels and hydrologic conditions, rainfall distribution, flow constrictions or constraints for intervening flow paths, and degree of karstification.

The sites included: BS-36 is a (hand-dug) well open to the epikarst in the upland on the Boone slightly less than

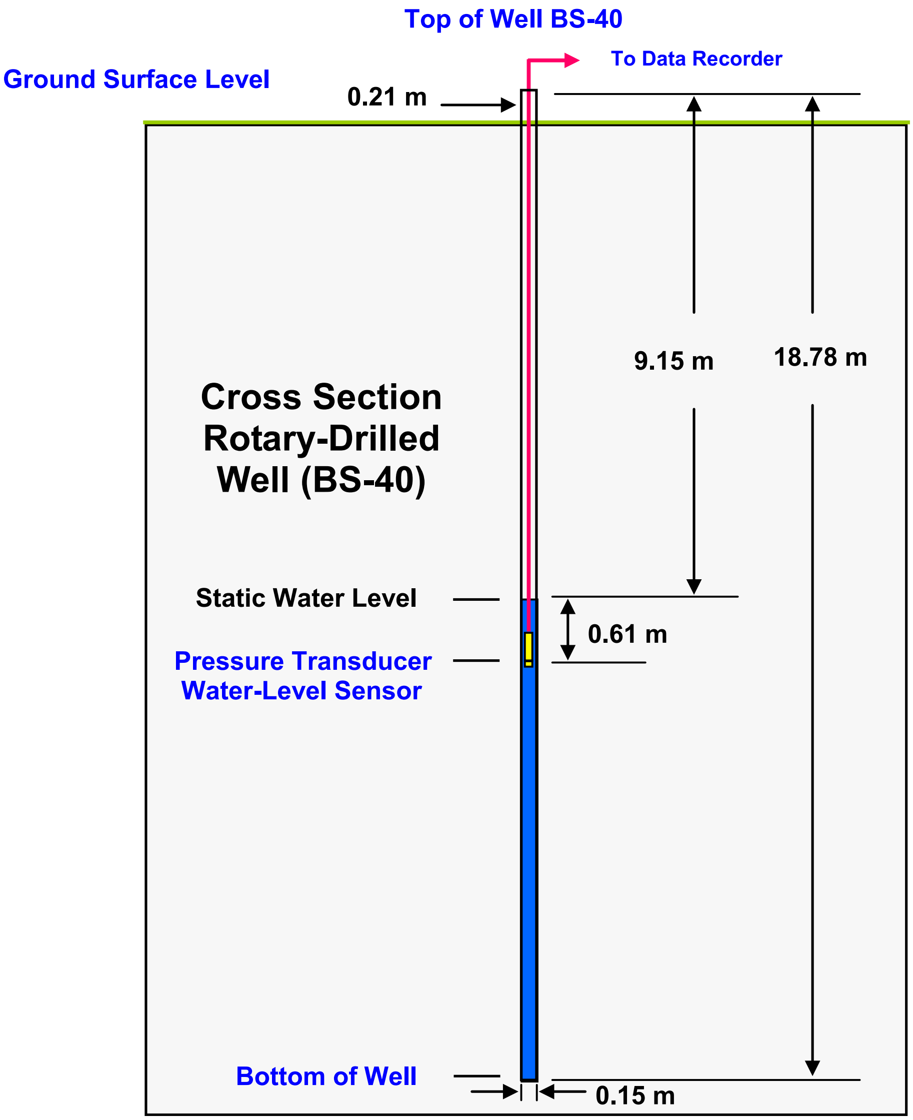


Fig. 11 Cross section of the third type of well in the study area, BS-40, which was constructed by a rotary drilling method. This is a more modern and effective means of well-drilling, and is capable of completing wells into hard, indurated, competent rock. The diameter of wells completed by rotary drilling are significantly smaller than hand-dug wells, and the completion methods are distinctly different. Instead of a stacked rock casing, these types of wells are lined with PVC or steel pipe, and the interval the driller leaves open to the borehole has holes, openings, a screened interval, or nothing (an open hole, if the rock will stay open when the drill bit is removed). Various types of casing with narrower slots or openings than the sediment size protect finer-grained materials from being drawn into the well. Well BS-40 was drilled in rocks shown as Qat, part of the sand, gravel and clay deposited by Big Creek. The diagram is not drawn to scale

2.7 km along an azimuth of 1° east of south from the south corner of the southern hog barn; BS-39 is a (hand-dug) well open to the epikarst near the boundary of the upland and the Big Creek alluvial plain slightly less than 425 m along an azimuth of 3° east of north from the northern corner of the northern hog barn; BS-40 is a (rotary drilled) well open to the Big Creek alluvium within the Big Creek alluvial plain about 520 m from the northern corner of the northern hog barn along an azimuth of 4° east of north; surface-water USGS Station 07055790, Big Creek near Mt. Judea, AR; and surface-water USGS Station 07055792, Left Fork Big Creek near Vendor, AR (Fig. 16).

Although the onset of water-level rise in response to precipitation for the stations above was considered to be coincident, variations in time-to-crest of the hydrographs from each site for the period of record showed a progression through time, generalized from fastest to slowest as:

1. USGS Station 07055790, Big Creek near Mt. Judea, AR (tie)
2. USGS Station 07055792, Left Fork Big Creek near Vendor, AR (tie)
3. BS-36
4. BS-40 (slight difference)
5. BS-39 (slight difference)

Considering the storm of 5/11 and 5/12 (Figs. 13, 14, 15), which generated the greatest precipitation for the period of record, time-to-crest for wells BS-40 ad BS-39 was greatest. Because the hydrographs of the surface-water stations were already in recession, high stream base level decreased rapidly, owing to high transmissivity of the surface streams as compared to groundwater, and the delay in time-to-crest seen in the hydrograph of BS-40 took longer to discharge existing water already in the system. The exact cause of the

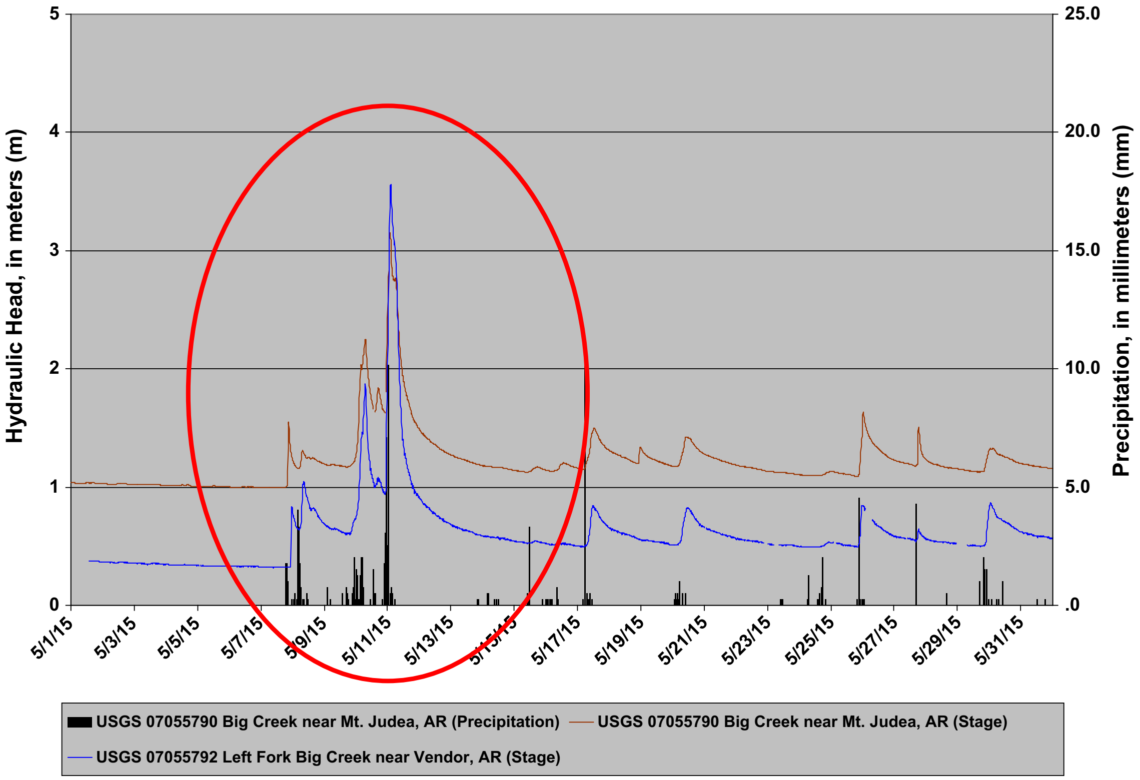


Fig. 12 Hydrographs of two surface-water gaging stations run by the U.S. Geological Survey in Big Creek Valley, Left Fork of Big Creek near Vendor, AR, and Big Creek near Mt. Judea, AR, for the month of May 2015. The hydrographs show the stage (stream level rise and fall) on the *vertical axis* plotted against time on the *horizontal axis*. Precipitation is shown by the *vertical lines* that are precisely plotted based on the duration and intensity of precipitation events. The scale for the stream responses is shown on the *left side* of the *y*-axis, and the scale for the precipitation is shown on the *right side* of the *y*-axis. The timing of the causes (precipitation) and effects (stream-stage response) can be subtracted, and is called the lag time. In this case, the time lag was zero, indicating that the stream levels rose essentially as soon as the precipitation started

delayed time-to-crest is not known at this time. Water level in BS-39 appeared to be controlled by BS-40, reflected in Fig. 14 for storms of 5/9, 5/11, 5/17, 5/20, 5/26, 5/27, and 5/30. For the most part, the peaks are similar, but BS-40 appears to reach time-to-crest slightly sooner than BS-39. We interpret this response to reflect the short-term, temporal base level created by increased flow in the Big Creek alluvium, which slows draining from BS-39. The implication of rapid draining is a further indicator of karst drainage, which is characterized by rapid loss of base flow. Data for the storms of record in the study area indicate only minor (1–3 days) gains of baseflow to streams during droughts resulting from the alluvial component of the system.

The hydrograph of well BS-36 generally crested rapidly, prior to the time-to-crest of Big Creek and Left Fork of Big Creek (Fig. 14). We interpret this as a reflection of the drainage basin size that contributes to BS-36 as being relatively small and flow distances being generally short, typically less than 1 km. In the cherty part of the Boone in upland settings, chert perches shallow water levels that recede with variable rates depending on the karstification of the interbedded limestone.

The hydrograph of well BS-36 for 8^{+} months during the interval from January 23, 2015, through August 27, 2015, showing the control of chert layers on groundwater recession is shown in Fig. 15. Zone A is confined at its base by a hydrologic break at a depth of about 1.67 m above the bottom of the well. The limestone interval above this depth appears to have well-developed secondary karst on the base of the chert, as reflected by the steep recessional limb above 1.67 m indicative of rapid draining. A chert layer (Break 1) is interpreted as inhibiting upward water-level rise for 11 major precipitation events for this time interval, and where the spillover occurs into Zone A for 4 of these events, the rapid water-level declines reflect the effectiveness with which the karst above Break 1 allows the rapid outflow of the added groundwater. Zones B and C reflect active vertical fluctuation of the water level through this interval, with water-level declines of about 0.3 m in several days after precipitation events. Break 2 at about 1.43 m above the bottom of the well is interpreted as a permeability break, likely not a chert layer but lithologically controlled by a very thin interval. The bases for this determination are: a)

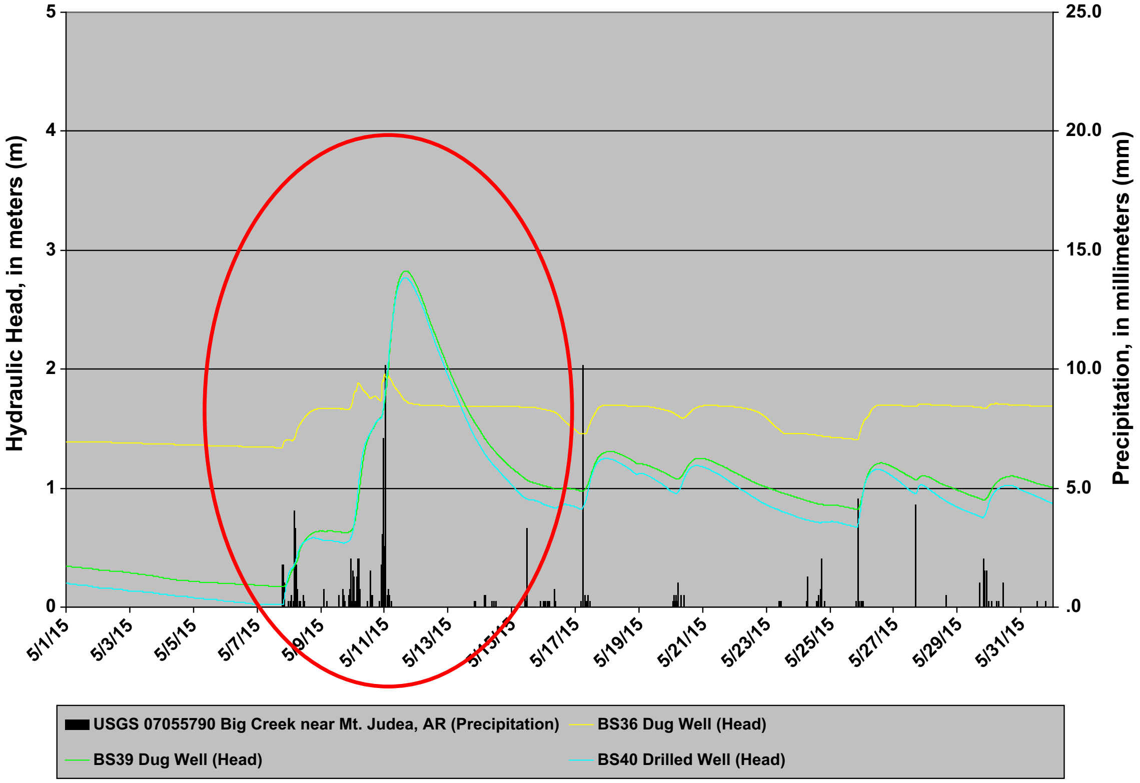


Fig. 13 Hydrographs of three groundwater wells, BS-36, BS-39, and BS-40 for the month of May 2015. The hydrographs show the groundwater level (rise and fall) on the *vertical axis* plotted against time on the *horizontal axis*. As in Fig. 12, precipitation is shown by the *vertical lines* and the scales for the figures are presented in the same locations. The timing of the causes (precipitation) and effects (groundwater-level response) can be subtracted, and is called the lag time. In this case, the time lag was essentially zero, indicating that groundwater levels started rising as soon as the precipitation started. The magnitude of the water-level increases is a reflection of the change in storage as the groundwater moves downgradient, and varies for different hydrologic settings in the Boone Formation (BS-36), the epikarst at the top of the Boone (BS-39), and the Big Creek alluvium and terrace deposits (BS-40) that lie above the Boone in Big Creek Valley

2 hydrograph rises terminate at Break 2; b) 3 hydrograph recessions terminate against this very thin layer; and c) 6 distinct breaks in recessional gradient occur at Break 2. Break 3, which occurs at 1.37 m above the bottom of well BS-36, is thought to represent the lowermost chert layer in the well that perches the slow-flow component of the karst groundwater until essentially all water in the well has been dissipated. The remarkably level groundwater surface for about 75 % of the total hydrograph record is consistent with the interpretation that the lower 1.37 m in this well was created as a cistern. This cistern is an effective storage zone that does not intersect any well-developed karstified zones in the well-bore. In this vertical interval, flow recedes very slowly until the next precipitation event generates a groundwater-level rise. This slowest recession rate, which drains the cistern at a rate about 0.15 m per month, is reflected in slow drainage to low-level seeps and springs along poorly developed, low-permeability karst flow paths. Three of these perched, low-discharge springs are known to be within about one hundred meters south and east of well BS-36 (Fig. 16).

The sequence of selected springs encircling well BS-36 is demonstrable karst discharge features from the middle portion of the Boone that contains limestone/chert couplets (Fig. 2) and deserve discussion in conjunction with hydraulic head in this aquifer (Fig. 15). Springs and seeps from this interval are common (Braden and Ausbrooks 2003). When extreme precipitation events occur, such as are shown when the hydraulic head in BS-36 is elevated into zone A (Fig. 15), lateral groundwater flow becomes confined by the overlying chert layers and produces ephemeral high-level artesian springs. The photograph in Fig. 16 shows one of these springs, which flowed after a storm of more than 250 mm over the course of several days in mid-May, 2015. Multiple springs became active during this time, some spouting more than 0.3 m above land surface at the point of resurgence. Deposited around the outflow of these springs were piles of angular chert gravel (several cm in diameter) which had been washed out of the aquifer by rapid groundwater flow. These gravel clasts had not traveled far in the subsurface, based on the angularity of the chert, but they obviously were moved by a fast-flow

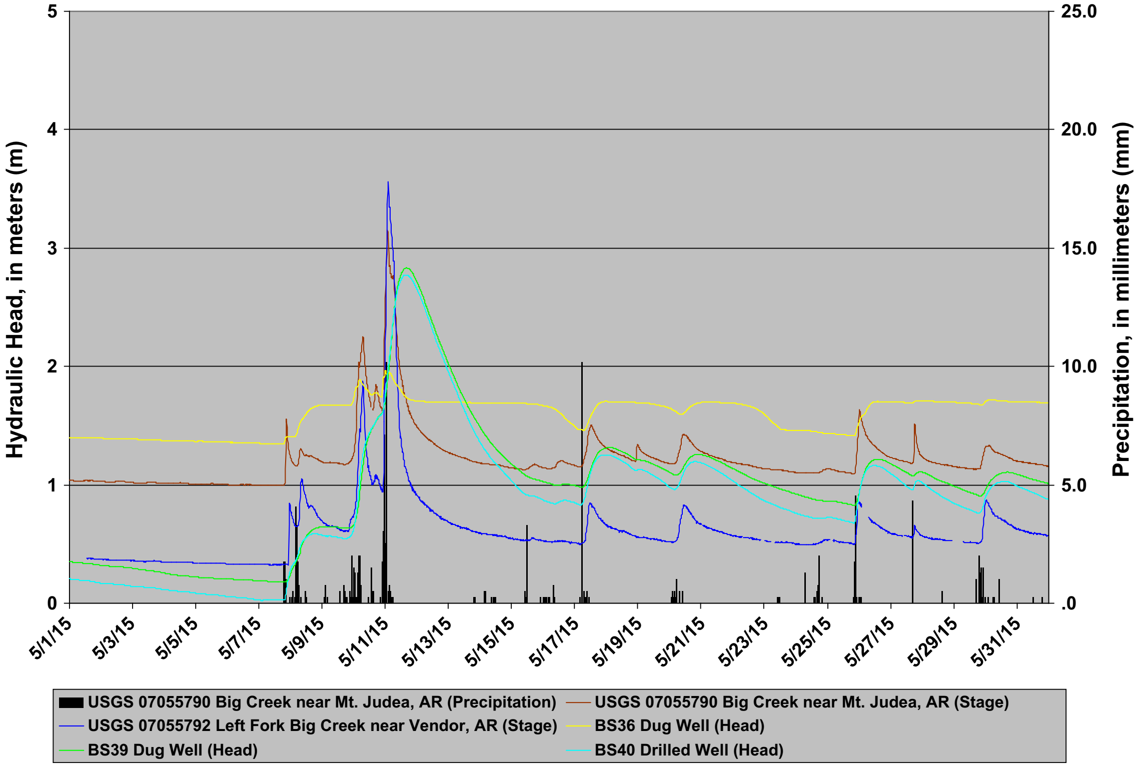


Fig. 14 Compilation of precipitation, and surface-water stage from Big Creek at Mt. Judea, Arkansas, and Left Fork of Big Creek near Vendor, Arkansas, and groundwater levels in Big Creek drainage basin at wells BS-36, BS-39, and BS-40, showing the nearly identical lag times of all water-level responses of wells and streams. The *hydrographs* shown represent the time interval from May 1, 2015 through June 2, 2015

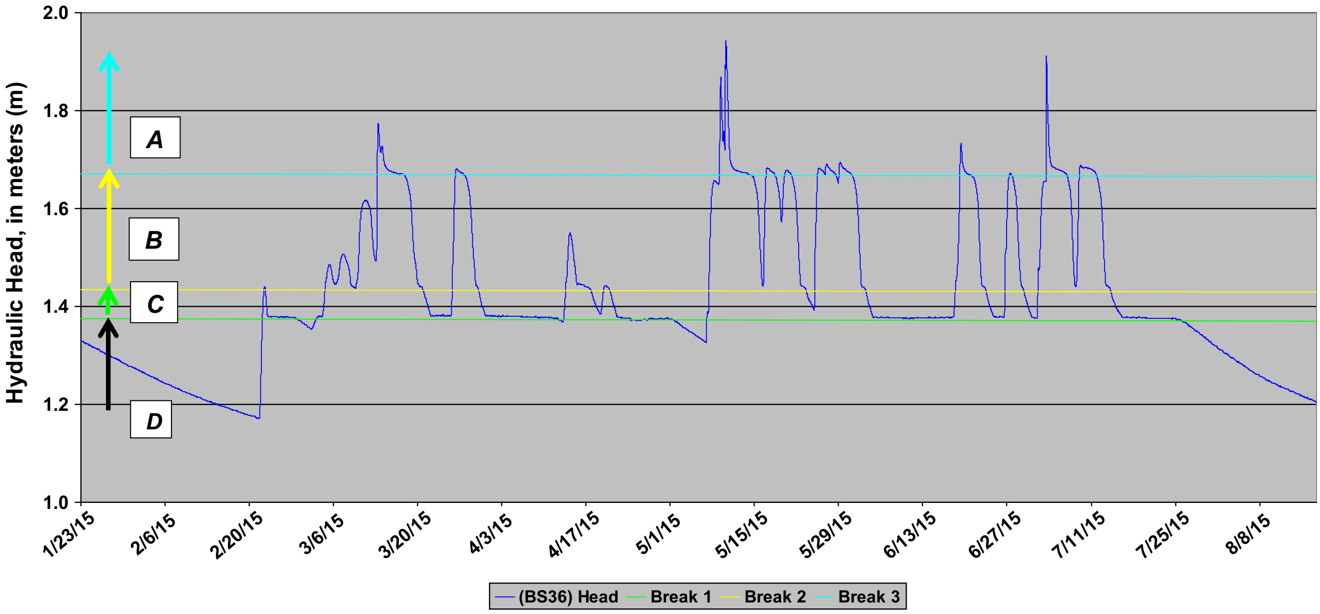


Fig. 15 Hydrograph of well BS-36 for 8^+ months during the interval from January 23, 2015 through August 17, 2015, showing the control of chert layers on groundwater recession. Four hydrologic zones are identified by 3 breaks in the plot of water level over the time of the hydrograph, and indicate that the presence of karst hydrogeology in this well surrounded by CAFO spreading field

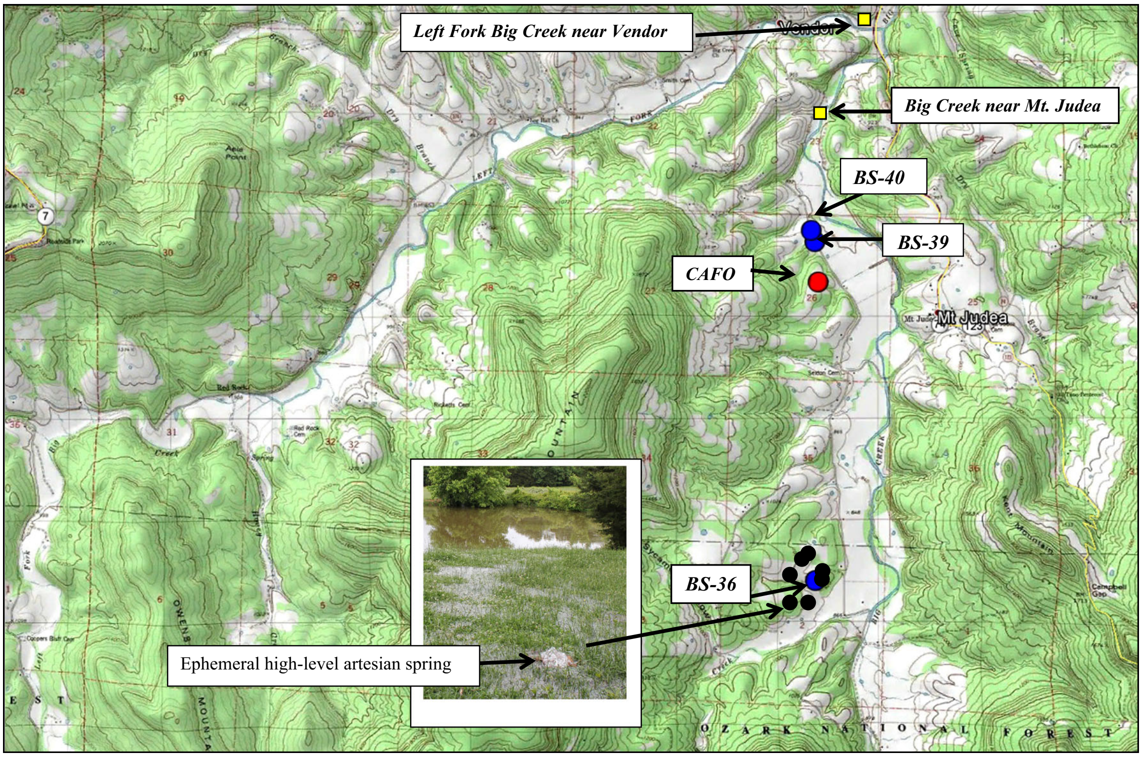


Fig. 16 Shaded topographic relief of the study area showing data collection sites. Surface-water sites are provided by the U.S. Geological Survey and are shown in *yellow*; groundwater sites are shown in *blue*; ephemeral springs, both artesian and perched that surround well BS-36 are shown as *black circles*; the CAFO is shown as a *red circle*

component of a karst aquifer because their size required continuous flow pathways large enough to allow gravel-sized particles and large flow volumes to be transported through. As is typical of karst aquifers, flow from these springs receded quickly, typically by much less than 24 h.

The hydrogeologic response of the springs described above is similar to others in Big Creek basin, and in fact, throughout the area of occurrence of the Boone. For example, many of the springs within the study area were found to be multi-orifice during an initial karst inventory, with numerous resurgences along near-horizontal bedding planes in karstified limestone lying between chert layers. Insofar as these springs were visited multiple times, during a wide range of variable groundwater levels, it became obvious that upper-level resurgences ceased flowing during droughts, establishing overflow/underflow conditions that were controlled by anisotropic permeability zones. Such findings are not unexpected in karst (Winter et al. (1998), Palmer 2007), and they serve as supporting evidence that the Boone is a karst aquifer.

Conclusions

This study provides continuous monitoring of precipitation, hydraulic head in wells, and stream stage in Big Creek Valley upstream from its confluence with the Buffalo National River to characterize the nearly identical timing of the response of these components of the hydrologic budget and to determine the karst nature of the Boone. Not only is the timing of stream-stage increase almost identical to groundwater-level rise in the streams and springs of the study area, but documented dissolution features of varying scales clearly indicate that the lack of obvious karst topography at air-photo scales is not a good indication that karst hydrogeology does not exist.

Although the complete hydrographs of streams and wells are not identical in the study area, lag time between precipitation onset and water-level response in wells and streams is rapid and indicates essentially indistinguishable from one another. The spikey nature of the stream hydrographs reflects low storage, high transmissivity, and rapid draining of the upper zones of the karst aquifer, whereas the longer-term, plateau-like draining in the lower zones reflects groundwater perching on chert layers that feed low-yield springs and seeps through lower storage and lower permeability flow paths. Groundwater drainage to thin terrace and alluvial deposits with intermediate hydraulic attributes overlying the Boone also shows rapid drainage to Big Creek, consistent with lateral input from karst sources, but with high precipitation peaks retarded by slower recession in the alluvial and terrace deposits as flow moves downstream.

Fast flow and coincidence of lag time in wells and surface water in response to precipitation events are key indicators of underlying karst hydrogeology. These data document the justification that the wells shown are useful and meaningful sites for the introduction of fluorescent dyes to trace groundwater movement and document groundwater velocity in the Boone aquifer in the study area. Insofar as karst occurs, and insofar as karst hydrogeology is heterogenous, dye-trace input sources that utilize dug wells in mantled karst are entirely justified, and the results of the dye tracing in wells at differing water levels are a meaningful and effective way to characterize the complexity of the groundwater flow system, which in this area shows multiple levels of variably karstified flow paths.

As discussed previously, the recurring and areally continuous chert layers in the limestone/chert couplets of the Boone provide a mantle that masks much of the underlying structure of the groundwater drainage from land surface or above. Groundwater flow follows the laws of physics. This means it flows from high energy (hydraulic head) to lower energy, following the path of least resistance. In the Boone, the path of least resistance is the karst fast-flow pathways in the pure limestones, be they thin-bedded and separated by chert, as in the middle part of the formation, or be they thicker bedded with obvious openings at land surface, as in the purer carbonate lithologies of the upper Boone and the St. Joe Formation.

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