Augmenting Groundwater Recharge Through Brush Control: A Feasibility Study—Phase II

Final Report to the Edwards Aquifer Authority

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Abstract

The influence of woody plants, Ashe juniper in particular, on recharge in the Edwards Plateau is poorly understood, partly because it is difficult to make direct measurements of recharge. In this study, we determine recharge characteristics for two caves within Camp Bullis and evaluate if recharge changes after removing the overlying juniper. In addition to evaluating recharge characteristics under natural rainfall conditions we conducted extensive rainfall simulation and irrigation experiments over the cave surfaces. In addition to recharge, measurements of surface runoff, interception and stem flow were made. Natural recharge and rainfall patterns were monitored from 2004-2009. One key finding of this study was that

recharge was highly episodic and only occurred for relatively large rainfall events. Significant recharge only occurred for rainfall events greater than 60 mm. During that five years that recharge was monitored, most of the recharge occurred during three relatively short wet periods. The other key finding was that there was no apparent change in the relationship between rainfall and recharge after three trees were removed. In other words, we saw no evidence that tree removal increased the amount of water recharging the caves. A limitation of this study is that the time period following cutting of the trees was relatively short (1-1.5 years) and not long enough to definitely rule out the possibility that reducing tree cover may lead to higher recharge.

Introduction

This report summarizes the findings of a 5-year (November 2004–December 2009) investigation of the water dynamics at two sites overlying shallow caves within the Camp Bullis facility in northern Bexar County, Texas. The results of the first phase of this study (November 2004–November 2007) were documented in the Phase I report (Wilcox 2008). In this Phase II report, we summarize the results from the entire study period, focusing on rainfall, cave recharge, and the rainfall simulation experiments conducted during Phase II.

The overall objective of the study was to determine whether and to what extent the spread of Ashe juniper has affected water recharge within the Edwards Aquifer Recharge zone. What makes this study unique is that we employed large-scale rainfall simulation as well as natural rainfall, and we monitored recharge in real time by measuring drip rates within caves. The more specific study objectives included

(1) to understand the relationship between cave recharge and natural precipitation (our recharge data include water that entered the cave through the ceiling during both natural and simulated rainfall events);

(2) to examine whether, and to what extent, removal of Ashe juniper affects the water budget at the hillslope scale.

Background

Shrublands occupy vast areas of the earth [*Scanlon et al.*, 2007]. Although restricted mainly to subhumid and drier climates, shrubs have significantly expanded their range and density over the past 150 years—a phenomenon known as *woody plant encroachment* [*Archer*, 1994; *Archer et al.*, 2001; *Asner et al.*, 2003]. The hydrological implications of this land-cover change are complex and certainly not well understood [*Huxman et al.*, 2005; *Newman et al.*, 2006; *Wilcox and Thurow*, 2006].

Understanding the effects of vegetation on the water cycle is especially difficult in karst environments, because of the challenges of monitoring water dynamics. The hydrology of these environments is inherently complex [*Wilcox et al.*, 2006], water movement is highly preferential, and storage is spatially variable. In addition, the soils are typically rocky and shallow and the underlying parent material is indurated, with occasional fractures or solutional features enabling quick flow [*Dasgupta et al.*, 2006]. The use of traditional monitoring approaches—such as time-domain reflectometry or neutron activation—is difficult if not impossible under these conditions, explaining why water-balance studies of karst shrublands rarely include direct measurements of storage within, and movement of water through, the vadose zone [*Wilcox et al.*, 2005]. For example, recharge is seldom measured directly but is instead estimated. In the case of the Edwards Aquifer, a karst aquifer and the major source of water for a large area within Central Texas, recharge is estimated primarily by gauging streams (to determine water loss over the Edwards recharge zone) combined with other estimates of recharge in the interfluvial areas [*Maclay*, 1995]. A second method of estimation is the water-budget method, whereby recharge is considered to be all the water not accounted for by evapotranspiration or surface runoff. Interestingly, the estimates of regional recharge yielded by these two methods are very different [*Huang and Wilcox*, 2006].

Recently, insights into the nature and dynamics of recharge in karst environments have been gained from cave drip studies [*Ayalon et al.*, 1998]. These studies have focused on the differences between drips fed by macropores (these drips, being preferential or fracture-fed, display a rapid response) and those fed by micropores (matrix or seepage-fed drips, which show a much slower response). Whereas much of the early cave hydrology work was based on infrequent, manual measurements of recharge, these recent studies have employed automated drip-monitoring devices to better capture the full spectrum of drip responses [*Baker and Brunsdon*, 2003]. This technique, obviously, can be used only in certain areas, but it does offer an additional source of information concerning the dynamics of recharge.

Karst shrublands are found mostly in semiarid-climate regions, where the relative infrequency of runoff- and recharge-producing rain events imposes an additional constraint on monitoring efforts: it may take years for enough such events to occur. One technique for solving this problem is rainfall simulation (commonly employed in studies of vegetation and water interactions in semiarid landscapes). Typically, the application area for simulated rainfall is about 1 m^2 or less [*Thurow et al.*, 1988; *Wilcox et al.*, 2007], although larger-scale experiments have been conducted [*Simanton et al.*, 1991]. Application of water above the shrub canopy has been employed in only a few hillslope-scale rainfall-simulation experiments [*Wilcox et al.*, 2008].

Study Area

The study area is located within the Edwards Plateau region in Central Texas. At around 100,000 km^2, this region is one of the largest contiguous areas of karst in the United States. In spite of the relatively dry climate, it boasts abundant groundwater, springs, and perennially flowing rivers—but as human population pressures increase, water is becoming more limited [*Sharp and Banner*, 1997]. The climate is semiarid to subhumid and exhibits a strong precipitation gradient, with averages ranging from 850 mm/year in the east to 400 mm/year in the west. Bordered on the south and east by the Balcones Escarpment, the Edwards Plateau region encompasses two major landforms: the Balcones Canyonlands, often referred to as the Texas Hill Country, and the Edwards Plateau proper (Figure 1). Both of these landforms are underlain by Cretaceous limestones and dolomites [*Wilcox et al.*, 2007].

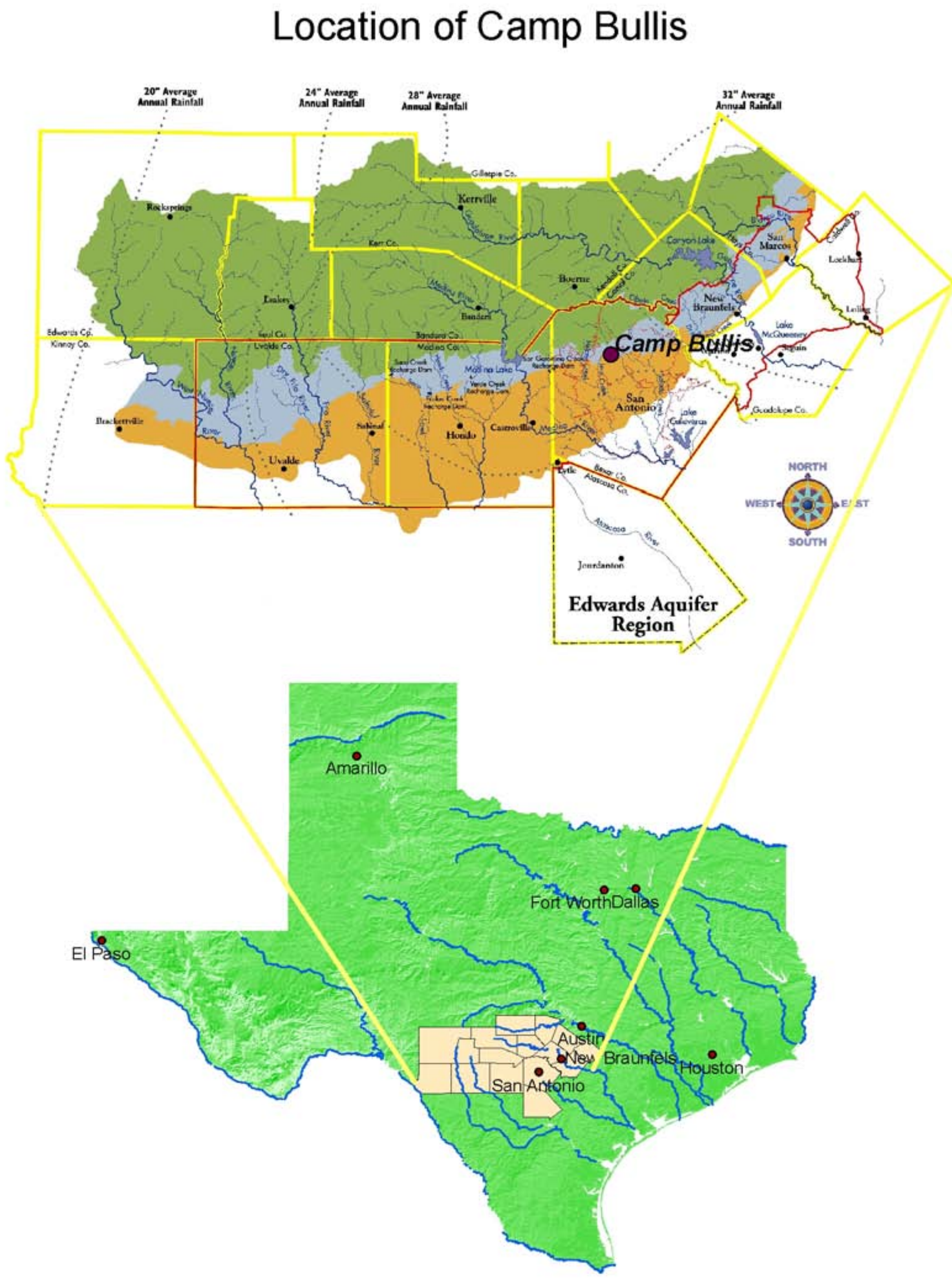


Figure 1. The study area, located within the Camp Bullis Military Reservation near San Antonio.

The study area is within the Camp Bullis military reservation (29º37’47.34”N, 98º32’48.91”W), in the southeastern portion of the Edwards Plateau and approximately 16 km north of downtown San Antonio (Figure 1). As part of its ongoing efforts to protect and manage endangered species, Camp Bullis has played an active role in locating, describing, and protecting caves within the boundaries of the reservation [*Veni*, 1988].

Long-term precipitation in the San Antonio area averages about 738 mm/year, varying from 257 to 1328 mm in individual years. Average annual rainfall for the San Antonio area from 1970 to 2000 was 836 mm, somewhat higher than the long-term average.

The first cave site, Bunny Hole, is a shallow cave located within the recharge zone of the Edwards Aquifer (Figure 2). According to the description by Veni (1988), it is a rare phreatic conduit system that pre-dates the origin of the modern Edwards Aquifer. The cave consists of a maze of passages that extend 198 m in length and reach a maximum depth of 5 m below the entrance. Passages average 1.5 m in width and are typically less than 1 m in height. Impassable holes and fissures extend down into the cave floor, as much as 2.5 m in some areas, and probably open into an inaccessible lower level. Three parallel crawlways run northeast to southwest over a linear distance of 46 m. Bunny Hole is oriented parallel to major Balcones faulting, and evidence suggests that it was formed under low-velocity groundwater flow. Joint planes exhibit little dissolution, possibly because of low hydrostatic pressure during phreatic development followed by speleothem development and case hardening of the walls and ceiling that hide the fractures. The floors of some passages were incised by water as it flowed down to the water table during vadose conditions. Dry, light-brown silt and gray-black organic sediment cover much of the cave floor (Veni, 1988). There are areas of collapse within Bunny Hole, many of them along solution bedding planes; three of these collapses extend to the surface. There are also three solutionally formed sinkholes that breach the surface of the cave; one of these is the cave entrance and the other two are small, impassable sinkholes.

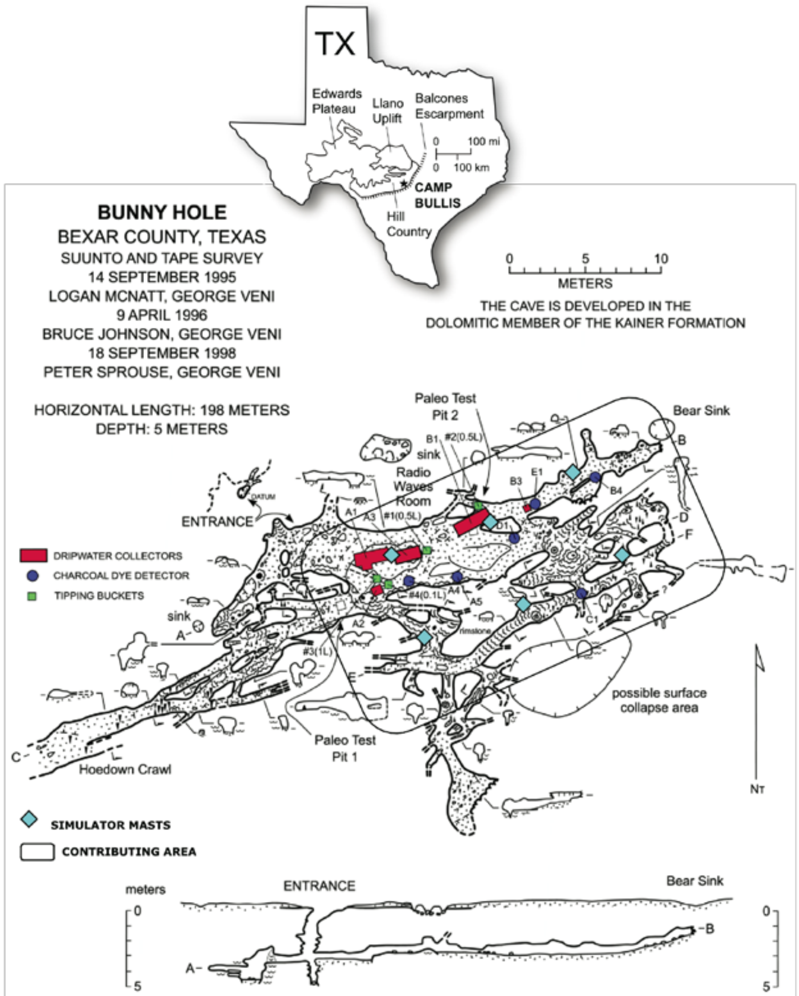


Figure 2. Planar and side views of Bunny Hole Cave. The locations of the dripwater collectors and the tipping buckets used to record drip rates are shown. The area estimated to contribute recharge to the cave is outlined as well.

The second cave, Headquarters Cave, is larger and deeper than Bunny Hole (Figure 3). It is 54 m long and consists of two large rooms with a ceiling about 5 m above the floor. The deepest part of the cave is about 12 m below the surface. Like Bunny Hole, this cave was probably formed under relatively low-velocity phreatic conditions that pre-date the modern Edwards Aquifer. The ceiling has collapsed in the center, leaving a large pile of rubble in the middle of the cave.

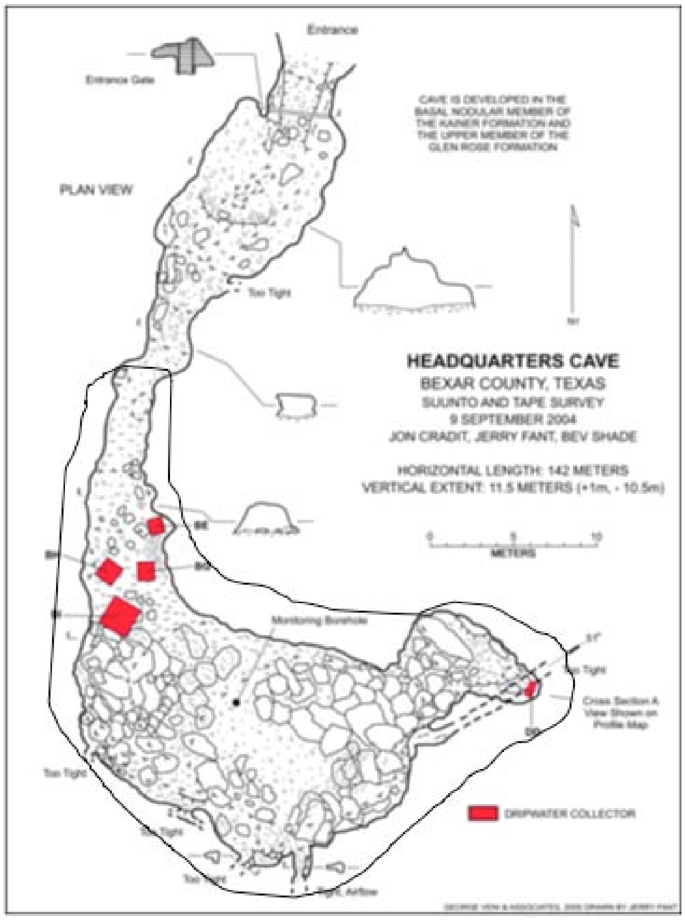


Figure 3. Planar view of Headquarters Cave. The locations of the dripwater collectors and the tipping buckets used to record drip rates are shown. The area outlined is the area irrigated by soaker hoses. Also shown is the borehole used to connect instrumentation in the cave with dataloggers on the surface.

At both these research sites, the woody vegetation is predominantly Ashe juniper (Juniperus ashei) and plateau live oak (Quercus fusiformis.). Canopy coverage by these species is almost complete, leaving only small, scattered openings over the cave footprints. understories are extremely sparse and consist of sprinkles of agarita (Berberis trifoliolata) and netleaf hackberry (Celtis reticulata), with some spotty herbaceous and grass cover. Rocky outcroppings, bare soil, and organic matter make up a significant portion of the ground surface.

Methods

Each research site is equipped with an automatic rain gauge from Texas Electronic. These devices were located in open areas and were equipped with a small tipping bucket that records data in 0.01-inch increments. Data were sent to a CR10X datalogger (Campbell Scientific, Logan, Utah) and recorded at 15-minute intervals.

Cave Recharge

As mentioned above, cave recharge was defined as water entering the cave through fractures or cracks in the cave ceiling, whether from natural or simulated rainfall.

Establishing Recharge Locations

The first task was to establish locations within each cave where drip collectors could be installed for measuring recharge. We used soaker hoses to irrigate the surface over the caves (with this method, no water is lost to spray or to interception by woody plants). In addition to locating the surface areas most sensitive to water infiltration, these irrigation tests helped us decide where to locate the rainfall simulator.

The soaker hose apparatus consists of three 51-mm polyvinyl chloride (PVC) pipes, each fitted with ten 19-mm hose bib connectors to accommodate ten soaker hoses. Each 19-mm hose can be placed where desired and can be turned on or off independently. This system is capable of a flow rate of 295 L per minute. Variable amounts of water can be applied to an area, depending on the number of hoses used and their spacing, the size of the area, and the rate of flow (Figure 4).

Figure 4: A below-canopy soaker hose test at Bunny Hole.

At Bunny Hole, on March 31, 2004, 15,900 L of water was applied over the eastern two-thirds of the cave at a rate of about 62 mm/hr. The test lasted 91 minutes and covered approximately 170 m2. Drips began inside the cave less than ten minutes after the start of irrigation. A second application took place at Bunny Hole on July 21 and 22, 2004, consisting of a six-part test to identify the specific areas where water was entering the cave. Grids 1 and 2 were laid out at 70° (ENE) on the southeastern side of the cave, and grids 3, 4, 5, and 6 were laid out at 342° (WNW), northeast of grids 1 and 2 (Figure 2). Each grid was approximately 7 m wide by 14 m long and demarcated the area to be saturated, directly underneath one of six hoses. Irrigation of grids 1 through 4, during which a total of 15,194.6 L of water was applied directly to the surface, produced only 46 L of recharge water in the cave —all of it in the region below grid 4 (recharge began to enter the cave approximately 30 minutes after the start of application to grid 4, whereas no water was recorded inside the cave from the applications to grids 1, 2, or 3). Irrigation of grids 5 and 6, during which 6,798.6 L of water was applied to the surface, produced 203.5 L of recharge.

These tests showed that those areas above the cave footprint (grids 4, 5, and 6) are more sensitive to recharge than the other locations tested. In other words, in the absence of surface runoff, only the area immediately overlying the cave (“cave footprint”) contributed to recharge. The dimensions of this *contributing area* were estimated to be about 22 m x 16.5 m (Figure 2).

At Headquarters Cave, the initial irrigation covered the southern two-thirds of the cave (Figure 3). Some 20,800 L of water (equivalent to 69 mm of rainfall) was applied, for 109 minutes, to an area measuring about 200 m^2. Recharge was first observed after approximately 90 minutes of water application.

Collecting Recharge

In addition to the irrigation test data, we evaluated various locations inside each cave to select the ones most suitable for installation of the drip collectors for monitoring simulated and natural rainfall events.

The drip collectors were especially designed for this study (Figure 5). Each was built inside the cave for its specific location and was constructed of 19-mm PVC pipe attached to a funnel formed by polyethylene sheeting stretched over a frame. The PVC pipe directs water into a steel tipping bucket having a stainless steel pivot. (Stainless steel is used to prevent rusting in the high-humidity cave environment.).

Figure 5. Drip collector and tipping bucket used for measuring cave recharge..

Bunny Hole contains four independent drip collectors, each with its own tipping bucket. We estimate that these collectors were capturing about 60% of the total vertical drips. (This estimate is based on a set of manual measurements made during the initial soaker-hose experiments; we determined flow rates by recording the time required to fill a container of a known size during a simulated rainfall event with varying intensities, then compared these rates with the recorded data from the drip collectors.) Headquarters Cave was instrumented in a similar fashion, with six drip collectors that route water to three tipping buckets. Except for their size and configuration, these collectors are identical to those in Bunny Hole, and their locations (Figure 3) were chosen in the same way. In addition, wire screening was placed over the top of each collector to keep cave biota from drowning and/or potentially damaging the collector.

Most of the dripping water at Headquarters Cave was captured by the collection system.

At both locations, data were stored in a datalogger located on the surface and connected to the equipment by wiring routed through a borehole. Solar panels powered the datalogger's 12V batteries. Natural-recharge data were recorded at 15-minute intervals, and simulated-recharge data were recorded at 5-minute intervals. All monitoring equipment inside the caves received monthly maintenance by Zara Environmental. Zara replaced the original dataloggers at Headquarters Cave in the summer of 2008, and those at Bunny Hole in the fall of 2008.

Rainfall Simulation Experiments

The rainfall simulator used for this study is described by Munster et al. [2006]. This device, equipped with six telescoping masts, was designed to simulate rainfall at the hillslope scale and has the capability to apply water above tree canopies. Each mast has a maximum extension of 11 m and is topped with a manifold that feeds four sprinkler heads. The median raindrop size varies slightly with application rate but is around 2 mm [*Munster et al.*, 2006]. A flow meter was used to determine the volume of water pumped to the sprinkler heads and thence distributed over the application area (Figure 2).

During these experiments we collected data on throughfall, stemflow, surface runoff, and cave recharge. Throughfall was monitored by 87 plastic rain gauges evenly spaced within the area overlying the cave. Surface runoff was routed through a gutter at the downslope end of the contributing area and then through a 15.24-cm H-flume equipped with a WL700-001 Ultrasonic Water Level Sensor (Global Water, Gold River, CA). The area wetted during these simulations (*wetted area)* was consistently estimated at around 26 m x 20 m.

For each rainfall simulation the following variables were measured: volume of water applied (P), cave recharge (R), surface runoff (Q), and stemflow (S). In addition, throughfall (T) was measured directly, as the average of the amounts collected by the 87 manual rain gauges. Volumes of water applied (P) and stemflow (S) were converted to a depth by dividing these volumes by the wetted area. In the same way, cave recharge and surface runoff were converted to a depth by dividing the volume of each component by the area contributing to cave recharge (22 x 16.5 m). A fifth component of the water budget, canopy interception (I), was estimated as

$$I = P - (T + S)$$

Removal of Ashe Juniper

Ashe juniper was removed by hand at both sites. At Bunny Hole, trees were removed in March 2008, while at Headquarters Cave trees were removed in October of 2008.

Results

Rainfall Simulation Experiments

Rainfall simulation experiments were conducted at Bunny Hole Cave but not at Headquarters Cave. In all, 15 sets of rainfall simulation experiments were carried out at the Bunny Hole site during 2004, 2005, 2008, and 2009—six before juniper removal and nine afterwards. The results of the first six simulations were included in the Phase I report, but are summarized here to facilitate comparison.

Most of the simulations consisted of three sets of runs with each set separated by about 30 minutes: a 1-hour run at a rate of about 21 mm/hr; a 2-hour run at a rate of 6 mm/hr; and a 45-minute run at a rate of 28 mm/hr. About 50 mm of water was applied during a 4-hour period.

Cutting and removal of the Ashe juniper changed the surface over Bunny Hole Cave in a fundamental way: the almost complete canopy that had covered the cave was reduced to about 10 small-to-moderate size oak trees. We estimate that the total remaining canopy cover was around 30%.

A major question, then, is—to what extent did removal of the junipers change the allocation of the water applied during the simulation events? Table 2 gives a detailed summary of the rainfall simulation results. The major components of interest are interception, surface runoff, and cave recharge.

Table 2. A summary of rainfall simulation experiments

Pre-Treatment data for Standard Simulations

Date	July 13, 2005				July 14, 2005			
	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	21.1	5.8	27.5		21.5	5.7	27.3	
Quantity (mm)								
Total Rainfall	21.1	11.6	22.0	**54.7**	21.5	11.4	21.8	**54.7**
Stemflow	0.9	0.1	1.1	**2.1**	0.9	0.1	1.4	**2.4**
Throughfall	16.3	6.6	17.3	**40.2**	18.9	6.8	18.3	**44.0**
Loss	3.9	4.9	3.6	**12.4**	1.7	4.5	2.1	**8.3**
Surface Runoff	0.0	0.0	1.6	**1.6**	0.1	0.0	1.7	**1.8**
Cave Recharge	0.2	0.8	3.2	**4.2**	2.5	1.4	5.2	**9.1**
Water Balance as a % of Rainfall								
Loss	18.5%	42.2%	16.4%	**22.7%**	7.9%	39.5%	9.6%	**15.2%**
Surface Runoff	0.0%	0.0%	7.3%	**2.9%**	0.5%	0.0%	7.8%	**3.3%**
Cave Recharge	0.9%	6.9%	14.5%	**7.7%**	11.6%	12.3%	23.9%	**16.6%**
Unaccounted for	80.6%	50.9%	61.8%	**66.7%**	80.0%	48.2%	58.7%	**64.9%**

Date	July 28, 2005			
	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	21.6	4.4	24.1	
Quantity (mm)				
Total Rainfall	21.6	8.8	19.3	**49.7**
Stemflow	1.7	0.5	2.0	**4.2**
Throughfall	19.0	8.5	17.2	**44.7**
Loss	0.9	-0.2	0.1	**0.8**
Surface Runoff	0.0	0.0	1.8	**1.8**
Cave Recharge	0.8	1.7	3.9	**6.4**
Water Balance as a % of Rainfall				
Loss	4.2%	-2.3%	0.5%	**1.6%**
Surface Runoff	0.0%	0.0%	9.3%	**3.6%**
Cave Recharge	3.7%	19.3%	20.2%	**12.9%**
Unaccounted for	92.1%	83.0%	69.9%	**81.9%**

Table 2. cont

Post-Treatment data for Standard Simulations 2008

Date	June 12, 2008				July 10, 2008			
	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	20.7	5.8	26.3		21.1	5.8	26.3	
Quantity (mm)								
Total Rainfall	20.7	11.5	21.1	**53.3**	21.1	11.7	21.0	**53.8**
Throughfall	17.8	9.0	19.9	**46.6**	22.0	10.1	20.9	**53.0**
Loss	2.9	2.5	1.2	**6.6**	-0.9	1.6	0.1	**0.8**
Surface Runoff	0.0	0.0	0.0	**0.0**	0.3	0.2	1.9	**2.3**
Cave Recharge	0.1	0.2	1.2	**1.6**	1.1	1.2	2.7	**5.0**
Water Budget as a % of Rainfall								
Loss	14.0%	22.1%	5.7%	**12.5%**	-4.3%	13.6%	0.7%	**1.6%**
Surface Runoff	0.0%	0.0%	0.0%	**0.0%**	1.2%	1.3%	9.0%	**4.3%**
Cave Recharge	0.5%	1.9%	5.9%	**3.0%**	5.4%	10.1%	12.9%	**9.4%**
Unaccounted for	85.5%	76.0%	88.4%	**84.6%**	97.6%	74.9%	77.4%	**84.8%**

Date	June 18, 2008				June 19, 2008			
	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	21.6	5.9	26.0		21.4	5.8	25.7	
Quantity (mm)								
Total Rainfall	21.6	11.7	20.8	**54.1**	21.4	11.6	20.5	**53.5**
Throughfall	22.1	10.1	20.7	**52.9**	23.2	6.4	19.1	**48.7**
Loss	-0.5	1.6	0.1	**1.2**	-1.8	5.2	1.4	**4.8**
Surface Runoff	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**
Cave Recharge	0.7	0.9	2.3	**3.8**	2.0	1.1	3.3	**6.4**
Water Budget as a % of Rainfall								
Loss	-2.5%	13.8%	0.6%	**2.2%**	-8.6%	44.9%	7.1%	**9.0%**
Surface Runoff	0.0%	0.0%	0.0%	**0.0%**	0.0%	0.0%	0.0%	**0.0%**
Cave Recharge	3.1%	7.8%	10.9%	**7.1%**	9.3%	9.6%	16.2%	**12.0%**
Unaccounted for	99.4%	78.4%	88.5%	**90.7%**	99.3%	45.6%	76.8%	**79.0%**

Table 2. cont.

Date	July 29, 2008				July 30, 2008				July 31, 2008			
	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	21.6	5.9	26.4		21.5	5.8	26.5		21.7	5.9	26.1	
Quantity (mm)												
Total Rainfall	21.6	11.7	21.1	**54.4**	21.5	11.7	21.2	**54.4**	21.7	11.9	20.9	**54.5**
Throughfall	21.3	10.0	20.9	**52.2**	22.4	11.6	22.1	**56.1**	24.0	11.9	21.3	**57.2**
Loss	0.3	1.7	0.2	**2.2**	-0.9	0.1	-0.9	**-1.7**	-2.3	0.0	-0.4	**-2.7**
Surface Runoff	0.0	0.0	1.7	**1.7**	1.1	0.3	3.6	**5.1**	1.2	0.4	3.9	**5.6**
Cave Recharge	0.3	0.8	2.7	**3.8**	2.1	1.5	4.2	**7.8**	2.3	1.6	3.7	**7.6**
Water Budget as a % of Rainfall												
Loss	1.2%	14.7%	1.1%	**4.0%**	-4.4%	0.5%	-4.1%	**-3.2%**	-10.8%	0.0%	-1.8%	**-5.0%**
Surface Runoff	0.0%	0.1%	7.9%	**3.1%**	5.2%	3.0%	17.1%	**9.4%**	5.7%	3.6%	18.6%	**10.2%**
Cave Recharge	1.5%	7.0%	12.7%	**7.0%**	9.5%	13.0%	20.0%	**14.4%**	10.7%	13.3%	17.5%	**13.9%**
Unaccounted for	97.3%	78.2%	78.4%	**85.8%**	89.6%	83.5%	67.0%	**79.5%**	94.4%	83.2%	65.7%	**80.9%**

Table 2. continued

Post-Treatment data for Standard Simulations 2009

Date	June 3,2009				June 4,2009			
	Run 1	Run 2	Run 3	**Total**	Run 1	Run 2	Run 3	**Total**
Duration (hr)	1.0	2.0	0.8	**3.8**	1.0	2.0	0.8	**3.8**
Rainfall rate (mm/hr)	21.4	5.7	25.6		21.7	7.5	25.3	
Quantity (mm)								
Total Rainfall	21.4	11.5	20.5	**53.3**	21.7	15.1	20.3	**57.1**
Throughfall	23.3	12.6	21.9	**57.8**	21.3	9.5	18.3	**49.1**
Loss	-1.9	-1.1	-1.4	**-4.5**	0.4	5.6	2.0	**8.0**
Surface Runoff	0.0	0.0	1.6	**1.6**	0.8	0.1	2.5	**3.3**
Cave Recharge	0.5	0.9	2.7	**4.1**	2.0	1.7	4.8	**8.5**
Water Budget as a % of Rainfall								
Loss	-9.0%	-9.6%	-7.0%	**-8.4%**	2.1%	36.9%	9.7%	**13.9%**
Surface Runoff	0.0%	0.0%	8.0%	**3.1%**	3.7%	0.5%	12.2%	**5.9%**
Cave Recharge	2.5%	7.5%	13.2%	**7.7%**	9.3%	11.1%	23.5%	**14.8%**
Unaccounted for	106.5%	102.1%	85.8%	**97.6%**	85.0%	51.5%	54.6%	**65.4%**

Interception: We can estimate roughly how much of the water applied during rainfall simulation is lost through interception by the tree canopy. Although we know the exact volume of water applied, we do not know the exact wetted area. We were careful to carry out simulations on days when the wind was light, but even so some wind drift is inevitable. We estimated that the wetted area was about 20 m x 26 m. This size estimate, along with the volume of water applied, allows us to calculate the average depth of the water applied. Then, with the detailed measurements of throughfall (the amount of water landing on the surface) made by the network of manual rain gauges, interception by trees (and/or drift loss via wind) is derived as the difference between the amount of water applied and the amount of throughfall.

As would be expected, water loss (interception + drift) was higher for the period before juniper removal than after. For the pre-removal period, we found that under dry conditions about 20% of the water applied was lost; this percentage decreased as conditions became wetter. For example, during the second standard simulation (July 14, 2005), which took place 24 hours after the first standard simulation, interception made up only 14% of the total water applied. Conditions were the wettest and coolest during the third standard simulation (July 28, 2005). Over the preceding two weeks, about 50 mm of natural rainfall had occurred, 11 mm of which fell in the 5 hours just before the start of the simulation. Equally important, it was cloudy during the simulation, which most certainly reduced evaporation. As a result, virtually no interception was measured during the third simulation.

For the post-removal period, the loss factor was smaller, ranging from 12% to –8%. This loss could still be attributed partially to interception (by the oak trees remaining on the site, which covered about 20% of the area over the cave) and the remainder to wind drift. For some simulations, the amount of water in the throughfall collectors was greater than the amount of water applied. This suggests that the application area during those simulations was slightly smaller than estimated.

Stemflow: We measured stemflow only during the period before juniper removal. It accounted for between 4% and 8% of the water reaching the ground surface and was highest under the wettest conditions.

Cave Recharge: On average, the cave recharge measured accounted for between 7% and 17% of the water applied. For some individual runs, recharge was as high as 24%, and—as would be expected—increased as conditions became wetter. There were no obvious differences between the pre- and post-juniper removal periods. As highlighted in Figure 10, the most obvious difference in recharge could be attributed to antecedent soil moisture conditions: under wet conditions, recharge was the highest. Four sets of standard simulations were done back-to-back, i.e., rainfall was applied on sequential days (July 13 and 14, 2005; June 18 and 19, 2008; July 29, 30, and 31, 2008; and June 3 and 4, 2009). Recharge was always the highest on the second day of simulations. On the one occasion when rainfall was simulated three days in a row, differences between day 2 and day 3 were not great (Figure 10).

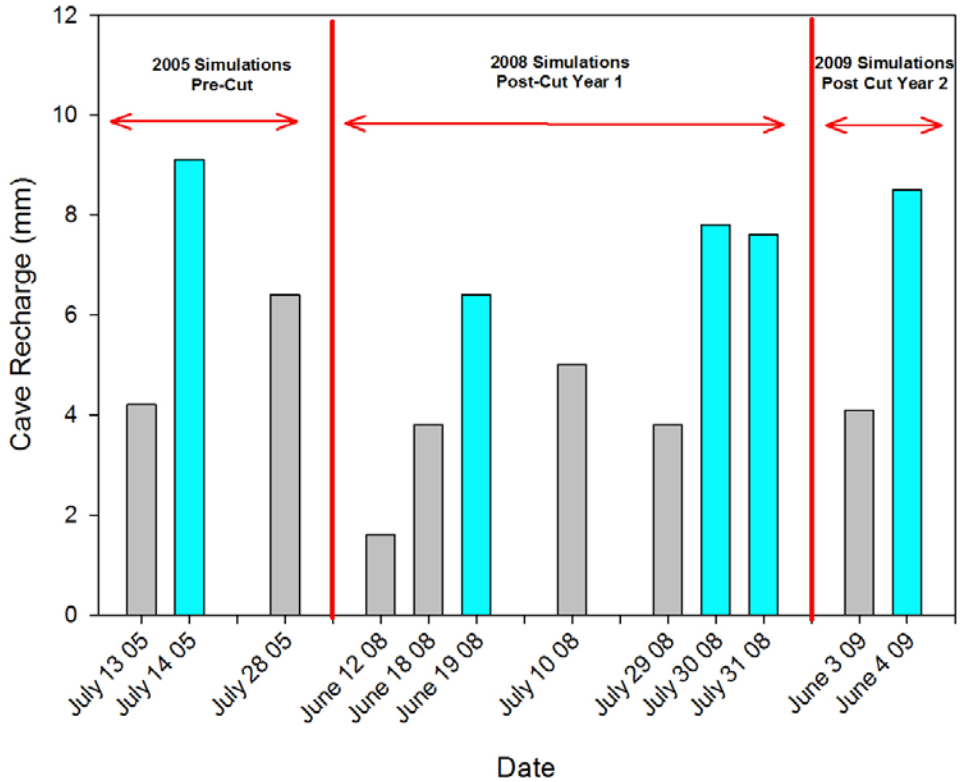


Figure 6. Total recharge for the standard rainfall simulations conducted over the course of the study.

Increases in recharge for wet antecedent conditions is evident from the event hydrographs, as is the ephemeral nature of cave recharge (Figure 11). Recharge began and ended within minutes of the rainfall simulations, demonstrating direct pathways from the ground surface to the cave some 3–5 meters below. There was a lag of 15–20 minutes between cessation of the rainfall event and peak cave recharge, taken as the integrated time needed for water to move from the surface to the cave ceiling.

Surface runoff: One rather surprising result was the changes in surface runoff that occurred following juniper removal. While remaining a relatively small component of the water budget, surface runoff more than doubled, from about 3% of the water budget pre-removal to up to 10% of the water budget post-removal (Figure 7). Surface runoff was highest during the third runs of the standard simulations, which were conducted at higher intensities than the other runs (and when conditions were already the wettest).

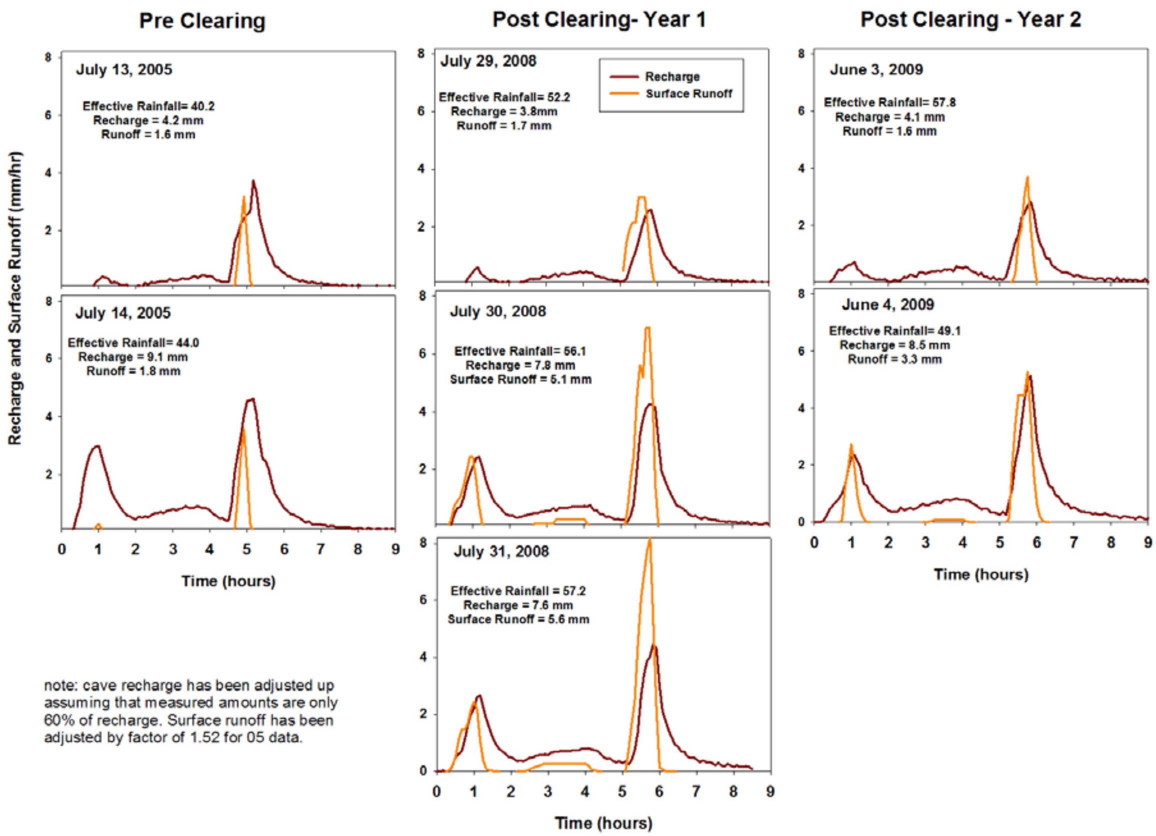


Figure 7. Hydrographs of runoff and recharge for three sets of standard simulations.

Naturally Occurring Rainfall and Recharge

RAINFALL

Rainfall was monitored at both cave locations: hourly at Bunny Hole and every 15 minutes at Headquarters Cave. In the case of data gaps due to equipment malfunction at one site, we used information from the other site to complete the record. The data from the two stations correspond quite closely, and the rainfall records from both correspond well with rainfall for San Antonio (Figure 6, Appendix I)—with the exception of the period March–August 2008. During this period, the Headquarters Cave site received much less rainfall than either Bunny Hole or the San Antonio area.

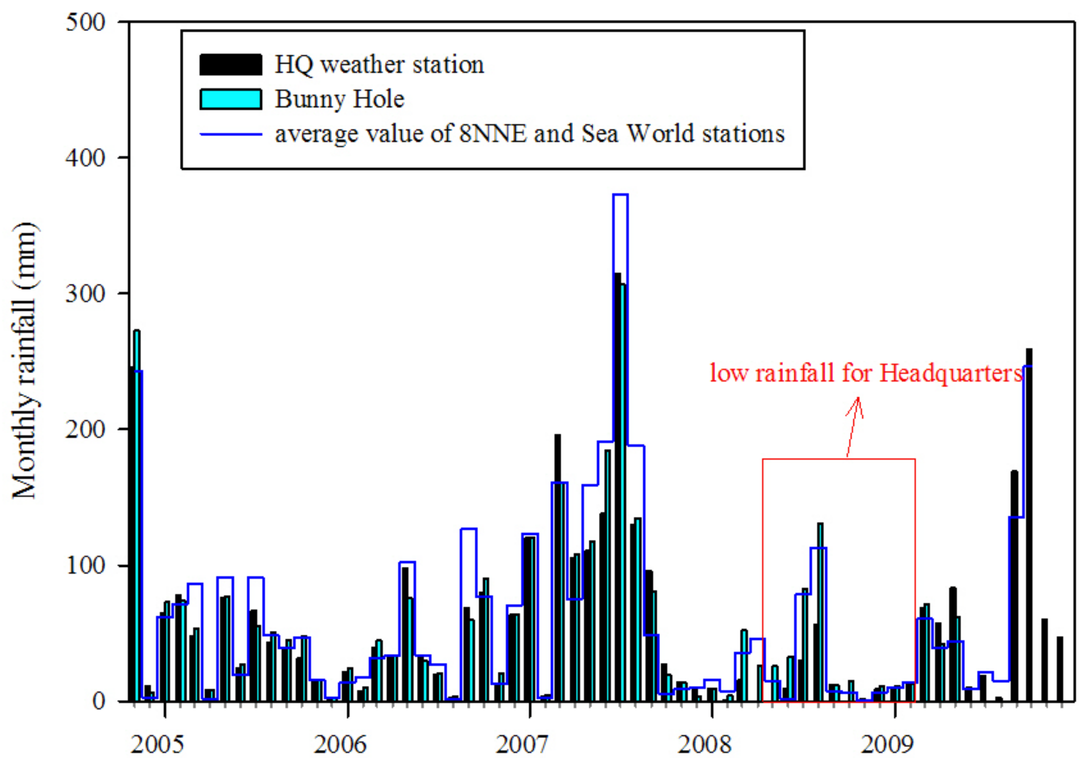


Figure 8. Monthly rainfall for the Headquarters Cave site and the Bunny Hole site compared to rainfall measured at two weather stations in San Antonio.

To examine the relationship between cave recharge and rainfall, we used a composite rainfall data set based on the Headquarters Cave site (where rainfall was recorded at more frequent intervals) supplemented with data from Bunny Hole (to fill gaps). We also used Bunny Hole rainfall data for the March–August 2008 period, because the Headquarters Cave data seemed anomalously low (Figure 8).

Compared with the 30-year average for San Antonio (1970–2000), average annual rainfall over the duration of the study was low: 684 mm, vs the 30-year average of 836 mm (Table 1). The lowest rainfall years were 2005, 2006, and 2008; the periods of least rainfall were April 2005–November 2006 and September 2008–September 2009. The wettest periods were November 2004, March–August 2007, and September–October 2009 (Table 1, Figure 9). The episodic nature of rainfall is highlighted in Figure 10, a plot of cumulative rainfall for the study period.

Table 2. Monthly and annual (composite) rainfall at Camp Bullis for the period of data collection. Values in red are below the 30-year average (1970–2000) for San Antonio.

Year	Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2004											245	11	
2005	65	78	48	8	76	24	67	43	39	32	15	2	496
2006	22	8	39	33	98	33	19	3	68	80	13	64	479
2007	121	3	196	105	111	138	314	130	96	27	14	10	1266
2008	9	1	52	26	22	33	83	131	12	0	1	9	379
2009	10	14	68	57	83	10	18	3	170	259	60	46	799
Average	45	21	81	46	78	48	100	62	77	80	58	24	684
30 Yr Avg.	42	44	48	66	120	109	52	65	76	98	66	50	836

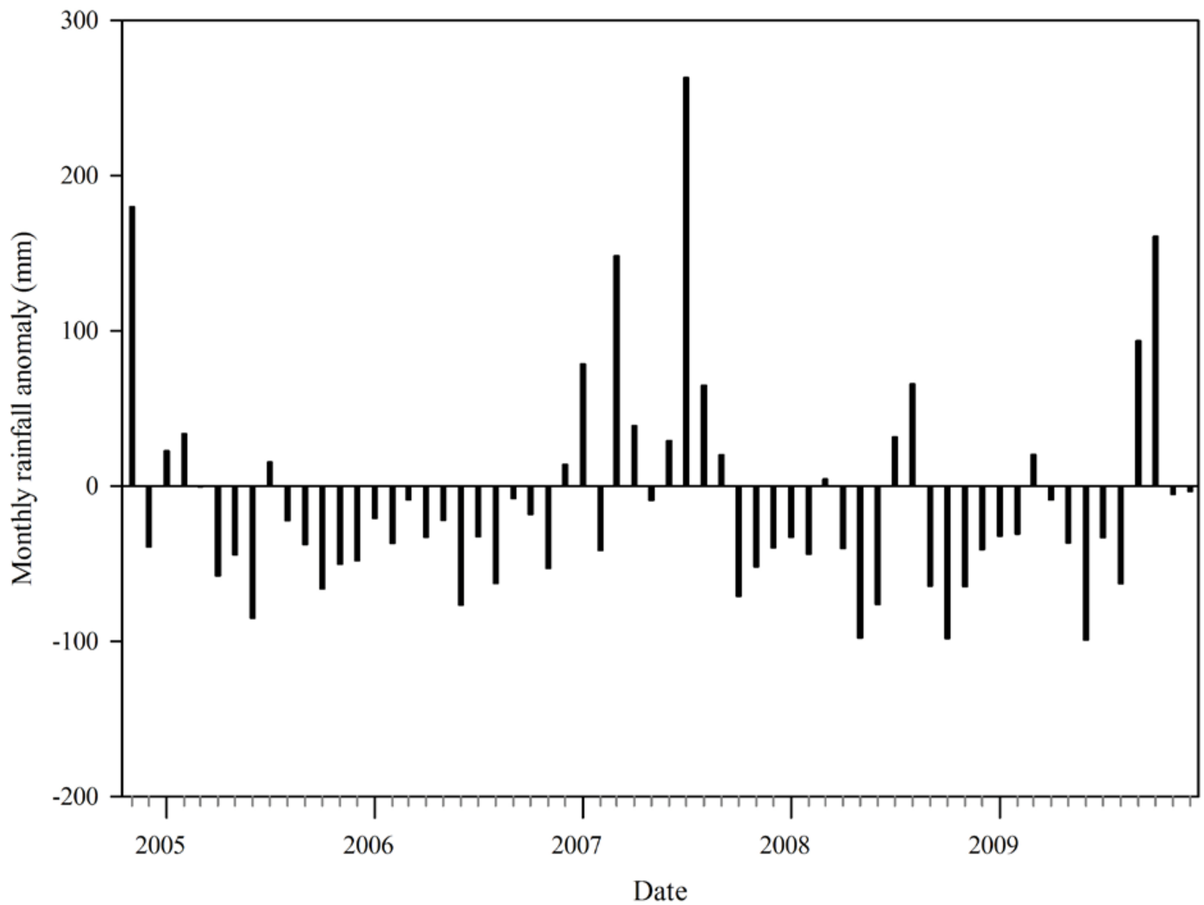


Figure 9. Monthly rainfall during the study period, expressed as a deviation from the monthly long-term average.

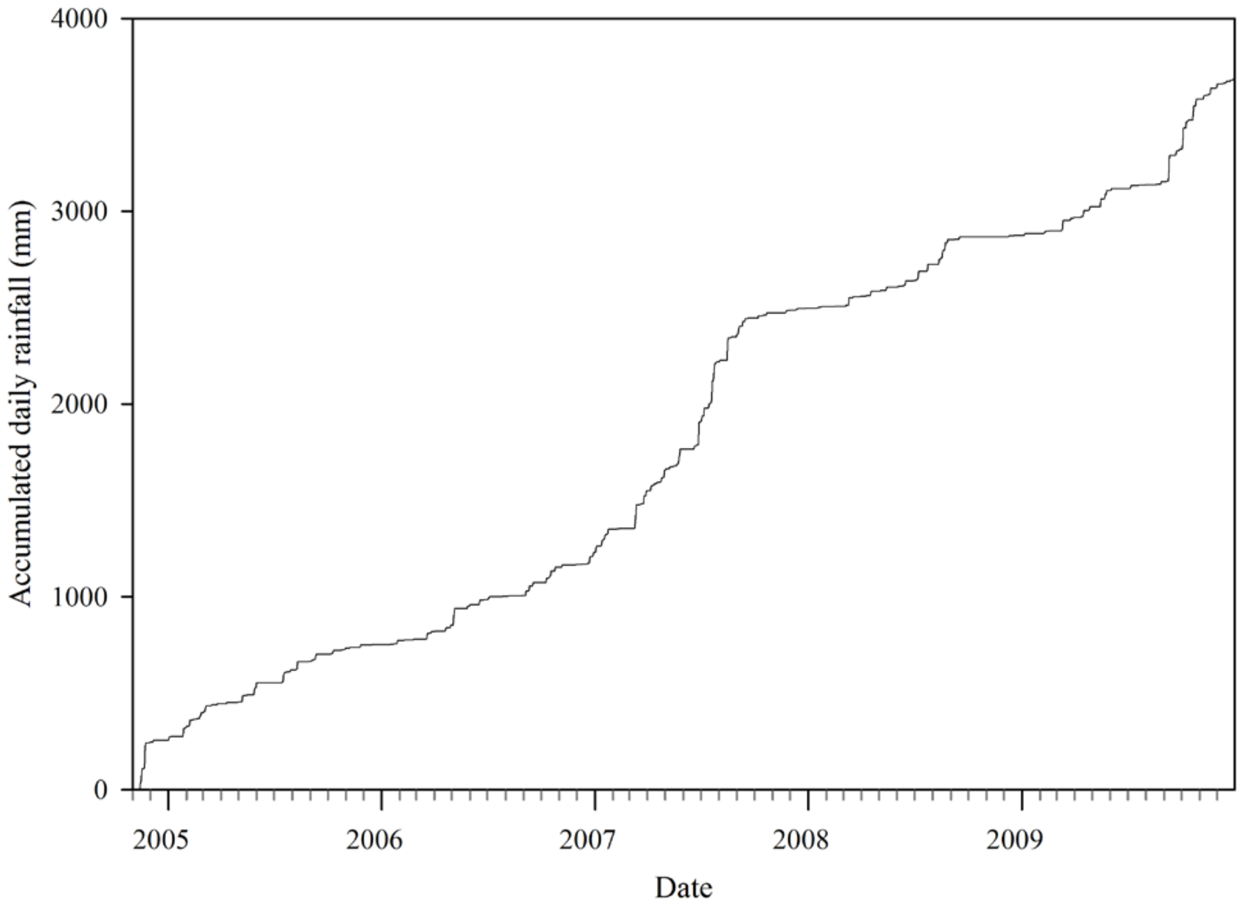


Figure 10. Cumulative monthly runoff for the study period.

One way to better understand how rainfall during the study period compared with historical rainfall is by examining the pattern of observed rainfall deviation from normal or average rainfall. Figure 11 plots the monthly deviation from San Antonio rainfall for 1988–2009. Several things are evident from this graph: Clearly, in this region the norm is extended dry periods punctuated by above- average rainfall. But it should be noted that the dry periods over the duration of the study were more extreme than at any time in the last 20 years.

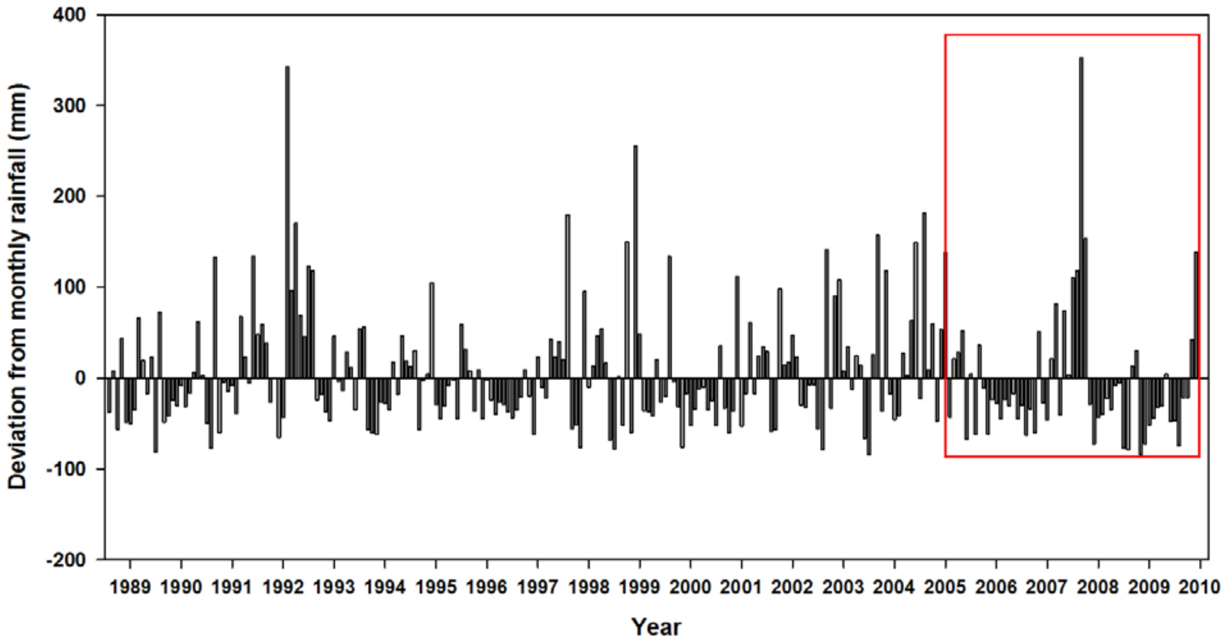
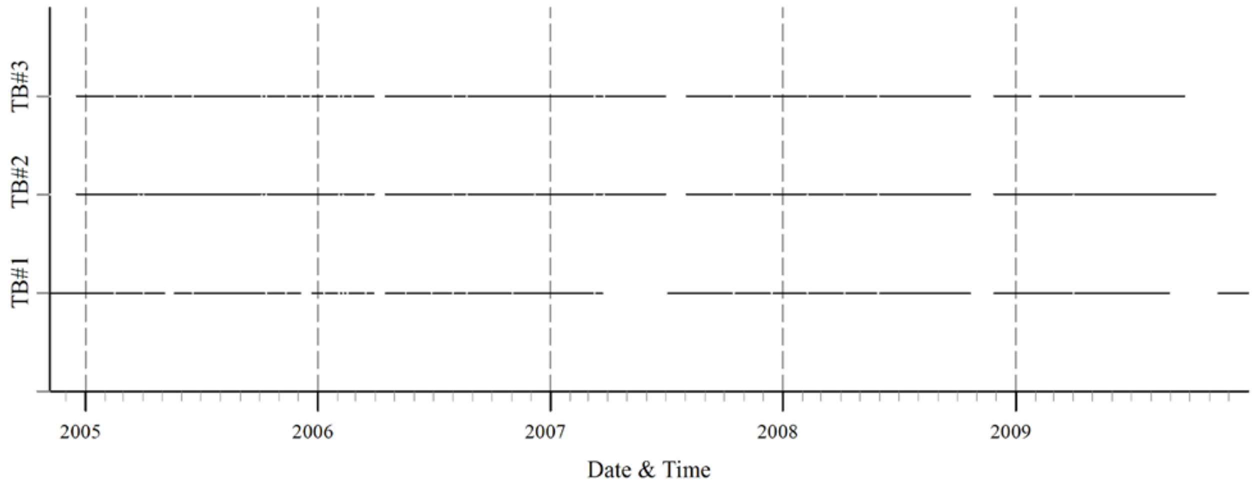


Figure 11. Monthly rainfall for the San Antonio area (1988–2009), expressed as a deviation from average monthly runoff. The area outlined in red represents the study period.

RECHARGE DURING THE PERIOD OF STUDY

Data gaps and how we dealt with them

One of the more challenging tasks we faced was keeping the tipping buckets functioning during the course of the study (the cave environment was a rather harsh one for complex instrumentation: in particular, the constant high humidity caused corrosion of electronic components, and from time to time cables were damaged by animals). Monitoring equipment was checked monthly, but even so there were some breakdowns that resulted in loss of data. A record of operational performance for each of the seven recharge-collection stations in the caves (three in Headquarters Cave and four in Bunny Hole) is shown in Figure 12.



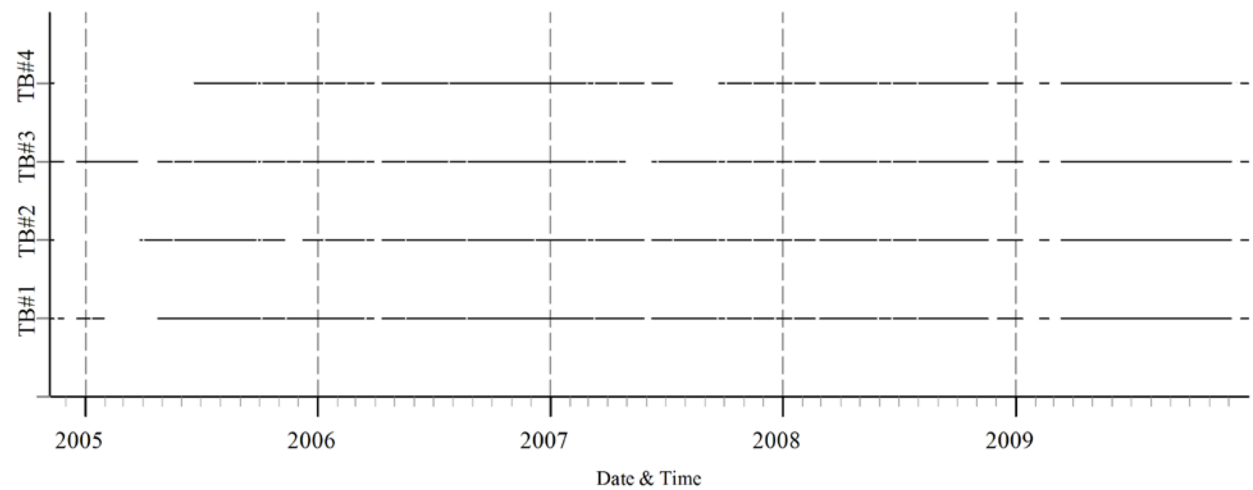


Figure 12. Period of operation for gages at Headquarters Cave (top graph) and Bunny Hole (bottom graph).

For any gaps in the data, we estimated recharge as follows:

1. If data for an event were available up to the peak flow stage, we filled in the missing portion of the hydrograph (recession limb) using data from existing similar hydrographs, since flow declines following rainfall have been found to be quite repeatable. Data for several events at Headquarters Cave were completed in this way.

2. Having found that the recharge collectors in each of the caves were highly correlated with one another (Figures 13 and 14), we made use of these relationships to estimate recharge amounts for collectors that malfunctioned during an event.

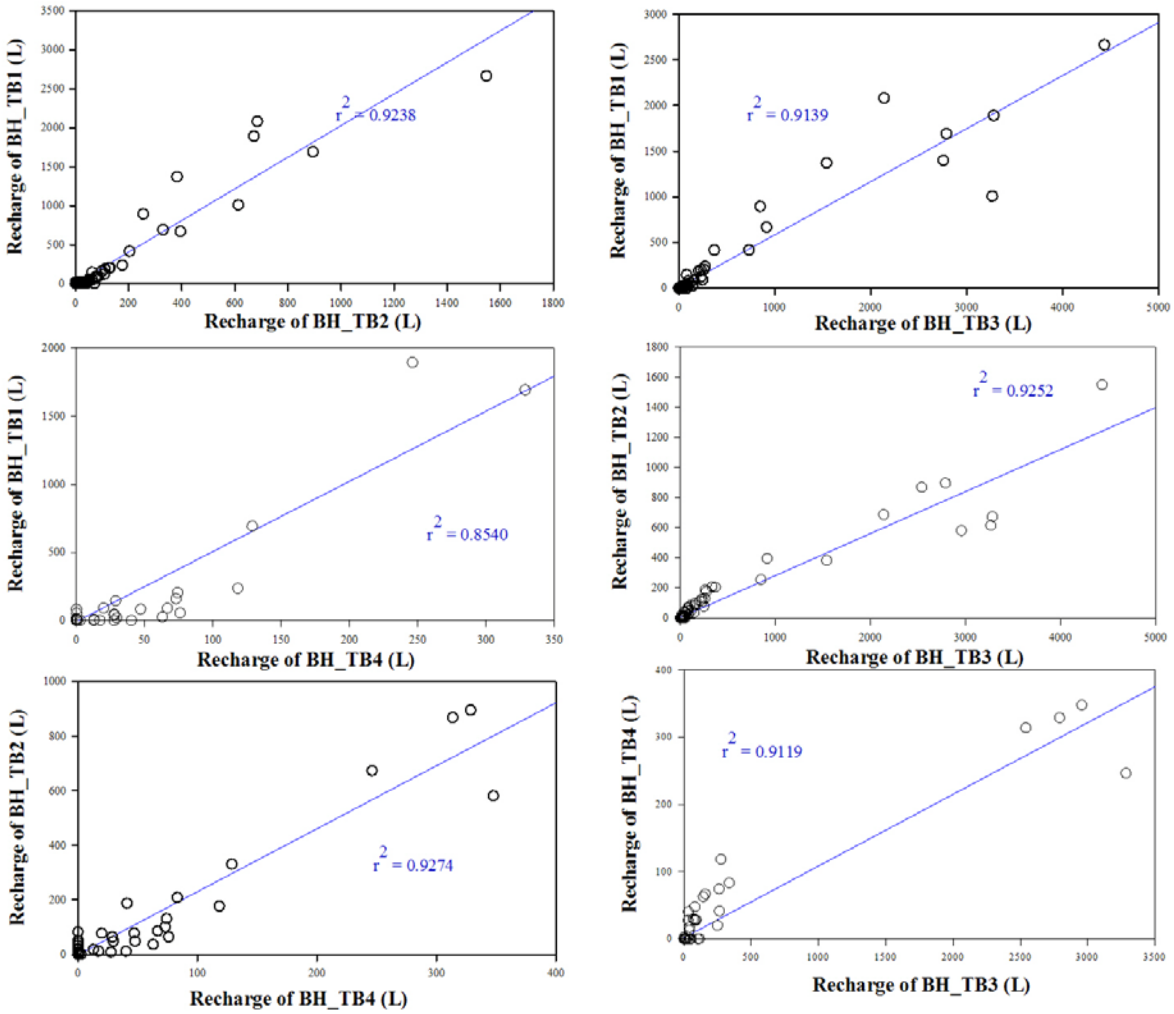


Figure 13. Correlation between the Bunny Hole recharge collectors.

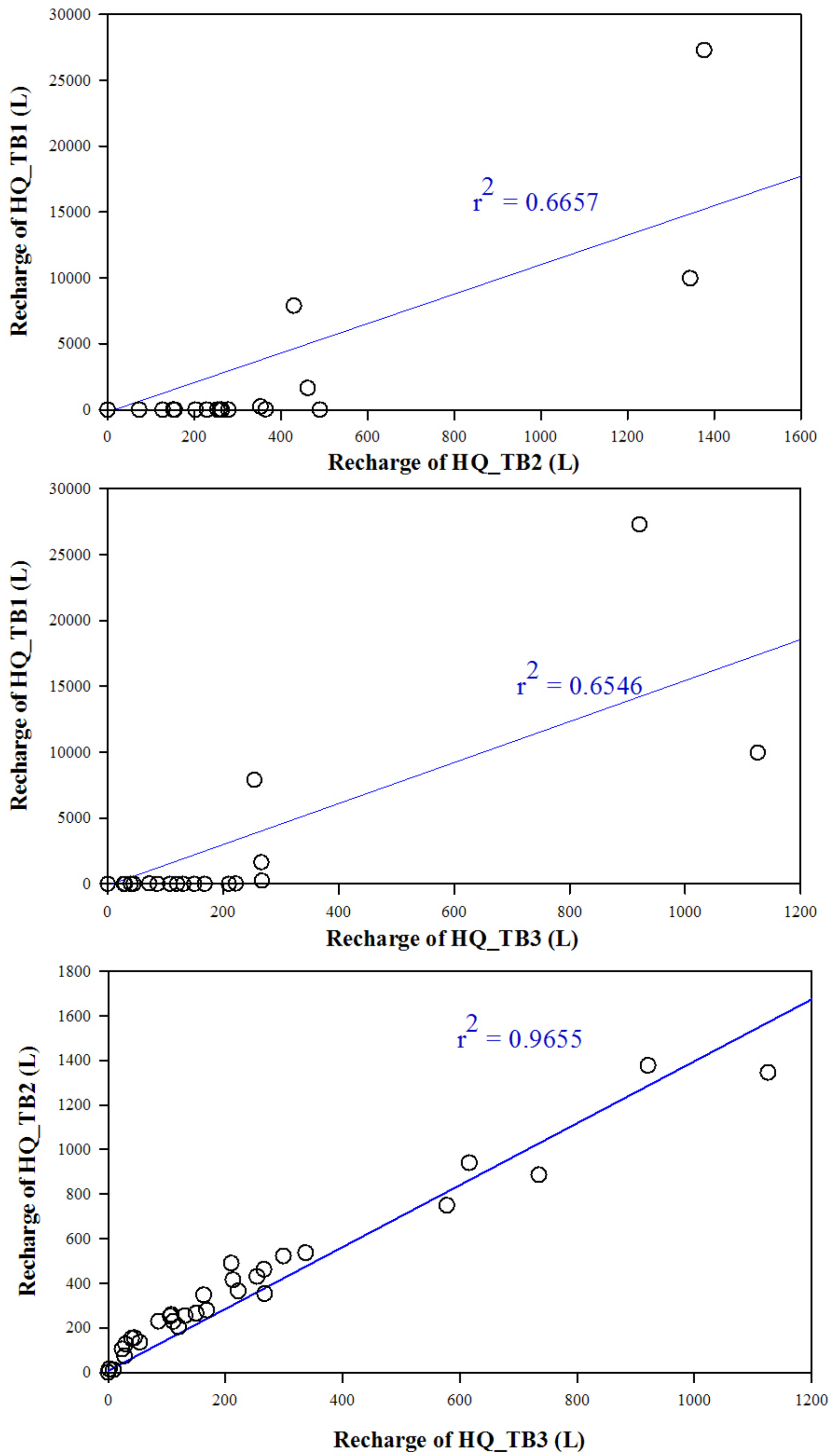


Figure 14. Correlation between the Headquarters recharge collectors.

3: Very occasionally, all of the recharge collectors malfunctioned during an event. In this case, we predicted recharge on the basis of the amount of rainfall.

Dynamics of Recharge

Recharge was extremely episodic, occurring in response to individual rainfall events. In other words, there was no base level of recharge that occurred on a fairly constant basis. In general, when recharge occurred, it began and ended within hours of the rainfall event (Figure 15). In all cases, recharge began soon after the onset of rainfall and declined relatively quickly after the cessation of rainfall. Overall, recharge at Bunny Hole was more “flashy” than that of Headquarters Cave and declined rapidly once rainfall had stopped.

The most extended hydrographs were produced by recharge from collector TB1 in Headquarters Cave: most of the recharge occurred within several days of the onset of rainfall. But the recharge captured by this collector was still closely tied to individual rainfall events. Typical hydrographs for the various collectors, for a rainfall event in March 2007, are shown in Figure 15. This event was particularly interesting because it consisted of three pulses of rain, which highlights the sensitivity of recharge to antecedent conditions. The third pulse of rain, although smaller than the first, produced much more recharge.

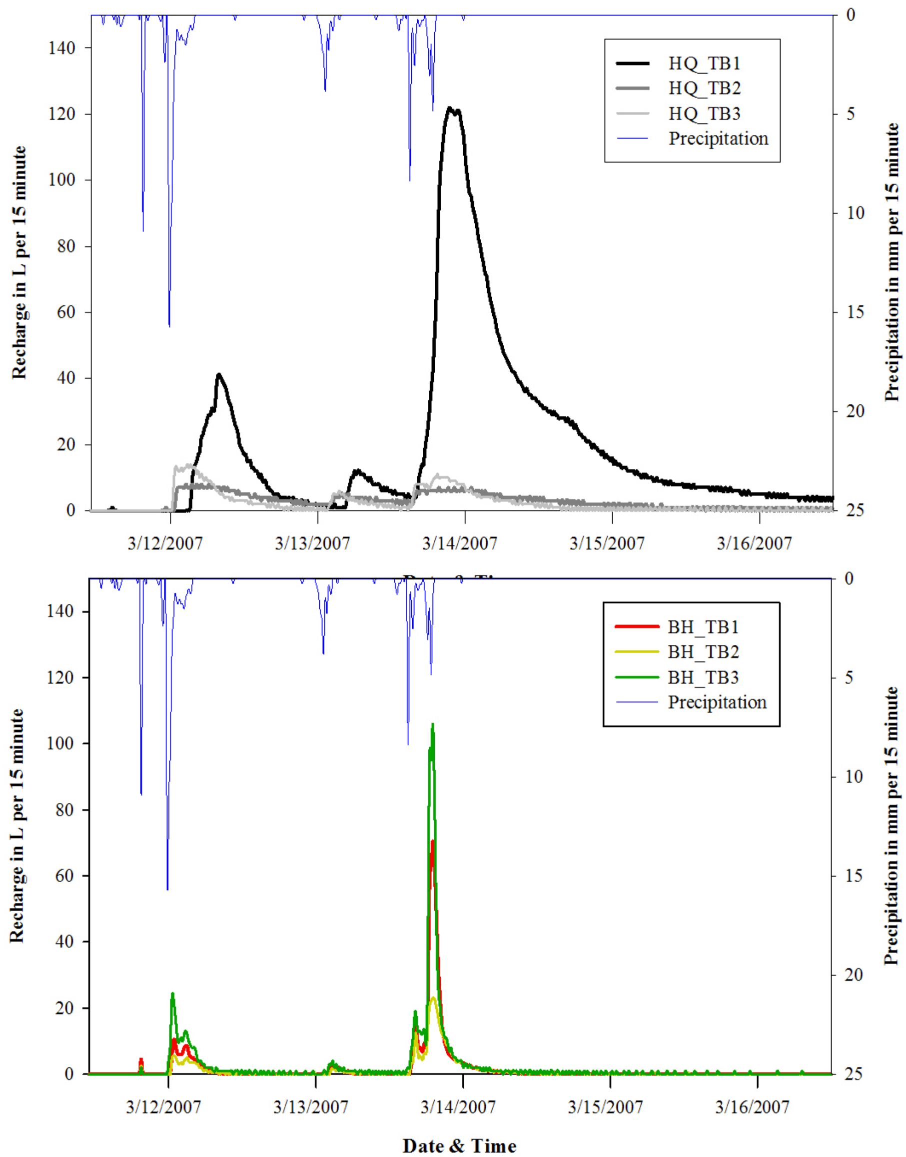


Figure 15. Recharge hydrographs for a rainfall event (123 mm) in March 2007, as recorded by the collectors at Headquarters Cave (upper graph) and Bunny Hole (lower graph).

The number and size of recharge events

Recharge events over the course of the study were ranked by magnitude for each of the collectors—for up to 70 rainfall events at Bunny Hole (Figure 16), and around 50 events at Headquarters Cave (Figure 17). Collector TB1 at Headquarters was noteworthy in that it recorded the fewest number of recharge events (only about 20), compared with about 60 recorded by each of the other collectors.

By far the greatest volume of recharge was measured by collector TB1 at Headquarters Cave—more than 10 times that of any of the other collectors. The least productive collector was TB4 in Bunny Hole.

Although a large number of recharge events occurred during the study period, the largest 10–12 events accounted for most of the recharge measured at each collector. The cumulative recharge responses for Bunny Hole and for Headquarters Cave differed in aspect: the Bunny Hole curve contains a clear inflection point at around 10–12 events, whereas for Headquarters Cave the inflection point is much more subtle.

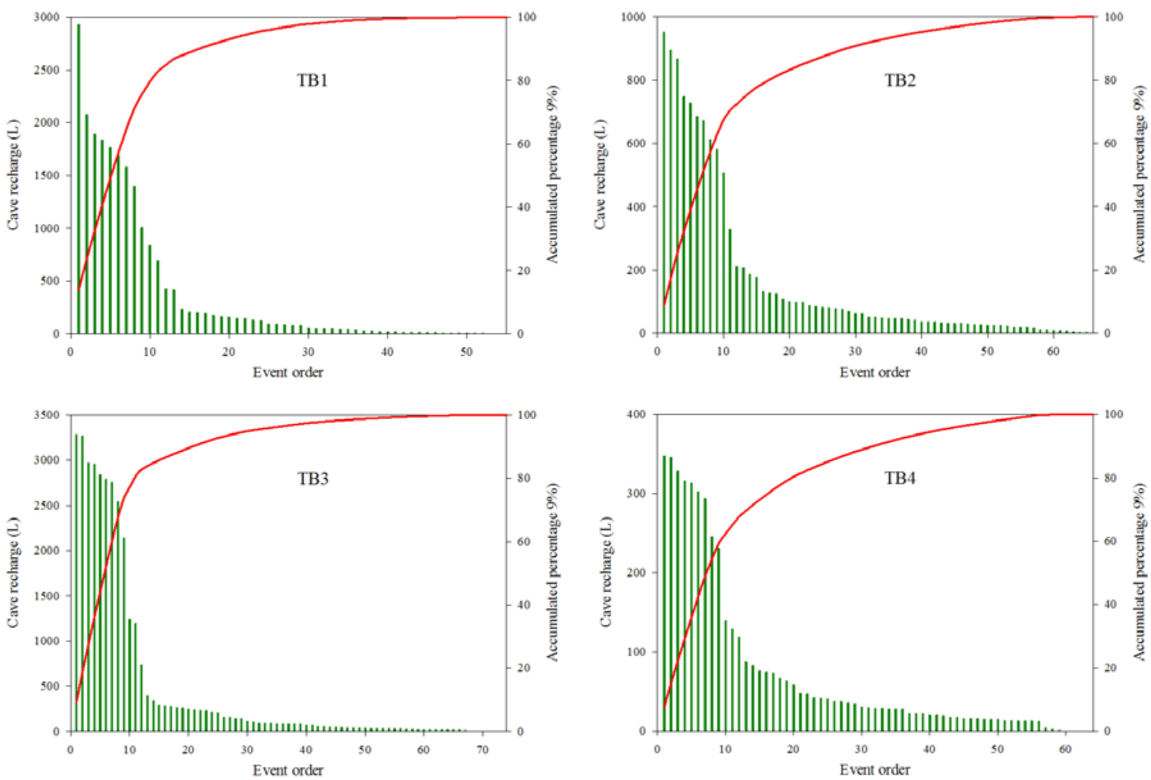


Figure 16. Recharge events for the collectors at Bunny Hole, ranked in order of magnitude.

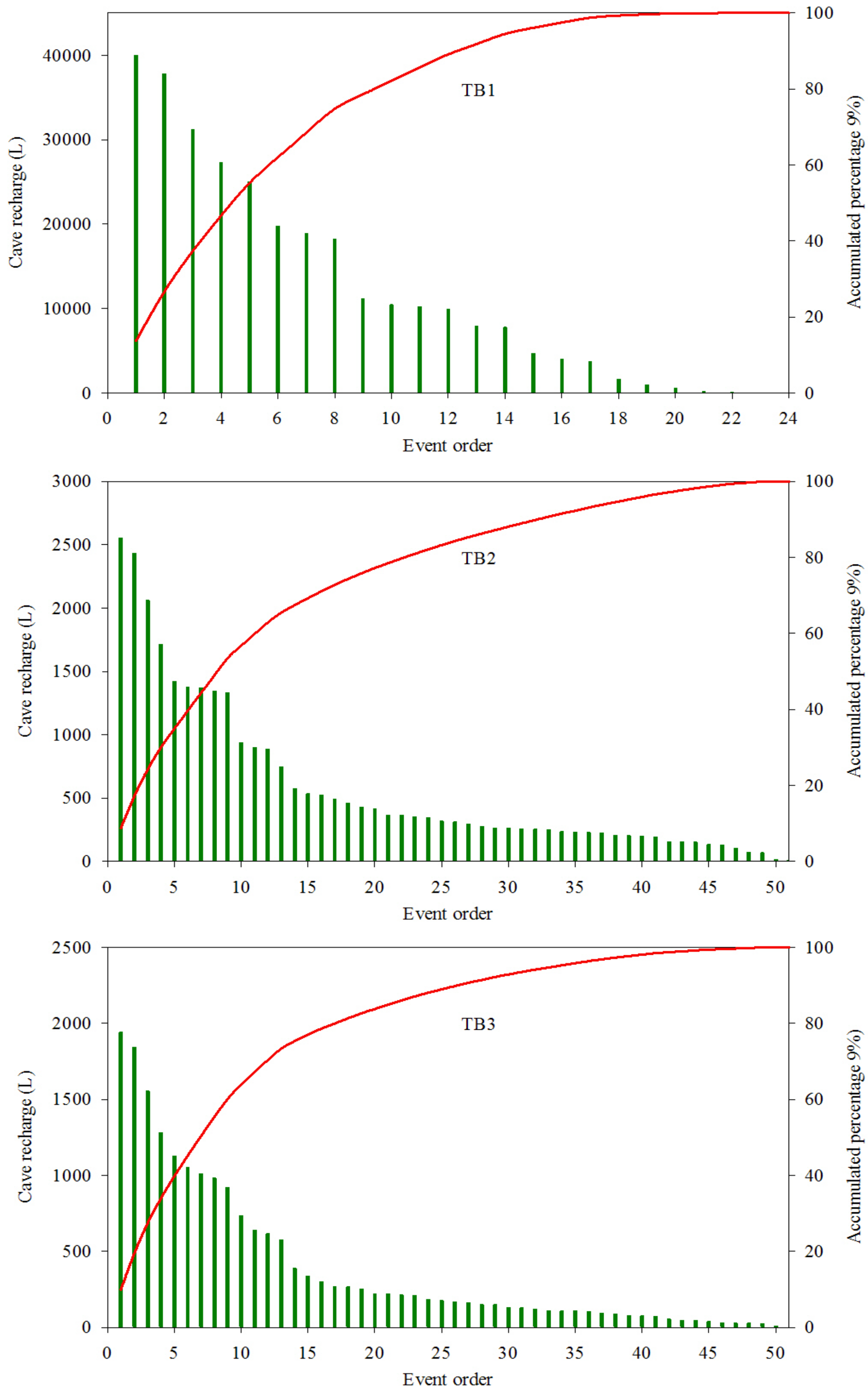


Figure 17. Recharge events for the collectors at Headquarters Cave, ranked in order of magnitude.

Timing and frequency of recharge events

As shown in the monthly recharge portion of Figure 18, there were three periods during the course of this study when recharge was significant. The highest amounts were recorded in November 2004, the summer of 2007, and September–October of 2009.

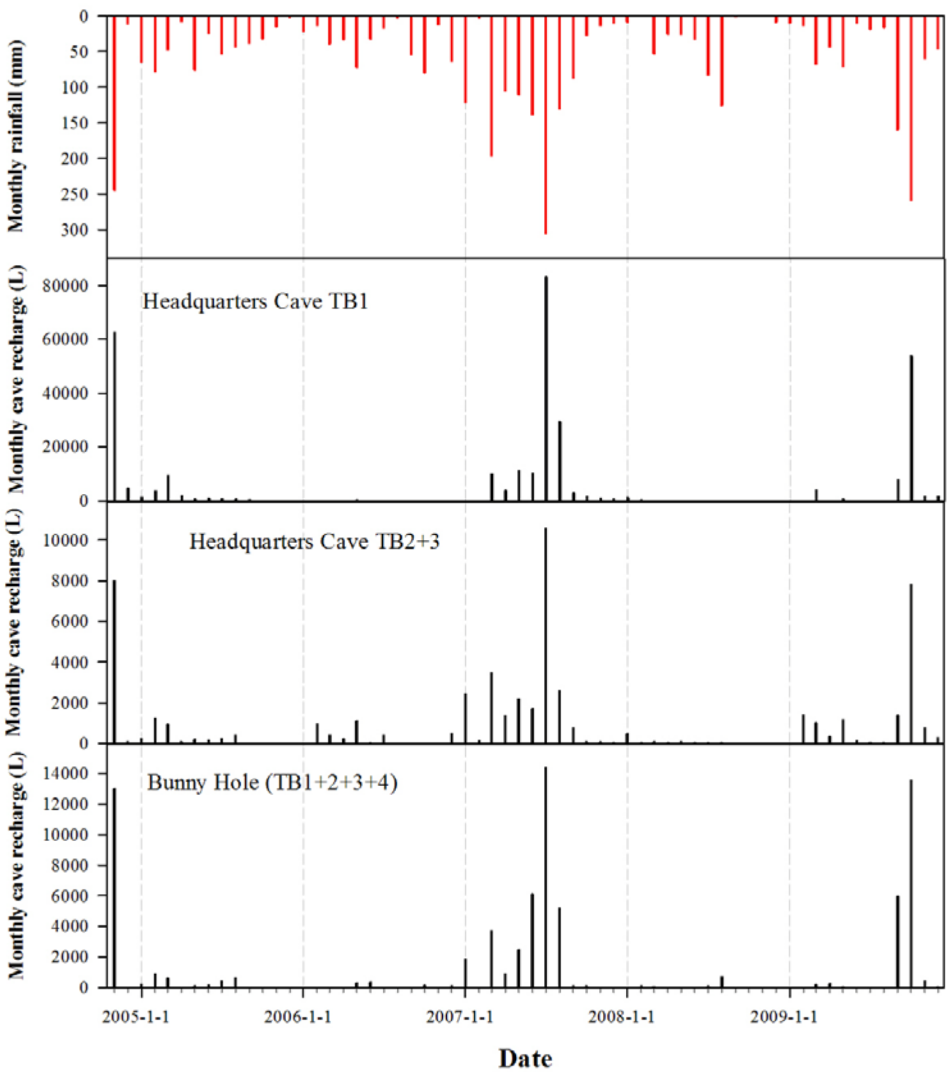


Figure 18. *Monthly rainfall at the site and monthly recharge recorded by the collectors at Headquarters Cave and Bunny Hole. Recharge has been aggregated between sets of collectors that exhibited similar behavior.*

Plots of the cumulative monthly totals for the two caves (Figure 19) underscore the episodic nature of recharge in this region. Recharge is high only during periods when rainfall is well above normal.

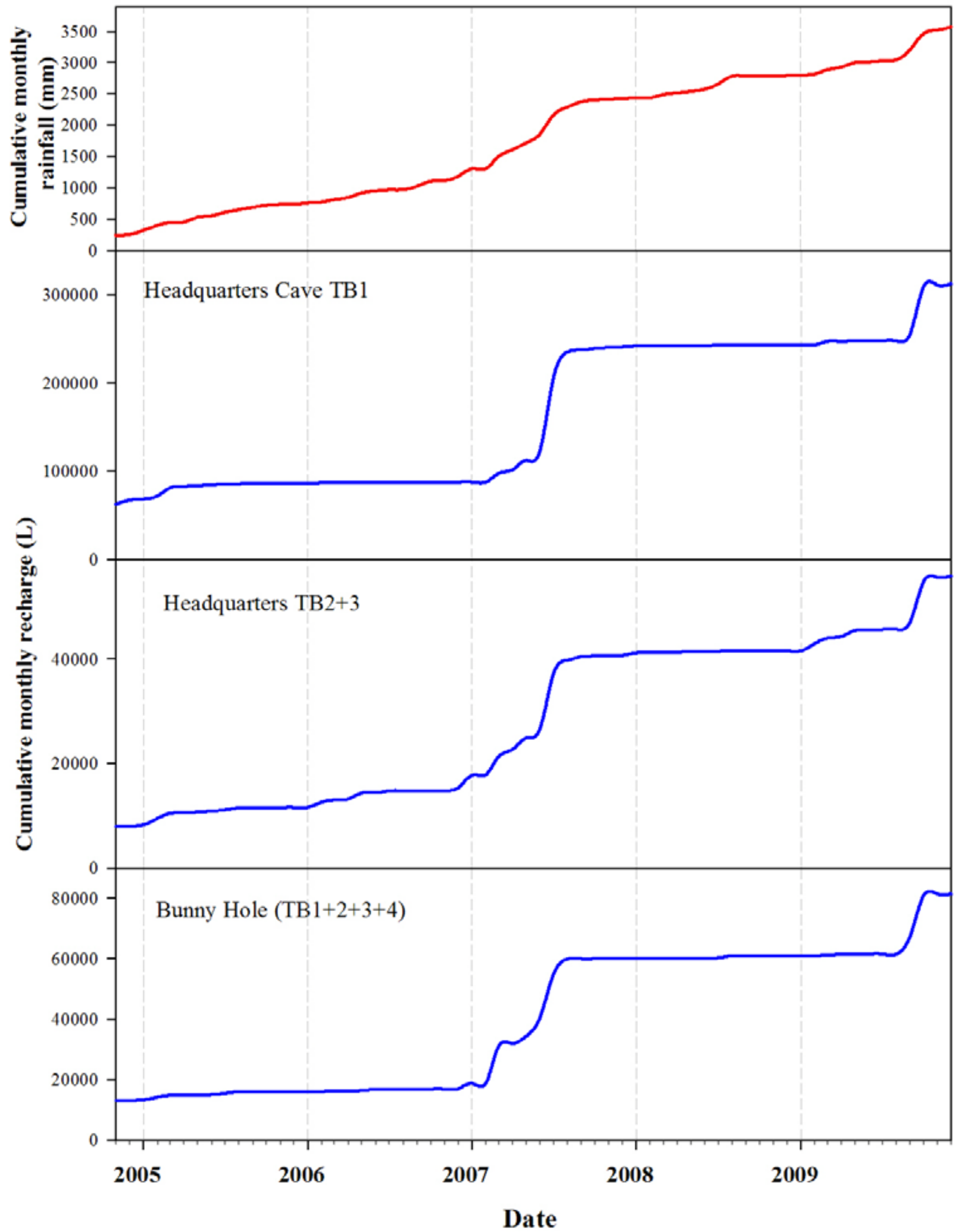


Figure 19. *Cumulative monthly rainfall and recharge for Headquarters Cave and Bunny Hole. Recharge has been aggregated between sets of collectors that exhibited similar behavior.*

INFLUENCE OF JUNIPER REMOVAL ON RECHARGE

The major objective of this study was to assess the effect of Ashe juniper on naturally occurring recharge. This assessment is based on the relationship between recharge and rainfall, and whether the removal of Ashe juniper changes that relationship. The rainfall/recharge relationships for the two caves are plotted at an event time scale in Figures 20 and 21 (Figure 20 includes rainfall simulation results for the Bunny Hole location); and the runoff/recharge relationships for the caves on a monthly scale in Figures 22 and 23. The event-based analysis does not include events that were estimated via correlation analysis, but the monthly analysis does include estimates for gaps in the data.

There is some “scatter” in the rainfall–recharge data, due no doubt to differences in antecedent conditions. As the rainfall simulation experiments made clear, recharge was greater under wet antecedent conditions than under dry. At Bunny Hole, small amounts of recharge were measurable from rainfall events as small as 20 mm, but in general an event of around 60 mm was required for recharge to be signficant (Figure 20). The pattern at Headquarters Cave was similar for the more shallow collectors (TB2 and TB3), but was accentuated for the deep collector TB1—which accounted for by far the most recharge, and was essentially unresponsive to rainfall events smaller than 60 mm.

The relationship between monthly rainfall and recharge is stronger. In other words, monthly rainfall is a relatively good predictor of recharge at all the locations. In general, monthly rainfall needed to exceed 100 mm to generate significant recharge.

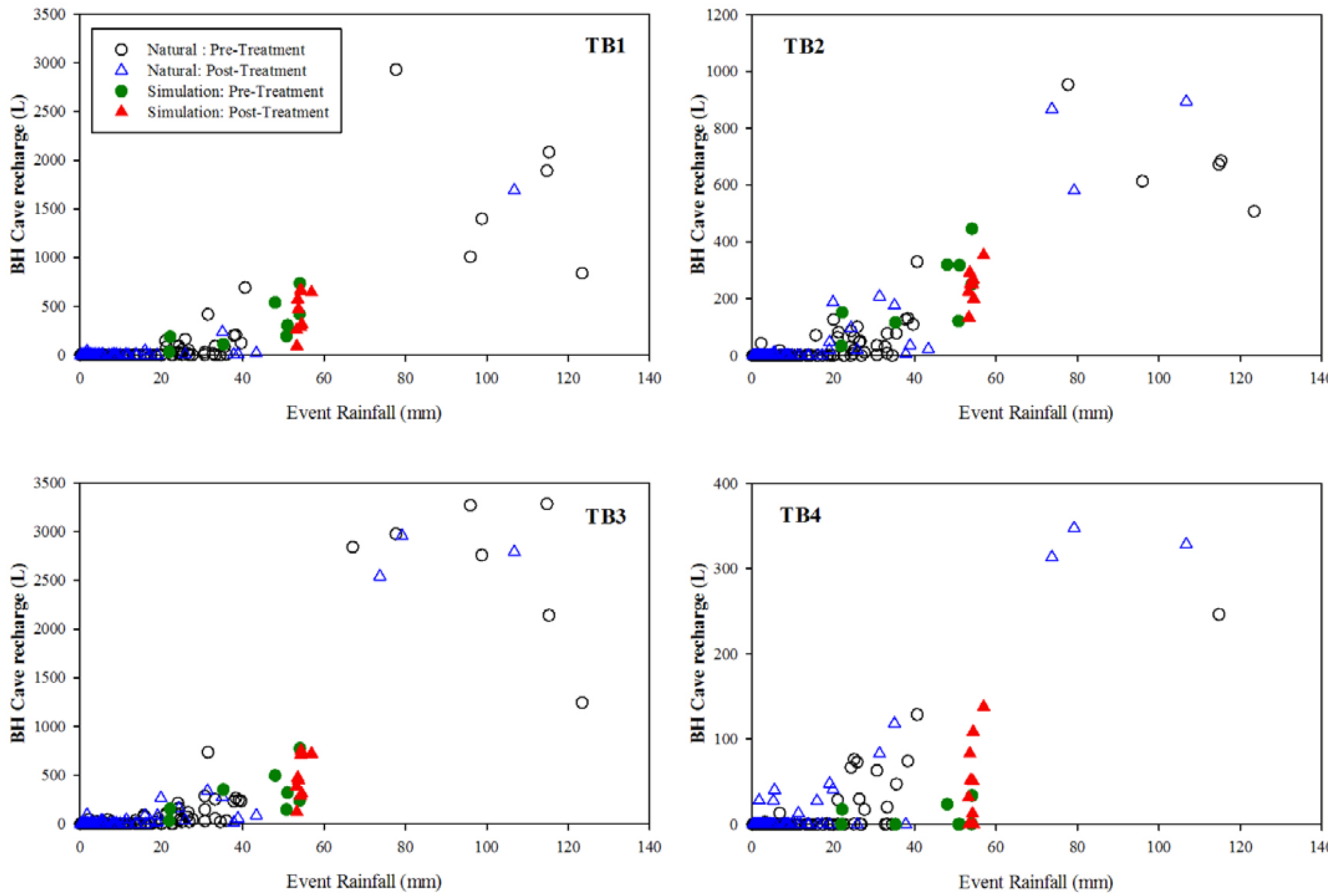


Figure 20: The relationship between recharge and rainfall on an event basis for the four gauges at Bunny Hole.

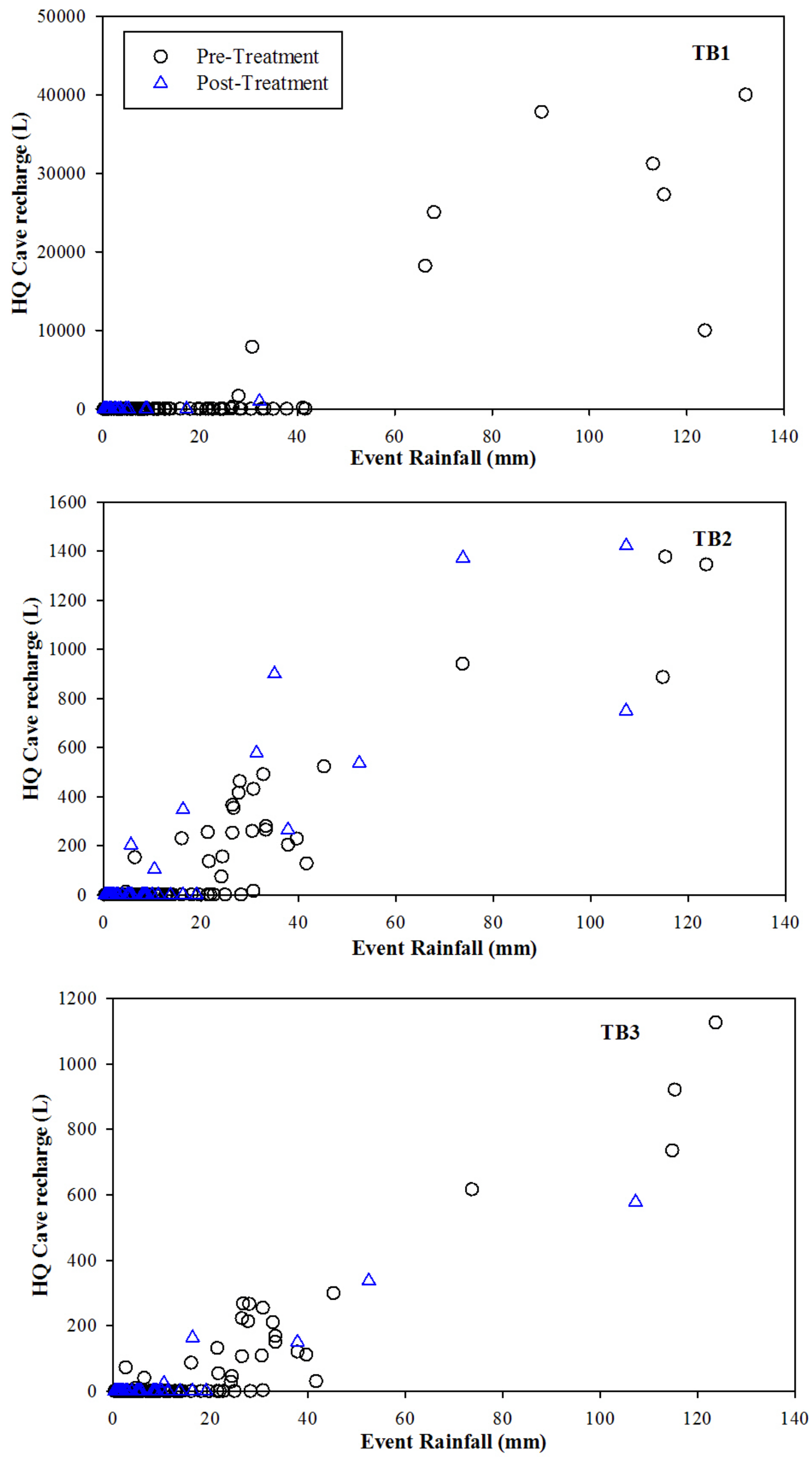


Figure 21: The relationship between recharge and rainfall on an event basis for the four gauges at Headquarters Cave.

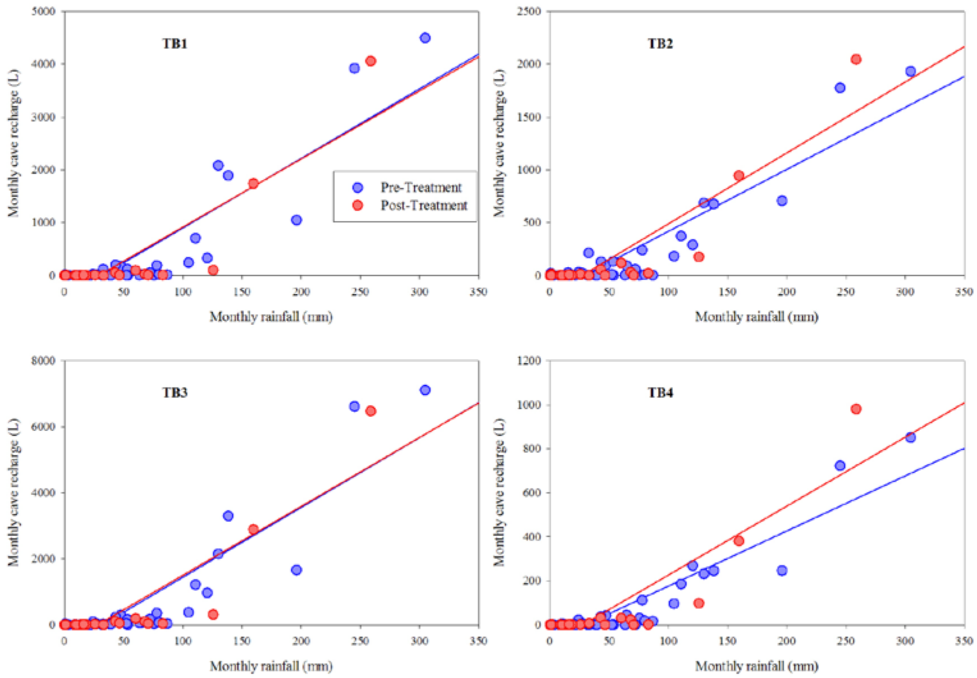


Figure 22: The relationship between recharge and rainfall on a monthly basis for the four gauges at Bunny Hole.

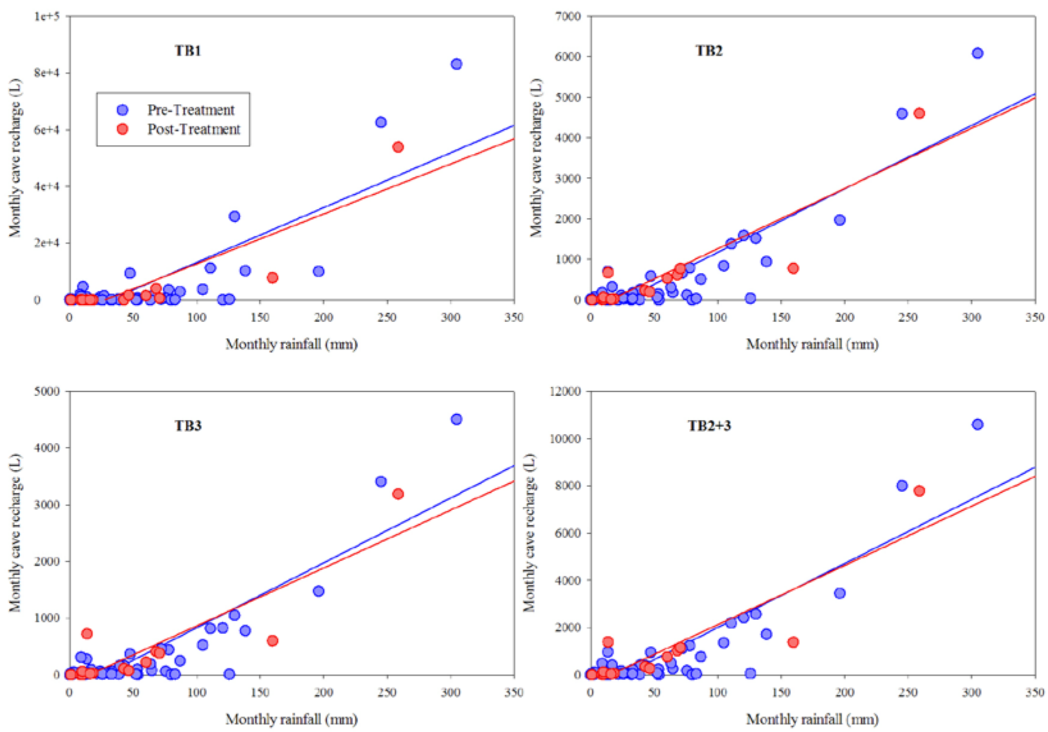


Figure 23: The relationship between recharge and rainfall on a monthly basis for the gauges at Headquarters Cave.

We see no evidence that tree removal changed the relationship between rainfall and recharge at any of the gauge locations. In other words, the amount of recharge produced following a given amount of rain was essentially the same before and after the trees were removed. We caution, though, that monitoring has only been done for 1–1.5 years following removal of the trees, which means that the number of rainfall events supplying data for the post-removal period is relatively small.

Conclusions

Rainfall and recharge were monitored at two cave locations within Camp Bullis from late 2004 through 2009, from natural rainfall, simulated rainfall, and irrigation of the cave surfaces. In addition to recharge and rainfall, other components of the water budget were estimated during periods of this study. In 2008, juniper trees were removed from both of the cave locations.

We found that recharge was highly episodic and event-based. In other words, cave recharge was not continuous, and was significant only if rainfall was well above average. In general, significant recharge occurred only if monthly rainfall exceeded 100 mm. Most of the recharge occurred during three months when rainfall was 250 mm or more.

There was no perceptible shift in the relationship between rainfall and recharge following removal of the juniper overstory. That is, we found no evidence that removing the trees had any effect (positive or negative) on recharge. At the same time, because the evaluation period following tree removal was relatively short, we cannot definitively rule out a linkage between woody plant cover and recharge without a longer period of observation.

We recommend that monitoring of rainfall and cave recharge continue at these locations. These data are truly unique. We know of no other location where long-term records and continuous measurements of cave recharge are being made. In addition to providing insight into the influence of woody plants on recharge, the findings of this study paint a unique portrait of recharge dynamics on the Edwards Plateau.

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