# WATER BUDGETS AND CAVE RECHARGE ON JUNIPER RANGELANDS IN THE EDWARDS PLATEAU

A Thesis

by

LUCAS FRANK GREGORY

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Water Management and Hydrological Sciences

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Approved by:

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# ABSTRACT

Water Budgets and Cave Recharge on Juniper Rangelands in the Edwards Plateau.

(May 2006)

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Chair of Advisory Committee: Dr. Bradford P. Wilcox

Increasing demand for water supplies in semi-arid regions, such as San Antonio, has sparked an interest in potential recharge management through brush control. Two shallow caves under woody plant cover in northern Bexar County, Texas were chosen as study sites where a detailed water budget would be developed. The Headquarters Cave site measures natural rainfall and cave recharge while the Bunny Hole site is instrumented to measure throughfall, stemflow, surface runoff, and cave recharge. Large scale rainfall simulation was used at Bunny Hole to apply water directly above the cave footprint allowing us to determine how recharge differs between natural and simulated rainfall events. Under natural conditions, Headquarters Cave recharged 15.05% of the annual rainfall while Bunny Hole received 4.28%. Natural canopy throughfall measured 59.96% of the water budget; stemflow accounted for 0.48% and canopy interception was 39.56%; no surface runoff was measured. Rainfall simulations conducted at Bunny Hole resulted in an average of 74.5% throughfall, 5.3% stemflow, 20.2% canopy interception, 2.8% surface runoff, and 6.9% cave recharge; simulation intensities were typically higher than natural event intensities. General water budgets across the Edwards Plateau

have concluded that evapotranspiration represents 65% of total annual rainfall while percolation and storage accounts for 30% and the remaining 5% is runoff. These studies have been focused on broad water budget parameters while this study looks at more detailed components. No other study to date has been able to combine throughfall, stemflow, surface runoff, and vertical recharge monitoring to quantify the water budget in the Edwards Plateau; these parameters are instrumental in determining a detailed water budget in juniper rangelands. Results from this study illustrate the significance of all aspects of the water budget and are the first to yield a firm measurement of actual upland recharge.

# ACKNOWLEDGEMENTS

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Lastly I would like to thank Camp Bullis and the Edwards Aquifer Authority for supplying the bulk of funding and some equipment for the project. BexarMet Water District has also been gracious enough to supply us with water for this project. Their desire to develop a better understanding of the water cycle and recharge processes in the Edwards Aquifer region are priceless for the environment and society.

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# INTRODUCTION

Water is one of our most precious natural resources and many people assume that it comes from the tap and will always be available for their every use. In reality, water is a limited resource that is currently over exploited and continues to be further strained by population growth. By the year 2050, the population of Texas will double and significantly increase demand for water across the state (TWDB, 2002). Approximately 58% of the water used in the Texas is groundwater; the majority of west Texas and a significant part of east Texas rely solely on groundwater (TWDB 2002). In the Edwards Aquifer recharge zone, recharge occurs much more rapidly than in many other areas. This is largely due to the highly cavernous karst limestone that makes up the aquifer. The majority of recharge occurs in stream beds where the channel crosses the fractured outcrop of the aquifer. Upland recharge is considered relatively small compared to recharge occurring in stream beds (Maclay, 1995), but exactly how much upland recharge occurs remains unanswered. The ability of caves to receive and transmit water from the surface is one such question. Specifically, the sensitivity of the cave footprint, the surface area overlying the cave, was investigated by applying water directly above the cave with a large plot rainfall simulator and comparing it to natural events that apply water over the entire hillslope. This approach attempts to shed light on the question regarding the contributing area of caves. Is recharge into the cave received only from the cave footprint, or does the area surrounding the cave also contribute to vertical recharge?

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This thesis follows the style and format of *Hydrological Processes.*

Woody plant species are moving in or expanding their coverage in most semiarid regions around the world. Van Auken (2000) describes the conversion of grasslands and savannas to woodlands as woody plant encroachment. He attributes the rapid increase in woody plant density to a combination of climate change, over grazing, and fire suppression. Over grazing and fire suppression can be linked to European settlement and is a world wide trend (Blackburn, 1983; Archer, 1994; Hester et al., 1997; Dugas et al., 1998; Wu et al., 2001). One species that has expanded across Central Texas and the Edwards Plateau is Ashe juniper (*Juniperus ashei*). This is a native species that was historically limited to rocky outcrops, steep slopes, and waterways in Central Texas where there was insufficient soil for substantial grass growth, but has expanded into other areas of the landscape (Smeins and Merrill, 1988; West, 1993).

Rangelands in general are an excellent source of clean water (Thurow and Carlson, 1994) and are the source of most surface flow and aquifer recharge in the southwestern United States (Carlson et al., 1990). Numerous water supplies for Texas cities are solely dependent on runoff and deep percolation from Texas rangelands (Smeins et al., 2001). Vegetation management has been considered as one option to increase both onsite and offsite water yields on rangelands (Hibbert, 1983); this refers to removing species such as Ashe juniper and replacing them with species that use less water. Not all rangelands make good candidates for effective water yield management due to lack of precipitation. In many locations, practically all moisture will be lost through evapotranspiration in a soil-water deficient environment. Typically, there is no real potential for increasing streamflow unless annual precipitation exceeds 450-500 mm (Wilcox, 2002).

In order for brush control to yield more water from a rangeland, several conditions must be met. Replacement vegetation should be species that use less water than the woody species removed, are shallow rooted, or produce low biomass to potentially use management as a tool to increase water yield (Hibbert, 1979). Specifically, evapotranspiration needs to be reduced and can theoretically be done by replacing woody plants with grasses that use less water. Woody cover needs to be reduced to no more than 20% in order to have a meaningful contribution to water yield (Wu et al., 2001). Another consideration to meet is that average yearly rainfall should total at least 450 mm for brush control to be effective (Hibbert, 1983; Wilcox, 2002). Recharge characteristics are the last consideration to evaluate. If soils are shallow and parent materials are permeable and allow rapid recharge, brush control could be feasible.

## Literature Review

### *Ashe Juniper Water Balance*

Ashe juniper has an inherent advantage over herbaceous species because of its dense mat of shallow fibrous roots as well as an extensive deep root system that allows these trees to access water not accessible by herbaceous plants. Ashe juniper is an evergreen species that is photosynthetically active year round while most grasses do not. Ashe juniper also has physiological adaptations that enable them to extract water from deep within the soil (Thurow and Carlson, 1994). This, coupled with woody species ability to extract water from depth, enables juniper to out compete grasses and forbs for water on the Edwards Plateau (Richardson et al., 1979). Ashe juniper has the potential ability to alter the local hydrology of an area if it grows in abundance (Smeins et al., 1994), but how and to what extent is not well understood (Wilcox, 2002). Woody species such as Ashe juniper may modify both runoff and recharge through altering soil infiltration characteristics through root penetration and organic matter addition, preserving soil moisture through shading and mulching, decreasing soil moisture via transpiration and interception, and altering subsurface flow through macropores created by root activity (Blackburn, 1975; Seyfried, 1991; Breshears et al., 1998; Breshears and Barnes, 1999; Ludwig et al., 1999; Jackson et al., 2000).

Increases in interception and transpiration are likely as brush density increases (Wilcox, 2002). Dugas et al. (1998) conducted a paired watershed study in Seco Creek where they removed Ashe juniper cover from one plot and left the other untreated. The treated watershed showed an average evapotranspiration (ET) rate of 0.3 mm/day lower than the untreated watershed. A rainfall portioning study conducted by Owens et al. (2006) indicates that 10 different study sites monitored over a three years period found an average canopy interception loss of 35%; sites with 20% canopy coverage lost an average of 60 mm per year to canopy and litter interception while sites with 100% canopy coverage lost an average of 320 mm per year. These changes are the major mechanism by which woody plants have the potential to alter streamflow or recharge (Wilcox, 2002). This and anecdotal evidence has led to the widespread perception that streamflow and recharge can be significantly altered with aggressive vegetation control (Wilcox, 2002).

*Evapotranspiration (ET)*

Evapotranspiration comprises all of the processes by which water changes phase from a liquid to a gas (Wilcox et al., 2003b). Evapotranspiration rates are one component of the water budget that more accurate measures are needed for use in calculating the total water budget. A common method to calculate ET is to measure all other components of the water budget and the portion that is left is considered ET. These measurements have also been the cause for much debate due to the wide range of published numbers. Other effective methods of measuring evapotranspiration are sap flux measurements, Bowen-ratio energy balance, and eddy-correlation. ET on the Edwards Plateau has been found to be about 65% of annual rainfall (Dugas et al., 1998).

*Interception*

Plants have the ability to substantially influence an area's water budget because of interception (Thurow et al., 1987). Juniper canopies are ideally structured to intercept rainfall and redirect it to the base of the tree as stemflow, thus altering the hydrology of the site (Owens et al., 2006). Intercepted rainfall commonly adheres to vegetation and becomes lost via evaporation; however, some of the intercepted precipitation becomes stemflow or throughfall and is redistributed below the canopy (Thurow and Carlson, 1994). Vegetation canopies in general have only a finite capacity to capture water;

therefore the percentage of precipitation intercepted for individual storms is highly variable (Wilcox et al., 2003a). Interception in tree canopies is affected by the amount, intensity, and duration of rainfall (Thurow and Hester, 1997) Changes in interception can also occur according to seasons when trees loose their leaves or rainfall changes to snow (Breshears et al., 1998). Removal of brush cover gives rainfall that was once intercepted a less obstructed pathway to the mineral soil (Hester, 1996) thus increasing the chances for precipitation to become runoff or recharge.

A wide range of findings for interception rates in Ashe juniper have been found. Slaughter (1997) considered only canopy interception and determined that 7-16% of average rainfall was intercepted. This estimate did not include interception by the litter layer and is considered to be an under-estimate of actual interception. Thurow and Hester (1997) found much higher interception values averaging 79%. Their methodology included canopy, litter, and mineral soil interception making their estimate much higher. Owens et al. (2006) included canopy and litter interception in their calculations and concluded that over the three year study period average interception was approximately 40% of total rainfall.

*Transpiration*

Transpiration is the loss of water from plants in the form of vapor (Kramer, 1983). Evaporation of water in the leaves and is responsible for the ascent of plant water and the rate at which water is taken in through the roots. Transpiration is the vehicle which carries nutrients and minerals into the plant and is considered beneficial because of this and the cooling effect it has on the leaves (Ward and Elliot, 1995). Ashe juniper is an evergreen species that retain their leaves year round and actively transpire when most grasses can not. Ashe juniper also has the ability to maintain active gas exchange during periods of water stress (Owens and Schreiber, 1992). A direct transpiration measurement study conducted by Owens (1996) concluded that mature Ashe juniper trees can transpire as much as 125 L/day.

*Stemflow*

Stemflow is an important aspect of juniper physiology that contributes to its ability to capture and redirect water to the base of the tree. Water that is captured by the leaves or stems becomes stemflow when the water holding capacity of the tree is exceeded and water begins to flow down the stems; usually towards the trunk of the tree. Owens et al. (2006) assumed that stemflow would impact 0.5 $m^2$ around the base of the tree resulting in 21 times more water in that area than an equal sized area would receive from bulk rainfall. Not all stemflow makes it all the way down the stems to the base of the tree; some drops off of the stems before reaching the base of the tree and is then termed throughfall. Stemflow has been measured using collars around the trunk of the trees that direct water to tipping buckets that record volume to a data logger (Sorenson, 2004; Gregory et al., 2005; Owens et al., 2006). Volumes for individual natural storm stemflow amounts were reported to be about 0% for small events (<2.54 mm) and up to 4% for the highest rainfall events. A three year average from their study on the Edwards Plateau revealed that approximately 5% of the bulk rainfall was redirected as stemflow

(Owens et al., 2006). Sorenson (2004) reported much higher stemflow percentages from simulated rainfall events ranging from 5.9-16.1%. Stemflow has also been proven as an important transport mechanism for lateral subsurface flow. Taucer et al. (2005) illustrated that stemflow can rapidly move into the subsurface through fractures, conduits, and preferential flow paths with the use of dye tracing studies.

*Throughfall*

Throughfall is described as precipitation that makes its way through the canopy and reaches the ground surface below. Spatial distributions of throughfall are often quite random; therefore a uniform depth of water is not applied to the soil surface. Canopy and leaf structure are influential factors in the distribution of rainfall. Measuring throughfall allows us to estimate how much precipitation is intercepted by the canopy. This can be accomplished by subtracting measured throughfall and stemflow from total precipitation; thus yielding an accurate estimate of canopy interception. Automated throughfall collectors have been widely used across the Edwards Plateau and Edwards Aquifer regions. These collectors consist of a series of 20.3 cm funnels placed under the tree canopy that collect throughfall and route it to a tipping bucket for recording (Porter, 2005; Gregory et al., 2005). Another more widely used method uses a float in a collection device to measure the actual depth of throughfall captured by the 20.3 cm funnels (Sorenson, 2004; Owens et al., 2006).

Throughfall rates have been reported by Owens et al. (2006) to range from about 2% for small natural events (< 2.54 mm) and up to almost 80% at the highest levels recorded. Over the course of their three year study, they found that throughfall averaged about 55%. For simulated events conducted by Porter (2005), throughfall accounted for 68-88.1% of total water applied; Sorenson (2004) found higher throughfall ranging from 83.9-94.1%. Water applied in both of these studies was applied at rates of 13.3-157.9 mm per hour.

*Runoff Generation*

The amount and type of runoff generated is greatly affected by soil infiltration characteristics. Infiltration capacity is the rate that soil is able to accept water into the profile; the amount and type of vegetation present have been shown to have a significant influence soil infiltration capacity (Wilcox, 2002). In general, litter and dust accumulated beneath trees and shrubs increases the porosity, organic matter content, and the infiltration capacity of the soil under the shrub or tree (Dunkerly, 2000). Infiltration rates under brush have been shown to be much higher than those under adjacent midgrass or shortgrass dominated areas (Knight et al., 1984). Shrubs enhance the soil structure under the canopy by root action and decrease erosive action through interception, thus increasing infiltration rates (Hester et al., 1997). Woody species such as Ashe juniper may modify both runoff and recharge through altering soil infiltration characteristics through root penetration and organic matter addition, preserving soil moisture through shading and mulching, decreasing soil moisture via transpiration and interception, and altering subsurface flow through macropores created by root activity (Blackburn, 1975; Seyfried, 1991; Breshears et al., 1998; Breshears and Barnes, 1999;

Ludwig et al., 1999; Jackson et al., 2000). It has also been found that infiltrability, vegetation cover, and litter biomass are positively correlated (Wilcox et al., 1988).

Runoff is considered to be water that is moved offsite. Surface runoff begins when the amount of water at the soil surface exceeds the infiltration rate and storage capacity of depressions (Horton overland flow) or through saturation excess flow (Thurow and Carlson, 1994; Agnese et al., 2001). Runoff generally occurs as Horton overland flow. High intensity precipitation events and soils with low infiltration capacity are factors that contribute to the generation of Horton overland flow (Wilcox, 2002). Runoff generally accounts for less than 10% of the annual water budget; mostly as flood flow. In many cases, small plots will have up to 100% runoff while a hillslope scale measurement of the same event would yield 5% runoff (Wilcox et al., 2003).

Horton overland flow often decreases after shrub removal because herbaceous vegetation often grows vigorously after the brush is removed and because woody debris increases surface roughness (Wilcox, 2002); this effect was illustrated a study by Dugas et al. (1998) where a substantial decrease in surface runoff resulted from shrub removal. However; their study showed conflicting results, the first runoff event after shrub removal increased surface by 26% runoff while there was a substantial decrease after the second event. They felt that lack of ground cover during the first event caused the large increase and that the second event was more representative of post cut runoff due to the increased cover of bunch grasses. This change in runoff dynamics was attributed to the change in amount and kind of vegetation. Carlson et al. (1990) also show similar results. Under herbaceous and mesquite cover, surface runoff accounted for 4.6% of precipitation. For herbaceous cover only, runoff accounted for 1.6% and on bare ground it was 14.3%. Thurow and Carlson (1994) have also documented the effects of vegetation and its influence on the amount of runoff. Their work found that runoff generated from under shrub canopies has been proven non-existent in some places and very limited or substantially less than grassed areas; yet other studies carried out on the Edwards Plateau have demonstrated otherwise (Wilcox et al., 2005b). Sorenson (2004) conducted a paired plot study and found that surface runoff from a plot with Ashe juniper cover accounted for 2% of precipitation while an adjacent grass covered plot produced 12.67% surface runoff. Wilcox et al. (1997) concluded that runoff from a semiarid forest was remarkably variable and influenced by a number of agents and was produced by extreme events as is typical of other semiarid landscapes.

Shallow subsurface flow is sometimes called interflow or throughflow and is that portion of runoff that travels laterally through the soil, generally because of varying soil horizons. Shallow subsurface flow is very common in humid environments, but it can also be important in semiarid environments, especially when macropores are present (Wilcox et al., 2003b). Recent studies in New Mexico and Texas by Wilcox et al. (1997), Newman et al. (1998), Sorenson (2004), and Porter (2005) have all shown the importance of shallow subsurface flow in the plot or hillslope water budget. In the Texas Hill Country, lateral subsurface flow occurs as a result of shallow soils underlain by fractured parent material (Wilcox, 2002). A study by Wilcox et al. (1997) yielded results that show lateral subsurface flow was occurring as a result of macropore flow. They also found that a relatively impermeable layer restricted vertical movement of water and forced it to move horizontally instead. Newman et al. (2004) found similar results from a study evaluating runoff from snowmelt. Lateral subsurface occurred through macropores generated by live or decayed ponderosa pine roots. Martinez-Meza and Whitford (1996) have also shown the importance of shallow subsurface flow as a result of water redistribution by woody plant species. Dye was applied around the base of the tree where stemflow is reaches the surface for three different species. Results showed that stemflow waters were able to move the dye 5 to 37 cm into the soil and thus transport it deep into the soil for later use.

Studies evaluating shallow subsurface flow in Texas have found significant amounts of runoff can be attributed to shallow subsurface flow. Sorenson (2004) found that on average, 82.6% of total simulated rainfall applied to an Ashe juniper dominated plot was recorded as shallow subsurface flow while an intercanopy or grass dominated plots resulted in only 3% shallow subsurface flow. Huang et al. (2006) evaluated runoff from a small 19-ha catchment that had been cleared of Ashe juniper and found that streamflow increased 46 mm annually. This increase was a result of overland flow and shallow subsurface flow feeding the stream.

*Groundwater Recharge*

Recharge occurs when water enters the ground and moves downward until it reaches a water table or aquifer. Recharge in the Edwards Aquifer occurs primarily in stream channels crossing the Balcones Escarpment but also occurs in this area in upland areas as well. This area is highly fractured with many of these fractures extending down into the aquifer providing a direct path for water to enter the water table (Maclay 1995). Aquifer recharge is dominated by stream losses; all major streams in the area except the Guadalupe, which is a gaining stream, loose water to the aquifer (Maclay 1995).

Actual recharge rates and volumes have been explored in discreet areas such as caves and sinkholes with more broad measurements occurring elsewhere across the Edwards Plateau. Recent studies have shown the ability of caves to recharge large volumes of water that account for significant percentages of rainfall through discreet recharge features, bedding planes, conduits and solutionally enlarged fractures (Gregory et al., 2005). Recharge has also been monitored by measuring recharge in discreet sinkhole locations and adding estimated diffuse recharge amounts which are derived from the difference in precipitation, ET rates, and discreet recharge for micro-catchments and was found to be about 34% annually (Hauwert et al., 2005). A study by Dugas et al. (1998) evaluated potential recharge based on subtracting ET from precipitation and found that 30% of annual rainfall is available for recharge. Potential recharge was also estimated by Huang and Wilcox (2005) using the water balance equation for a small watershed north of San Antonio and was found to be 18% of total rainfall. Methods such as the channel water budget have been used to measure recharge for the Edwards Aquifer yet these do not account for recharge that takes place in upland areas. Maclay (1995) used this method to determine that average recharge in stream channels crossing the recharge zone was 635,500 acre-ft/yr during 1934-1988. He also states that aquifer recharge is dominated by streamflow losses and recharge from direct infiltration of precipitation is relatively small.

**Objectives**

The main objective of this study is to develop a detailed water budget on juniper rangelands in the Edwards Plateau. Previous Edwards Plateau water budgets have been established, but none have directly measured recharge. This study has the ability to monitor direct recharge into caves as a result of rainfall events; thus allowing us to explore the relationship between rainfall and recharge. Rainfall simulation directly above the caves allows us to monitor and compare natural and simulated rainfall events and determine if any differences exist. We expect that the caves will receive more recharge from natural than simulated rainfall events.

# STUDY AREA

Two research sites are on the southeastern portion of the Edwards Plateau approximately 16 km north of downtown San Antonio, Texas on Camp Bullis (+29.6ºN, -98.65ºW) . The Bexar County soil survey describes the topography in this area is moderately hilly which is typical of the Hill Country region of Texas. Soils in the research area are classified as Tarrant-Brackett association and are thin to very thin stoney, clayey soils over Edwards and Glen Rose limestone ranging from several centimeters to about 25 cm. This soil association lies in the northern third of Bexar county, are gently sloping to steep, and are occupied by ranches, military reservations, and are now subject to urban sprawl (Taylor et al., 1962). Towards the east and south of the Edwards Plateau, both surface water and groundwater are relatively abundant relative to the semiarid climate. Perennial streams and rivers that typically supply aquifer generally originate at the periphery between the Edwards Plateau uplands and the Hill Country (Wilcox et al., 2005a). Average annual precipitation in the San Antonio area is about 738 mm/year, but this has varied from 257-1328 mm between years (NOAA San Antonio, TX www.srh.noaa.gov/ewx/html/cli/sat/satmonpcpn.htm).

## Edwards Plateau Geology and Hydrogeology

The Edwards aquifer is contained in Lower Cretaceous age carbonate rock units. The aquifer is represented by three stratigraphic columns across the San Antonio region; the Maverick basin, the Devil's River trend, and the San Marcos platform. The Maverick basin consists of three different formations; the West Nueces, McKnight, and

Salmon Peak Formations. The West Nueces Formation is made up of approximately 23 m of nodular mudstone that is practically impermeable and is covered by 30 m of grainstone. The McKnight Formation is mostly lower and upper thin-bedded limestone separated by limey mudstone about 7 m thick. The lower limestone unit is about 20 m thick and the upper unit is about 15 m thick and is shaley limestone with collapse breccia and associated evaporites. The Salmon Peak Formation consists of about 100 m of dense, massive, lime mudstone and has 27 m of grainstone in the upper part (Maclay 1995).

The Devil's River trend consists of Devil's River Limestone and is generally about 183 m thick and ranges from 133 to 266 m thick. This limestone is made up of varying layers of ancient marine sediments. In the San Marcos platform, the Kainer Formation is the basal unit and ranges from 83 to 133 m thick. This formation consists of three members: the basal nodular, the dolomitic, and the grainstone member. The upper unit of the Edwards Group on the San Marcos platform is the Person formation which ranges from 60 to 83 m thick. The upper most unit of the Edwards aquifer in the San Marcos platform is the Georgetown Formation (Maclay 1995).

Overall, the thickness of the freshwater zone in the Edwards aquifer ranges from 133 to 266 m but averages 183 m thick. Thickness of the aquifer increases towards the west and south. The confining units of the aquifer in the San Antonio area consist of the underlying Glen Rose Limestone and overlying Del Rio Clay. Both of these units have a relatively low permeability. In many places, these confining units are broken by faulting but the rock's plasticity causes most of the fractures to be closed and exhibit low permeabilities (Maclay 1995, Schindel et al 2005). The Edwards Aquifer is contained within the Cretaceous age Edwards Group Limestone. A series of faults in the Balcones Fault Zone caused the Edwards Limestone (the water bearing unit of the aquifer) to be exposed at the surface on the southern boundary of the Hill Country. Down faulting has dropped the Edwards Limestone to large depths below the surface along the southern boundary of the aquifer. In several areas, fresh water can be found at depths of 1,333 m below the surface as a result of this faulting (Schindel et al. 2005).

**Research Site Geology**

Each of these sites is underlain by a shallow cave that has been equipped to study cave drip responses to rainfall events. Both caves are located within the Edwards Aquifer region and receive recharge from precipitation events. Bunny Hole is the smaller and shallower cave and is located within the recharge zone of the Edwards Aquifer which is known to be highly sensitive to rapid recharge of the groundwater reserves. The cave consists of a maze of passages that extend 198 m in length and reach a maximum depth of 5 m. Passages average 1.5 m in width and are typically less than a meter in height. Impassable holes and fissures extend up to 2.5 m deep into the floor in some areas and probably extend down to another inaccessible lower level. Three parallel crawlways arranged in a trend from northeast to southwest, and cover a linear distance of 46 m. Dry, light-brown silt and gray-black organic sediment covers much of the cave floor (Veni, 1988).

Bunny Hole is developed in the Dolomitic Member of the Kainer Formation, within the recharge zone of the Edwards Aquifer. It is a rare phreatic conduit system that pre-dates the origin of the modern Edwards Aquifer. Evidence suggests that Bunny Hole was formed under low velocity groundwater flow and is oriented parallel to major Balcones faulting. Joint planes exhibit little dissolution possibly due to low hydrostatic pressure during phreatic development and later speleothem development and case hardening of the walls and ceiling that hide the fractures. The floors of some passages were incised as a result of water flowing down to the water table during vadose conditions. Much of the collapse within Bunny Hole occurred along solutioned bedding planes with three of these collapses extending to the surface. There are also three solutionally formed sinkholes that breech the surface of the cave; one of these is the cave entrance and the other two are small impassable sinkholes. Together, these sinkholes drain an area that is approximately 60 m along the cave axis by 50 m wide up the hillslope to the southeast (Veni, 1988).

Headquarters Cave is a larger and deeper cave than Bunny Hole. Headquarters Cave measures 54 m in length and consists of two large rooms with the ceiling about 5 m above the floor. The cave reaches a depth of 11.8 m below the surface at its farthest extent. A bat friendly gate has been installed on the entrance of the cave to allow passage of indigenous bat species and other cave biota yet keep unwanted entrants out (Veni, 1988).

Headquarters Cave was probably formed under relatively low-velocity phreatic conditions that pre-date the modern Edwards Aquifer. These conditions created at least two large rooms as water levels in the aquifer declined to those of the present day. The two accessible rooms in the cave are voids formed between the cave ceiling and the rubble that collapsed. Recharge through fractures and the later development of the entrance, a result of the retreating hillslope truncating the cave, slightly modified the cave's morphology and deposited sediments within the cave (Veni, 1988).

**Regional Vegetation**

The area called the Balcones Canyonlands encompasses much of the contributing and recharge areas of the Edwards Aquifer. This region is predominantly woodland and forest vegetation while grasslands are typically limited to broad drainages, valleys, and adjacent slopes. Mesic slopes in this region support deciduous woodlands and forests containing Texas oak (*Quercus texana)*, Plateau live oak (*Quercus fusiformis),* Ashe juniper (*Juniperus ashei)*, black cherry (*Prunus serotina)*, and Texas ash (*Fraxinus texensis)*. In the central and western portion of the area Lacy oak (*Quercus glaucoides)* is important while scalybark oak (*Quercus sinuata)* is more important in the east. Southern and western facing slopes are commonly evergreen and dominated with Ashe juniper with plateau live oak, Texas oak, and scalybark oak as commonly intermixed species. These xeric woodlands typically contain no understory woody layer and less diverse in woody species than deciduous forests (Riskind and Diamond, 1988).

Many of the grasslands in the Balcones Canyonlands region have been heavily grazed by livestock and subject to various brush control techniques causing them to be patchy. This area is largely considered an extension of the Mixedgrass Prairie; thus well-watered, moderately grazed uplands of the region resemble tallgrass communities, but increasing aridity to the west or overgrazing leads to midgrass or shortgrass communities. Little bluestem (*Schizachyrium scoparium*), Texas wintergrass (*Stipa leucotricha*), white tridens (*Tridens muticus*), Texas cupgrass (*Eriochloa sericea*), tall dropseed (*Sporobolus asper*), sideoats gramma (*Bouteloua curtipendula*), seep muhly (*Muhlenbergia reverchonii*), and common curlymesquite (*Hilaria belangeri*) are among the dominant species in moderately grazed areas. Heavily grazed grasslands and drier soils contain more shortgrasses such as curlymesquite, threeawns (*Aristida* spp.), Texas grama (*Bouteloua rigidiseta*), red grama (*B. trifida*), hairy grama (*B. hirsuta*), hairy tridens (*Erioneuron pilosum*), and white tridens (Riskind and Diamond, 1988). Ashe juniper was originally limited to rocky outcrops, steep slopes, and waterways in Central Texas, but has expanded its range in recent history. Ashe juniper is a native species on the Edwards Plateau, but its rapid expanse has become invasive (Van Auken, 2000).

**Research Site Vegetation**

Dominant woody vegetation on both research sites consist of Ashe juniper (*Juniperus ashei*) and plateau live oak (*Quercus fusiformis*.). Canopy coverage by these species is very dense with only small openings scattered over the cave footprints. The understory of the research site is almost non-existent with scattered agarita (*Berberis trifoliolata*), netleaf hackberry (*Celtis reticulata*), and sparse herbaceous and grass cover. Rocky outcroppings, bare soil, and organic matter make up a significant portion of the ground surface.

# METHODOLOGY

This study incorporates numerous research approaches to quantify multiple facets of the water budget in a semi-arid rangeland landscape that has been subject to woody plant encroachment. Measured parameters include throughfall, stemflow, surface runoff, and vertical recharge through fractures while interception and soil/fracture storage can only be estimated. Timing, intensity, and duration of rainfall events can be problematic in attempting to monitor the previously mentioned parameters.

Runoff generally occurs on rangelands as a result of summer time convective storms of short duration and high intensity (Parsons et al., 1996; Wilcox et al., 2003a). This complication has led researchers (Wilcox et al., 1997; Sorenson, 2004) to turn toward rainfall simulation as means of creating predictable rainfall. Rainfall simulators enable controlled, reproducible events to occur unlike natural rainfall events and are described in explicit detail by Porter et al., 2006.

## Soaker Hose Apparatus

Soaker hoses were used to generate an irrigation event that applied water directly to the ground surface above both caves thus eliminating interception by the canopy. These tests were used to determine where sensitive areas above the cave were and where the rainfall simulator should be setup in order to see recharge inside the caves. The soaker hose apparatus consists of three 51 mm poly vinyl chloride (PVC) pipes that are fitted with 19 mm hose bib connectors allowing for 10 soaker hoses to be attached to each pipe. Each 19 mm hose can be turned on or off independently and can be placed where needed. This system has been able to produce a flow rate of 295 L per minute. Variable depths of water can be applied to an area, but it is dependent upon the hose spacing, the amount of hoses used, the area covered, and the flow rate.

**Rainfall Simulator and Equipment**

The rainfall simulator consists of six aluminum television antennas equipped with a PVC manifold that directs water to four sprinkler heads on each mast. The height of the irrigation masts can be adjusted from 3 to 11 m above the ground (Porter et al., 2006) allowing them to extend above tree canopy. These masts are attached to the ground through the use of steel base plates that have a rotating member that is inserted inside of the aluminum mast and allows it to be fastened in a level position regardless of terrain slope. Base plates are anchored to the ground with 25 cm steel spikes that are driven through the plate and into the ground; stabilizing the lower portion of the mast. Each mast is tethered with four cable guy wires that extend down to 25 cm steel spikes equipped with tie-down ratchets. This allows for the mast to be leveled and have tension applied from four directions thus stabilizing the mast.

The PVC manifolds are constructed in an H-pattern design that positions the sprinkler heads on the corners of the manifold. The sprinkler heads are S3000 Pivot Spinners, made by Nelson Irrigation Corp., and are fitted with varying size nozzles that yield flow rates of 25.4, 50.8, 76.2, and 101.6 mm per hour and produce a 360° spray pattern. Each sprinkler can be individually turned off and on through the use of PVC ball valves allowing for a range of 25.4 to 254 mm of rainfall per hour to be applied.

Rainfall rates can be further adjusted by regulating the speed of the WP30X Honda pump that is used to supply water from the storage tank up to the sprinkler heads.

Water is delivered to the manifolds via 51 mm hoses that attach with the use of aluminum camlock fittings and are suspended from the manifolds. Camlock fittings allow for hoses to be quickly disconnected and reconnected. A 76 mm water main delivers water to these hoses from permanent and portable storage tanks. A 19,000 L portable storage tank is used and can be moved to various locations; in addition, ten 1,520 L, two 7,600 L, and one 5,700 L rigid plastic water tanks are used to store water at the Bunny Hole research site. Water pressure and flow rate are both monitored through the use of a simple 0 to 690 kPa pressure gauge and a 76 mm diameter, WT turbine Meter from Meter Master that is capable of detecting flow from 15 to 2000 lpm with 95% accuracy. An inline water filter is employed to help prevent debris in the water from clogging the sprinkler heads and limit simulation stoppages (Porter et al., 2006).

**Automatic Rain Gauge**

Each research site is equipped with an automatic rain gauge from Texas Electronic. These devices use a small tipping bucket that records data in 0.01 inch increments. Data are sent to a CR10X datalogger (Campbell Scientific, Logan, Utah) and recorded on 15 minute intervals. The rain gauges are not located where they can collect simulated rainfall. Data collected are multiplied by 25.4 mm/inch to convert data to mm.

**Throughfall Collectors**

Extensive throughfall collection occurs only at the Bunny Hole research site and is an important aspect of the water budget that must be quantified in order to determine the amount of rainfall that actually reaches the ground surface. Manual and automatic methods are employed in an effort to decrease error in measured values. The manual method consists of 87 plastic rain gauges arranged in an evenly spaced grid that measures an area measuring 20 by 26 m. These gauges are read manually and recorded in a field notebook and later entered into a spreadsheet for processing. The automatic throughfall monitoring system is similar to the system described in Owens et al. (2006). Three separate collection devices are installed above Bunny Hole; each of which records a volume of water collected in a tipping bucket gauge to a CR10X datalogger from Campbell Scientific Inc.

Each collection device is made up of a series of seven 20.32 cm plastic funnels that direct water into a 19 mm PVC pipe. This pipe slopes downhill to a plastic storage tub that has a 0.1 L steel tipping bucket installed inside. Water from the PVC pipe drips into the tipping bucket and is recorded onto the dataloggers. Volumes collected can then be scaled to account for the entire plot area and obtain a representative depth of throughfall in millimeters over the entire plot. Steel screen wire has been installed on each funnel to help keep leaf litter out of the collection system, but it does not prevent all trash from entering the funnels. To solve this problem, clean out locations have been established at the end of each pipe where large amounts of water can be flushed through the system to remove litter or a wire snake can be forced through to remove large clogs.

Preventative maintenance is performed on the throughfall collectors once a month; this entails lubricating the tipping buckets, checking the tipping buckets for level, and monitoring the ease of flow through the length of the collectors. Data is also collected during maintenance from the automatic and manual collectors.

**Stemflow Collection**

Stemflow is another aspect of the water budget that adds to the amount of water that actually reaches the ground. On the research site located above Bunny Hole two Ashe juniper and two live oak trees instrumented to collect stemflow. Collection devices are made from screen wire available at any hardware store covered in heavy duty plastic trash bags. Tree bark is stripped away to yield a relatively smooth surface that is easier to seal and make water proof. Adhesive caulk is placed on the tree in the smooth area and the plastic covered wire is fashioned into a collar around the tree and stapled in place. Constructing these collars usually yields a water-tight device; however, leaks can occur and are easily sealed with silicone caulking.

Water is transported from the collection devices to a plastic storage container that houses a metal tipping bucket via clear surgical tubing. The tubing is connected to the collar with a threaded PVC male adapter that extends through the collar on the tree and is fastened to it with a water-tight washer and nut. Near the tub, the surgical tubing is inserted into a 19 mm PVC pipe that extends through the plastic tub and has a tee located above the tipping bucket to allow water to be collected. The 1 L tipping bucket collects stemflow and records the amount of water collected on a CR10X data logger in 15 minute intervals when monitoring natural rainfall and 1 minute intervals when monitoring simulated events. An in depth survey of tree species, stem diameter at breast height, and the number of each species was conducted for use in scaling the amount of stemflow up from the four instrumented trees to account for all of the trees within the plot. Maintenance is performed on the stemflow collectors monthly and consists of cleaning out the collection collars, checking the collars for leaks, lubricating the tipping buckets, re-leveling the tipping buckets, and making sure the surgical tubing connecting the collar and the tipping bucket is free of debris.

**Interception Quantification**

Interception capacity of Ashe juniper trees is a highly variable component of the water budget that we are not able to directly measure. Owens et al. (2006) conducted a three year study on several Ashe juniper communities in the Edwards Aquifer recharge zone and measured interception ranging from 12% to 96% depending on event size, intensity, and duration.

At Bunny Hole, interception can be estimated for both natural and simulated events. During simulated rainfalls, a known amount of water is applied to the plot and can be expressed as a depth of precipitation. Automatic and manual throughfall readings and stemflow readings are taken during these events and quantify the depth of water that made it through the tree canopy and to the ground surface. The difference between the depth of water applied and the depth of water collected as throughfall and stemflow results in the amount of interception by the vegetation canopy. Interception can also be estimated for natural events through the same practice. A depth of rainfall over the plot is recorded by two separate automatic rain gauges located near the plot. Natural throughfall and stemflow are both automatically recorded if all equipment is properly functioning. Some accuracy is lost for smaller rainfall events that may not produce enough precipitation for the throughfall and stemflow collectors to yield a representative measurement over the plot.

**Surface Runoff**

Surface runoff is monitored at Bunny Hole and Headquarters Cave locations for natural and simulated events. The collection devices at each site consist of 10.7 m of 16-gauge galvanized steel formed into a gutter that extends into the ground 5.1 cm to prevent water from flowing underneath the gutter, a 12.7 cm trough for water to flow toward the measurement device, and a 12.7 cm back splash to keep surface runoff from overtopping the catchment device and continuing down slope. The gutter at both sites extends from a 15.24 cm H-flume to form a “V” that directs water to the flume. Gutter is held together and to the flume with bolts and is concreted in the ground to keep it in place and prevent water from washing out around the foot of the gutter. The H-flume is constructed from 22 gauge steel and painted with rust proof paint to prevent deterioration. Situated at the low point of the catchment, the flume captures all surface runoff that is in its contributing area. At Bunny Hole, water that passes through the flume enters into the cave via the cave entrance; at Headquarters Cave, the surface runoff monitoring set-up is located southeast of the cave approximately 100 m and does not contribute any water into the cave. The reason that this device is not located directly above the cave is that there is not a good location to install the collection device directly over the cave surface.

Each H-flume is equipped with a WL700-001 Ultrasonic Water Level Sensor from Global Water in Gold River, CA. This device uses ultrasonic sound waves to calculate the distance from the sensor to the water by monitoring how long it takes for the sound waves to travel from the sensor to the water and back to the sensor. The sensor automatically adjusts its measurement to account for changes in temperature and averages the water depth per 15 second interval. The sensor requires at least 18V and is powered by two 12V deep-cycle marine batteries wired to output 24V. Two 30W solar panels are also wired to output 24V and are connected to the batteries via a 24V voltage regulator. Data are stored on CR10X dataloggers (Campbell Scientific, Logan, Utah) and are downloaded monthly when maintenance is conducted. Maintenance consists of checking and re-filling the water in the stilling well of the H-flume if needed and checking the battery voltage.

**Cave Drip Collectors**

Drip collectors are installed at both research sites to monitor simulated and natural rainfall events. Bunny Hole contains four independent drip collectors that have their own tipping bucket. Drip collector locations were chosen through monitoring drips during natural events, an irrigation event where water was applied directly above the cave footprint, and by evaluating which locations inside the cave were most suitable to collector construction (Wilcox et al., 2005a). Drip collectors were built inside the cave for a specific location and are constructed from 19 mm PVC pipe. Each frame has polyethylene plastic sheeting pulled over it to form a funnel. PVC pipe is connected to the plastic sheeting and directs water into the steel tipping buckets equipped with stainless steel pivot devices. Stainless steel is used to suppress the effects of the cave's high humidity and resultant rust.

Observations of drips and drip rates inside the cave revealed that we are capturing about 60% of the total vertical drips. To calculate this, cave drips not collected by the drip collectors were measured to get a flow rate by recording the elapsed time required to fill up a container of a known size. This was done during a simulated rainfall event with varying intensities and the individual drips were then compared to the recorded data from the drip collectors. This is only an estimate, but we were able to get a flow rate for all of the significant drips entering the cave ceiling. Water balance equations have been adjusted to account for this when estimating the percentage of water that accounts for vertical recharge. Some water enters the caves horizontally, but we are not equipped to monitor this type of recharge.

Headquarters Cave is instrumented similar to Bunny Hole. Headquarters Cave is equipped with six drip collectors that route water to three tipping buckets. Drip collectors are made exactly the same way in Headquarters Cave as they are in Bunny Hole; the only difference is the size and configuration of the collector. The location of these collectors was chosen after visual evaluation of drips after an irrigation event focused on the cave footprint which identified the most active drips. Screen wire is also stretched across the top of the drip collectors in an effort to keep cave biota from drowning and potentially tearing up the collectors.

Data at both locations is stored in a datalogger located on the surface. A bore hole provides a pathway for wiring from the equipment to the data logger. Solar panels supply power to 12V batteries that operate the data storage equipment. Data for natural monitoring are recorded on 15 minute intervals and downloaded weekly via telephone modem. During simulated events, data are stored on 5 minute intervals in order to gain a higher resolution of data. Maintenance on all monitoring equipment inside the caves is done on a monthly basis (Wilcox et al., 2005a).

# RESULTS

## Initial Tests

Initial observations were made during natural rainfall events at each research site to determine where active drip locations were and if a drip collector could feasibly be constructed to collect the drips. In addition, soaker hose experiments were used to determine what the sensitive area above the caves are and where water applied to the surface had an influence on cave recharge. Using these data, we determined the best location to install a rainfall simulator for monitoring cave responses to simulated rainfall events.

### *Bunny Hole*

The initial soaker hose test was conducted at Bunny Hole on March 31, 2004 lasting 91 minutes and covering approximately 170 $m^2$. 15, 900 L of water was applied over the eastern two-thirds of the cave at a rate of about 62 mm/hr. Drips inside the cave began to respond in less than ten minutes from the start of irrigation.

A six part test was used at Bunny Hole on July 21 and 22, 2004 to determine which specific areas were contributing to cave recharge. Grids 1 and 2 were laid out at 70° ENE and were located on the southeastern side of the cave (Figure 1). Grids 3, 4, 5, and 6 were situated northeast of grids 1 and 2 and were laid out at 342° WNW. Each grid was approximately 7 m wide by 14 m long and saturated the area directly underneath the hoses. Runs 1 thru 4 used a total of 15,194.6 L of water applied directly to the surface; of this only 46 L was recorded in the cave as a result of this

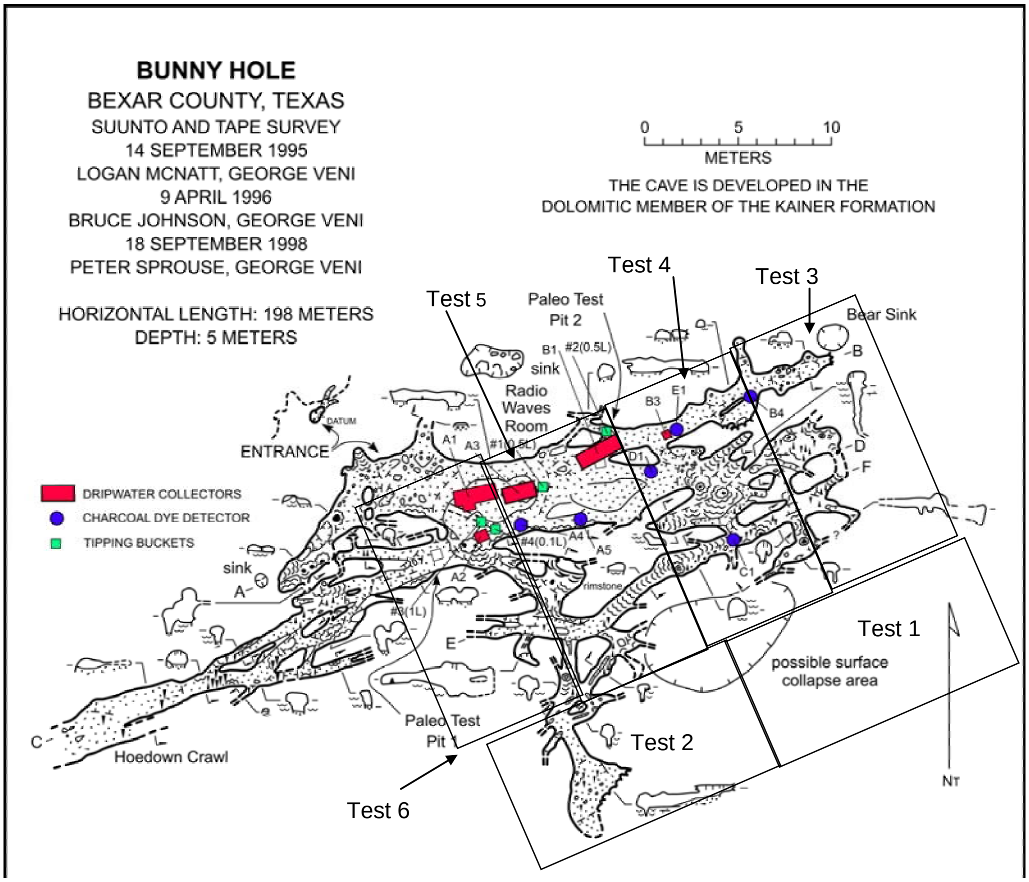


Figure 1. Cave map of Bunny Hole adapted from Veni G, and Associates 2005 to show the approximate layout of the soaker hoses for the six part experimental test. Each grid is labeled to show the order of the test.

application. Collected recharge began to enter the cave approximately 30 minutes after the water application at grid 4 began. No water was recorded inside the cave as a result of irrigation on grids 1, 2, or 3. Runs 5 and 6 were conducted July 22, 2004 and administered 6,798.6 L of water to the surface. Drip collectors were able to account for

203.5 L of this water as recharge. Runs 4, 5, and 6 determined that those areas above the cave footprint are more sensitive to recharge than the other locations tested.

*Headquarters Cave*

On March 3, 2004 a similar test was conducted at Headquarters Cave over the southern two-thirds of the cave (Figure 2). 20,800 L was applied over 109 minutes at a rate of 37.8 mm per hour; recharge was observed after approximately 90 minutes of water application. The wetted area from this experiment was about 200 $m^2$.

A follow up irrigation experiment was conducted at Headquarters Cave on July 27, 2005 over the same general area. This experiment was conducted to compare results from the initial test to see there were any noticeable changes in cave response. 27, 205.8 L of water were applied over the course of 171 minutes and covered approximately 200 $m^2$. This equaled a depth of 89.8 mm and an application rate of 31.5 mm/hr. Drips inside the cave as a result of the irrigation event were first recorded 170 minutes after the beginning of the event. Water was dripping inside the cave prior to the irrigation event at the approximate rate of 1 L per hour; the drip rate drastically increased when irrigation water reached the cave as seen in Figure 3. The drip response continued for approximately 27 hours after it began.

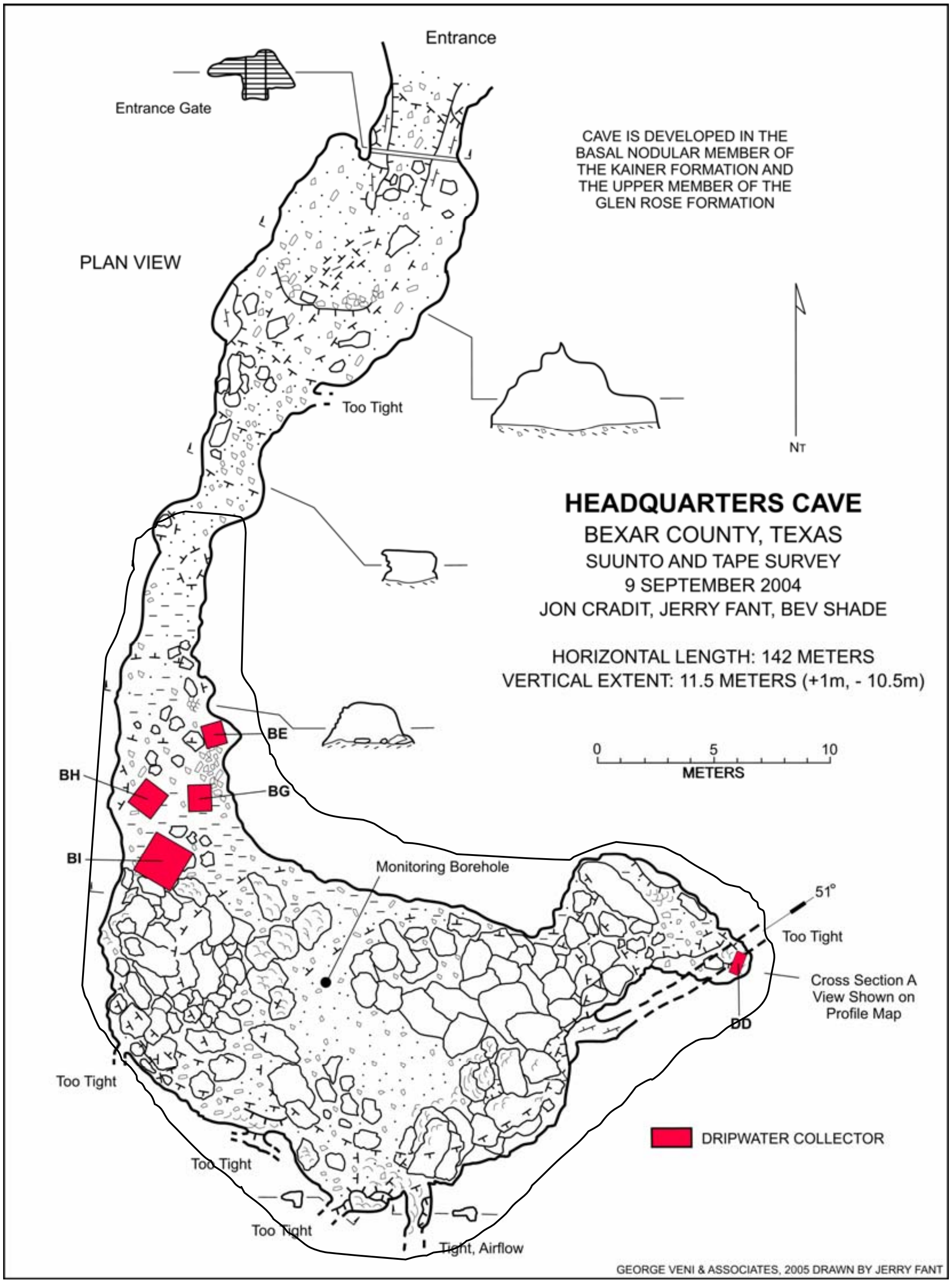


Figure 2. Map of Headquarters Cave adapted from Veni G, and Associates 2005 to show the approximate location of water application during soaker hose irrigations

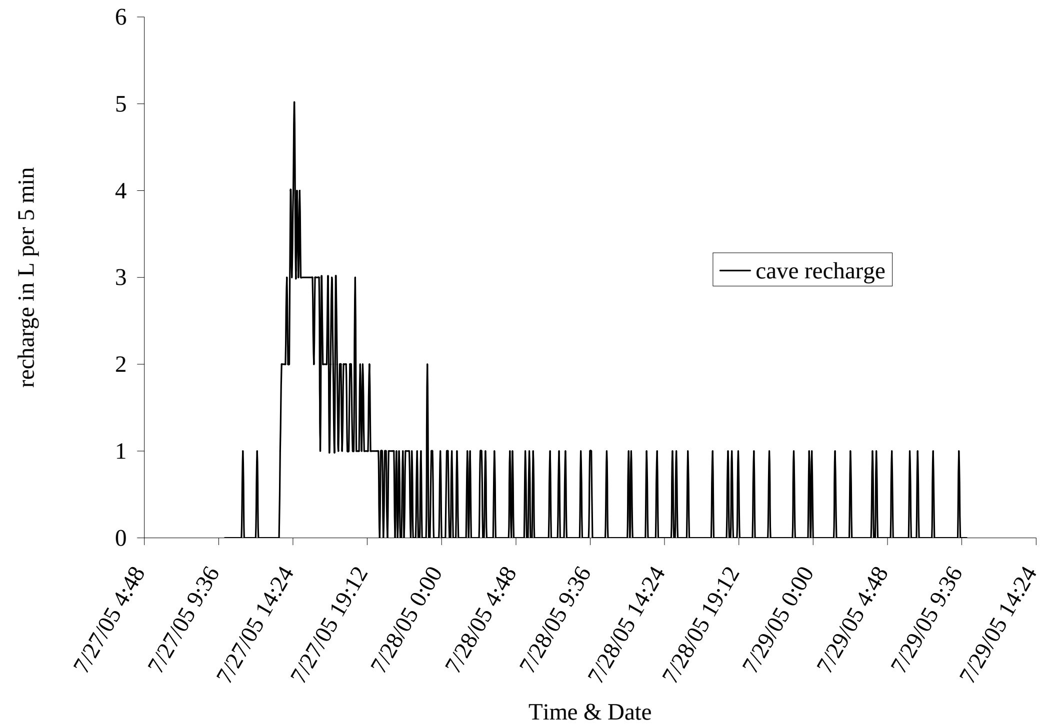


Figure 3. Hydrograph showing recharge response in L per 5 minutes to a soaker hose irrigation at Headquarters Cave conducted July 27, 2005 on the southern two-thirds of the cave footprint

## Natural Rainfall

Monitoring of cave recharge and natural precipitation began at Headquarters Cave on November 5, 2004 and has continued from that date forward. Not all drip collectors have been working at all times for various reasons, but these cases have been documented and can be seen in Figure 4. Monitoring at Bunny Hole began on July 15, 2004 and at several points since monitoring began, some or all of the tipping buckets were jammed or not recording (Figure 5). These instances have been documented and have been accounted for in water budgets. Natural rainfall data was not available to us until October 2004, so water budgets at Bunny Hole begin at that point.

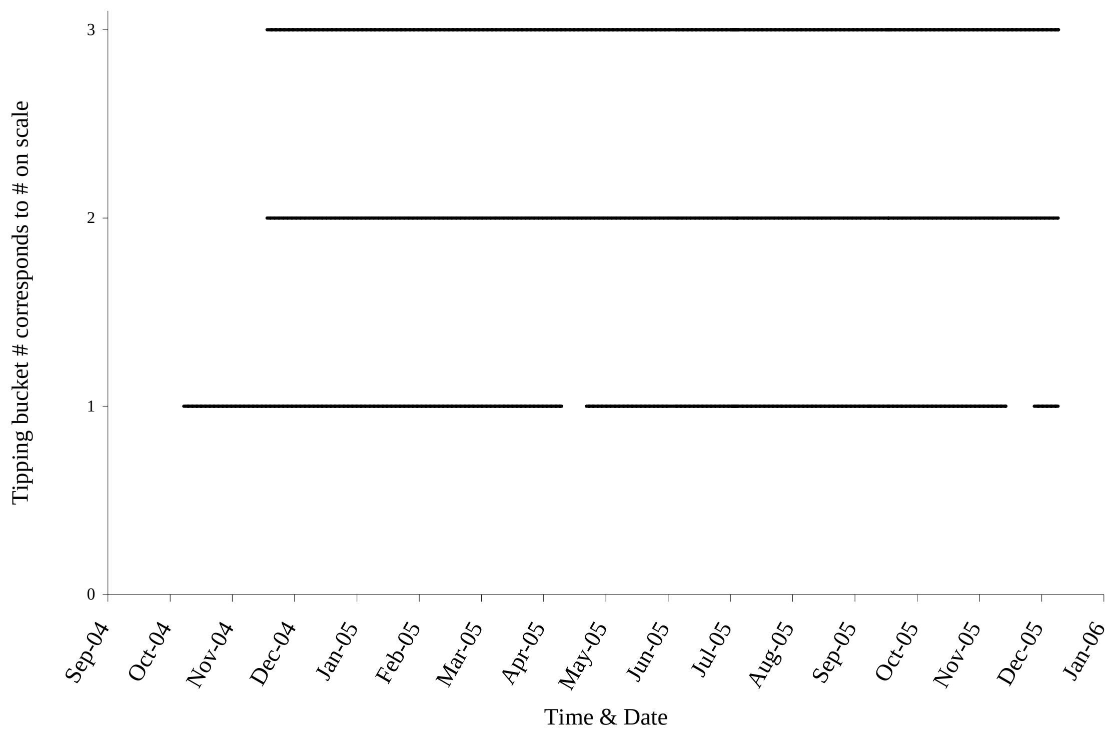


Figure 4. Bar chart showing cave tipping bucket operation periods at Headquarters Cave

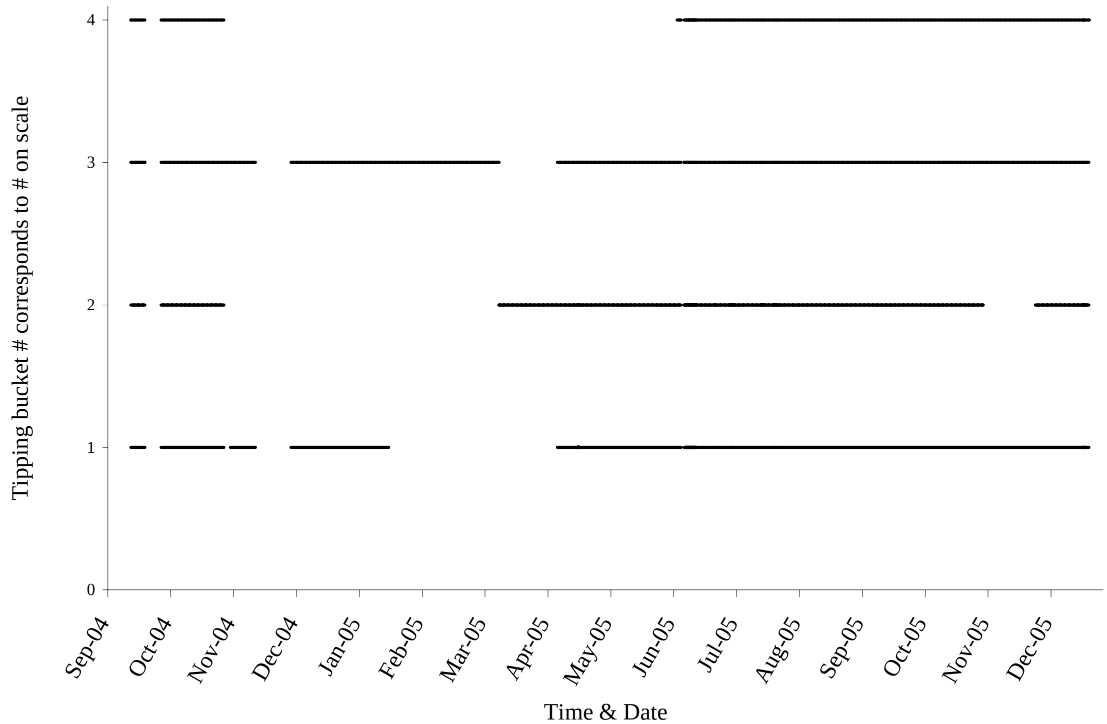


Figure 5. Bar chart showing cave tipping bucket operation periods at Bunny Hole

A numerical representation of operational periods shown in Figures 4 and 5 is given in Table I for Headquarters Cave and Bunny Hole. The table shows what percentage of time during the respective monitoring period that each individual bucket was working and the percentage of data collected that each bucket was responsible for. In addition, total L of recharge collected by each bucket are presented along with the corresponding percentage of total recharge collected.

Table I. Individual tipping bucket operation and collection percentages

**Headquarters Cave**

| **November 2004 thru December 2005** | **Bucket #1** | **Bucket #2** | **Bucket #3** |
|---|---|---|---|
| % of time bucket was operational | 93.94 | 90.53 | 90.53 |
| total L collected by each tipping bucket | 86420 | 2175 | 1358 |
| % of total L collected by each tipping bucket | 96.07 | 2.42 | 1.51 |

**Bunny Hole**

| **October 2004 thru December 2005** | **Bucket #1** | **Bucket #2** | **Bucket #3** | **Bucket #4** |
|---|---|---|---|---|
| % of time bucket was operational | 76.77 | 65.03 | 88.59 | 52.31 |
| total L collected by each tipping bucket | 6647.40 | 2026.50 | 15093.50 | 134.80 |
| % of total L collected by each tipping bucket | 27.81 | 8.48 | 63.15 | 0.56 |

*Natural Events at Headquarters Cave*

Data collection began at Headquarters Cave on November 5, 2004 and the cave was already receiving water from earlier rainfall events. For purposes of calculating a percentage of rainfall that recharged the cave, we are using the cave footprint area of 303 $m^2$ to multiply depth of rainfall to get volume and divide the volume of cave recharge to get depth. Only tipping bucket #1 recorded data during the month; however the cave still received 62,591 L of recharge from this one drip. Precipitation occurred in five significant events over the course of the month equaling 323.3 mm. Based on volume of water that fell on the cave footprint, cave recharge totaled 63.89% of monthly precipitation. Figure 6 illustrates the cave's response to the rainfall event and how the drips progress after the event has ceased. Prior to the spike in recharge on November 17$^{th}$, recharge was entering the cave at approximately 2 L/hr as recorded by tipping bucket #1. Cave recharge began to increase about 3 hours after rainfall began and the recession limb of the hydrograph never returned to pre-rainfall levels due to the ensuing event that took place on November 22nd.

The cave began receiving increased amounts of recharge from this event less than two hours after the beginning of intense rainfall. The following day, November 23rd, another rainfall event took place producing 30mm of rainfall in one hour. The recession limb of the hydrograph for this event declined in an exponential fashion for the remainder of November and into December before reaching hourly recharge rate similar to those before the November rainfall events on December 24th.

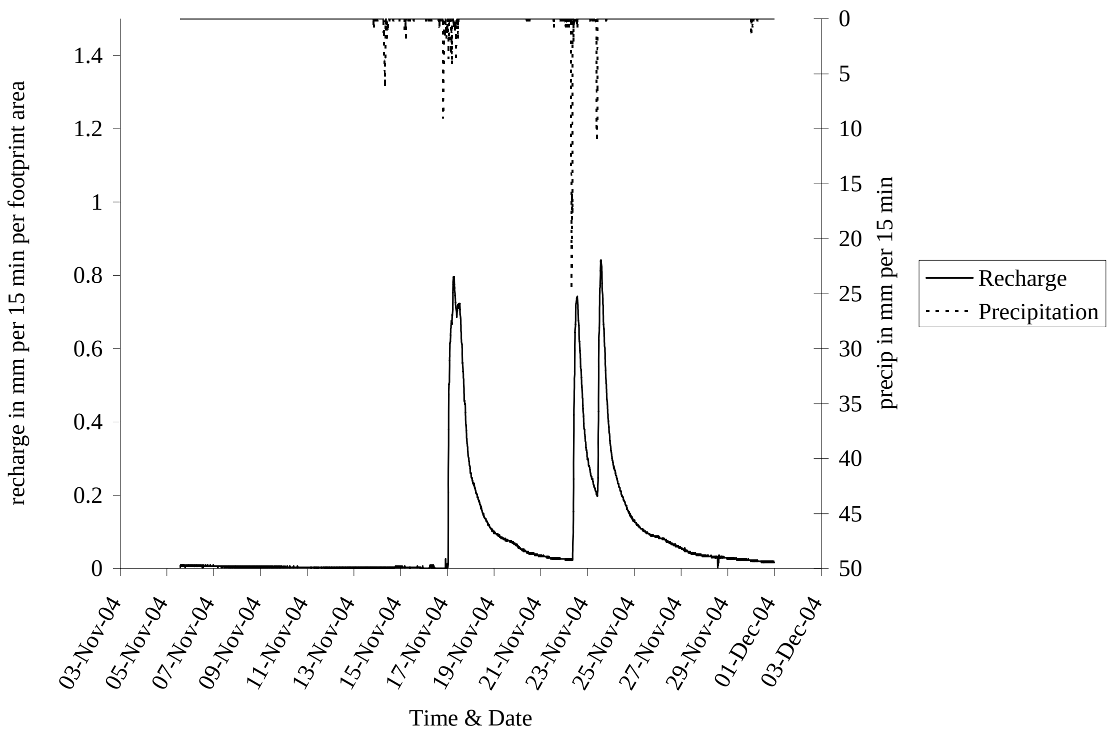


Figure 6. Hydrograph of November 2004 displaying cave recharge in relation to precipitation at Headquarters Cave

December 2004 was a much drier month than November was yielding only 10.7 mm of rainfall. Only one tipping bucket was operational through December 15th, when the remaining two buckets were fixed and began recording. Measured cave recharge for December added up to 4,688 L while only 3,233 L of rainfall occurred over the cave footprint. This causes recharge to equal 145% of the total rainfall applied to the plot. Continued drip response to the rainfall events taking place the end of November 2004 can be attributed for this seemingly extra recharge. December 2004's hydrograph can be seen in Appendix A along with all other monthly hydrographs from Headquarters Cave.

Overall, 2005 was a relatively dry year with only a handful of significant rainfall events producing large recharge volumes. Yearly average precipitation for the San Antonio area is about 738 mm; in 2005 only 483.9 mm were recorded at our research sites. The water budget for Headquarters Cave for the entire year presents total rainfall in mm and L over the cave footprint and cave recharge in L, mm over the footprint area, and as a percentage of total yearly rainfall. Cave recharge for the year totaled 22,675 L or 15.05% of the 483.9 mm or 150,227 L of rainfall that fell over the cave footprint (see Figure 4 for tipping bucket failures). During this time, 93% of the drips were collected based on the amount of tipping bucket down time for the year. In comparison to November 2004, this is less than one third of the recharge that was received during that month. Appendix B shows the yearly hydrograph and water balance for 2005 and the complete hydrograph from November 2004 to December 2005 at Headquarters Cave.

Monthly hydrographs and water budgets can be seen in Appendix A; greater detail is revealed here than in the yearly plot. This allows us to see responses to individual rainfall events more clearly and compare them with other like events and responses. Table II shows monthly partitions of the water budget for 2005 at Headquarters Cave. Each water budget shows how much rainfall occurred as a depth in mm and a representative volume in L over the cave footprint during the month and what the resulting cave recharge was in L, mm in depth over the cave footprint area, and as a percentage of the total rainfall for the month.

*Natural Events at Bunny Hole*

Monitoring of natural rainfall events began in late July 2004 at Bunny Hole; however, numerous malfunctions in the equipment caused gaps in the data that resulted in incomplete measurements. The Bunny Hole research site was instrumented with stemflow, throughfall, and precipitation measurement devices in addition to the cave monitoring equipment. The cave footprint area of 170 $m^2$ was used to calculate the volume of rainfall by multiplying the depth in mm by the area to get L and to convert the recorded cave recharge in L to a depth of recharge over the plot area.

Table II. Water budget partitioned out on a monthly basis at Headquarters Cave for 2005

| | Liters | mm | Percent | | Liters | mm | Percent |
|---|---|---|---|---|---|---|---|
| **November-04** | | | | **December-04** | | | |
| precipitation | 97959.9 | 323.3 | 100.00 | precipitation | 3242.1 | 10.7 | 100.00 |
| cave recharge | 62591 | 206.6 | 63.89 | cave recharge | 4688 | 15.5 | 144.60 |
| | Liters | mm | Percent | | Liters | mm | Percent |
| **January-05** | | | | **February-05** | | | |
| precipitation | 19625.3 | 64.8 | 100.00 | precipitation | 23627.9 | 78.0 | 100.00 |
| cave recharge | 1532 | 5.1 | 7.81 | cave recharge | 4789 | 15.8 | 20.27 |
| **March-05** | | | | **April-05** | | | |
| precipitation | 14392.5 | 47.5 | 100.00 | precipitation | 2462.8 | 8.1 | 100.00 |
| cave recharge | 10254 | 33.8 | 71.25 | cave recharge | 1881 | 6.2 | 76.38 |
| **May-05** | | | | **June-05** | | | |
| precipitation | 22934.1 | 75.7 | 100.00 | precipitation | 8393.1 | 27.7 | 100.00 |
| cave recharge | 705 | 2.3 | 3.07 | cave recharge | 1043 | 3.4 | 12.43 |
| **July-05** | | | | **August-05** | | | |
| precipitation | 20149.5 | 66.5 | 100.00 | precipitation | 13083.5 | 43.2 | 100.00 |
| cave recharge | 915 | 3.0 | 4.54 | cave recharge | 892 | 2.9 | 6.82 |
| **September-05** | | | | **October-05** | | | |
| precipitation | 11695.8 | 38.6 | 100.00 | precipitation | 8696.1 | 28.7 | 100.00 |
| cave recharge | 333 | 1.1 | 2.85 | cave recharge | 161 | 0.5 | 1.85 |
| **November-05** | | | | **December-05** | | | |
| precipitation | 4617.7 | 15.2 | 100.00 | precipitation | 539.3 | 1.8 | 100.00 |
| cave recharge | 71 | 0.2 | 1.54 | cave recharge | 99 | 0.3 | 18.36 |

Tipping buckets worked 91.7% of the time during this period. Down times occurred in Nov ’04, Dec ’04, May ‘05, June ‘05, July ‘05, and Dec ‘05.

November 2004 yielded good data from inside the cave and from the rain gauge but throughfall and stemflow collectors failed to work properly. The monthly total for rainfall over the cave footprint was 323.3 mm; of this, 10,299.6 L of recharge were recorded. When all drip collectors are working, 60% of drips are collected inside Bunny Hole; however, during November 2004 the drip collectors only recorded data for 67% of the month. Some of these data are not correct because the buckets were found to be rusted in place during the monthly maintenance trip on the 14th. Therefore we estimate that actual recharge was much higher than the estimated 17,166 L. The hydrograph in Figure 7 shows the rapid response of the cave to recharge and the rapid decline in the falling limb of the recession curve. The first response seen in the cave occurs on November 14th when tipping bucket #3 begins collecting data 30 minutes after the onset of rainfall; approximately 8 mm of rainfall had occurred at this point. After rainfall has stopped, the hydrograph quickly declines from a maximum of 11 L per 15 minutes to 1 L per 15 minutes within 4 hours. On November 16th, an event producing 65.3 mm of rainfall in 16.5 hours occurred and resulted in a maximum recharge rate of 252 L per 15 minutes. The initial response inside the cave occurred about 30 minutes after the beginning of rainfall and peaked 30 minutes later. The falling limb of the hydrograph began its decent at this point and returned to pre-event levels about 34 hours after the beginning of the response.

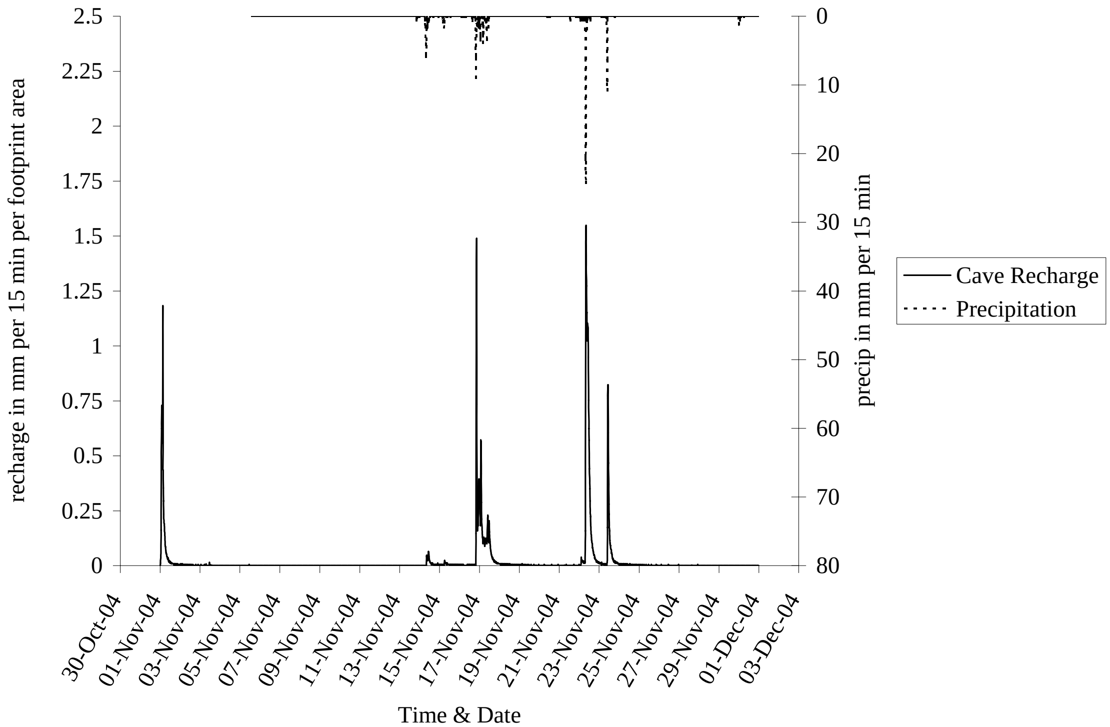


Figure 7. Hydrograph of November 2004 displaying cave recharge in relation to precipitation at Bunny Hole

Equipment malfunctions of various types were experienced and were mostly corrected in March 2005; however, problems with the tipping buckets were not completely resolved until June 18, 2005 (Figure 5) and intermittent problems with the throughfall and stemflow collectors have occasionally occurred. During March 2005 all data recording systems worked properly. That month, 47.2 mm of rainfall fell on the footprint of the cave totaling 8,024 L. Recharge into the cave accounted for 486.7 L or 6.07% of this total. The automatic throughfall device measured 23.6 mm or 50% of precipitation while the stemflow collars only captured 0.01 mm of stemflow. Based on these numbers, interception for the month was estimated to be 49.97%. Figures 8 and 9 graphically show the data for precipitation, throughfall, stemflow, and cave recharge from March 2005. Hydrographs for all months that data were available comparing precipitation to cave recharge and throughfall to stemflow for the Bunny Hole site can be seen in Appendix C and D respectively. Throughout the year, the Bunny Hole site exhibited variability in all of the water budget components measured. Monthly totals of cave recharge ranged from 0.06% up to 10.11% while throughfall measured extended from 5.91% up to 85.8%. Stemflow and interception also varied as well with ranges from 0% to 1.33% and 13.53% to 93.54% respectively. Monthly water budgets that detail each component mentioned above can be seen in Table III.

Table III. Bunny Hole water budget partitioned on a monthly basis for 2005

| | Liters | mm | Percent | | Liters | mm | Percent |
|---|---|---|---|---|---|---|---|
| **October-04** | | | | **November-04** | | | |
| precipitation | 16065.0 | 94.5 | 100.0 | precipitation | 54961.0 | 323.3 | 100.0 |
| stemflow Oak | 11.3 | 0.1 | 0.1 | stemflow Oak | 34.0 | 0.2 | 0.1 |
| stemflow Juniper | 14.5 | 0.1 | 0.1 | stemflow Juniper | 43.5 | 0.3 | 0.1 |
| stemflow total | 25.8 | 0.2 | 0.2 | stemflow total | 77.4 | 0.5 | 0.1 |
| throughfall | 5967.0 | 35.1 | 37.1 | throughfall | 1698.3 | 10.0 | 3.1 |
| cave recharge | 8187.5 | 48.2 | 51.0 | cave recharge | 14419.4 | 84.8 | 26.2 |
| [a] interception | 10072.2 | 59.2 | 62.7 | [a] interception | 53185.3 | 312.9 | 96.8 |
| **December-04** | | | | **January-05** | | | |
| precipitation | 1037.0 | 6.1 | 100.0 | precipitation | 11475.0 | 67.5 | 100.0 |
| stemflow Oak | 0.0 | 0.0 | 0.0 | stemflow Oak | | | |
| stemflow Juniper | 0.0 | 0.0 | 0.0 | stemflow Juniper | | | |
| stemflow total | 0.0 | 0.0 | 0.0 | stemflow total | | | |
| throughfall | 25.5 | 0.2 | 2.5 | throughfall | | | |
| cave recharge | 0.0 | 0.0 | 0.0 | cave recharge | 56.7 | 0.3 | 0.5 |
| [a] interception | 1011.5 | 6.0 | 97.5 | [a] interception | | | |
| **February-05** | | | | **March-05** | | | |
| precipitation | 13600.0 | 80.0 | 100.0 | precipitation | 8024.0 | 47.2 | 100.0 |
| stemflow Oak | 34.0 | 0.2 | 0.2 | stemflow Oak | 11.3 | 0.1 | 0.1 |
| stemflow Juniper | 58.0 | 0.3 | 0.4 | stemflow Juniper | 14.5 | 0.1 | 0.2 |
| stemflow total | 91.9 | 0.5 | 0.7 | stemflow total | 25.8 | 0.2 | 0.3 |
| throughfall | 3070.2 | 18.1 | 22.6 | throughfall | 4012.0 | 23.6 | 50.0 |
| cave recharge | 245.0 | 1.4 | 1.8 | cave recharge | 408.8 | 2.4 | 5.1 |
| [a] interception | 10520.9 | 61.9 | 77.4 | [a] interception | 4009.6 | 23.6 | 50.0 |
| **April-05** | | | | **May-05** | | | |
| precipitation | 1467.1 | 8.6 | 100.0 | precipitation | 17782.0 | 104.6 | 100.0 |
| stemflow Oak | 0.0 | 0.0 | 0.0 | stemflow Oak | 316.9 | 1.9 | 1.8 |
| stemflow Juniper | 0.0 | 0.0 | 0.0 | stemflow Juniper | 376.8 | 2.2 | 2.1 |
| stemflow total | 0.0 | 0.0 | 0.0 | stemflow total | 693.7 | 4.1 | 3.9 |
| throughfall | 574.6 | 3.4 | 39.2 | throughfall | 14246.0 | 83.8 | 80.1 |
| cave recharge | 0.0 | 0.0 | 0.0 | cave recharge | 45.5 | 0.3 | 0.3 |
| [a] interception | 892.5 | 5.3 | 60.8 | [a] interception | 3470.4 | 6.3 | 19.5 |
| **June-05** | | | | **July-05** | | | |
| precipitation | 4709.0 | 27.7 | 100.0 | precipitation | 9673.0 | 56.9 | 100.0 |
| stemflow Oak | 135.8 | 0.8 | 2.9 | stemflow Oak | 90.6 | 0.5 | 0.9 |
| stemflow Juniper | 188.4 | 1.1 | 4.0 | stemflow Juniper | 101.4 | 0.6 | 1.0 |
| stemflow total | 324.2 | 1.9 | 6.9 | stemflow total | 192.0 | 1.1 | 2.0 |
| throughfall | | | | throughfall | 1532.2 | 9.0 | 15.8 |
| cave recharge | 199.5 | 1.2 | 4.2 | cave recharge | 554.7 | 3.3 | 5.7 |
| [a] interception | | | | [a] interception | 8131.8 | 14.7 | 84.1 |

Table III. (Continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **August-05** | | | | **September-05** | | | |
| precipitation | 8891.0 | 52.3 | 100.0 | precipitation | 7684.0 | 45.2 | 100.0 |
| stemflow Oak | 362.2 | 2.1 | 4.1 | stemflow Oak | 249.0 | 1.5 | 3.2 |
| stemflow Juniper | 318.8 | 1.9 | 3.6 | stemflow Juniper | 188.4 | 1.1 | 2.5 |
| stemflow total | 681.0 | 4.0 | 7.7 | stemflow total | 437.4 | 2.6 | 5.7 |
| throughfall | 4817.8 | 28.3 | 54.2 | throughfall | 4267.0 | 25.1 | 55.5 |
| cave recharge | 898.5 | 5.3 | 10.1 | cave recharge | 26.0 | 0.2 | 0.3 |
| [a] interception | 4008.8 | 23.6 | 45.1 | [a] interception | 3375.7 | 6.1 | 43.9 |
| **October-05** | | | | **November-05** | | | |
| precipitation | 8117.5 | 47.8 | 100.0 | precipitation | 2806.7 | 16.5 | 100.0 |
| stemflow Oak | 90.6 | 0.5 | 1.1 | stemflow Oak | 11.3 | 0.1 | 0.4 |
| stemflow Juniper | 246.4 | 1.4 | 3.0 | stemflow Juniper | 29.0 | 0.2 | 1.0 |
| stemflow total | 336.9 | 2.0 | 4.2 | stemflow total | 40.3 | 0.2 | 1.4 |
| throughfall | 6964.9 | 41.0 | 85.8 | throughfall | 1247.8 | 7.3 | 44.5 |
| cave recharge | 5.2 | 0.0 | 0.1 | cave recharge | 4.3 | 0.0 | 0.2 |
| [a] interception | 1098.5 | 2.0 | 13.5 | [a] interception | 1521.7 | 9.0 | 54.2 |
| **December-05** | | | | | | | |
| precipitation | 431.8 | 2.5 | 100.0 | | | | |
| stemflow Oak | 11.3 | 0.1 | 2.6 | | | | |
| stemflow Juniper | 14.5 | 0.1 | 3.4 | | | | |
| stemflow total | 25.8 | 0.2 | 6.0 | | | | |
| throughfall | 25.5 | 0.2 | 5.9 | | | | |
| cave recharge | 0.7 | 0.0 | 0.2 | | | | |
| [a] interception | 403.9 | 2.4 | 93.5 | | | | |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation
blank spaces in the water budget indicate that the data collection device did not work
throughfall did not work properly during Jan., Feb., Mar., June, and July
stemflow did not work properly during Jan.
not all cave recharge tipping buckets were working until June 18, 2005

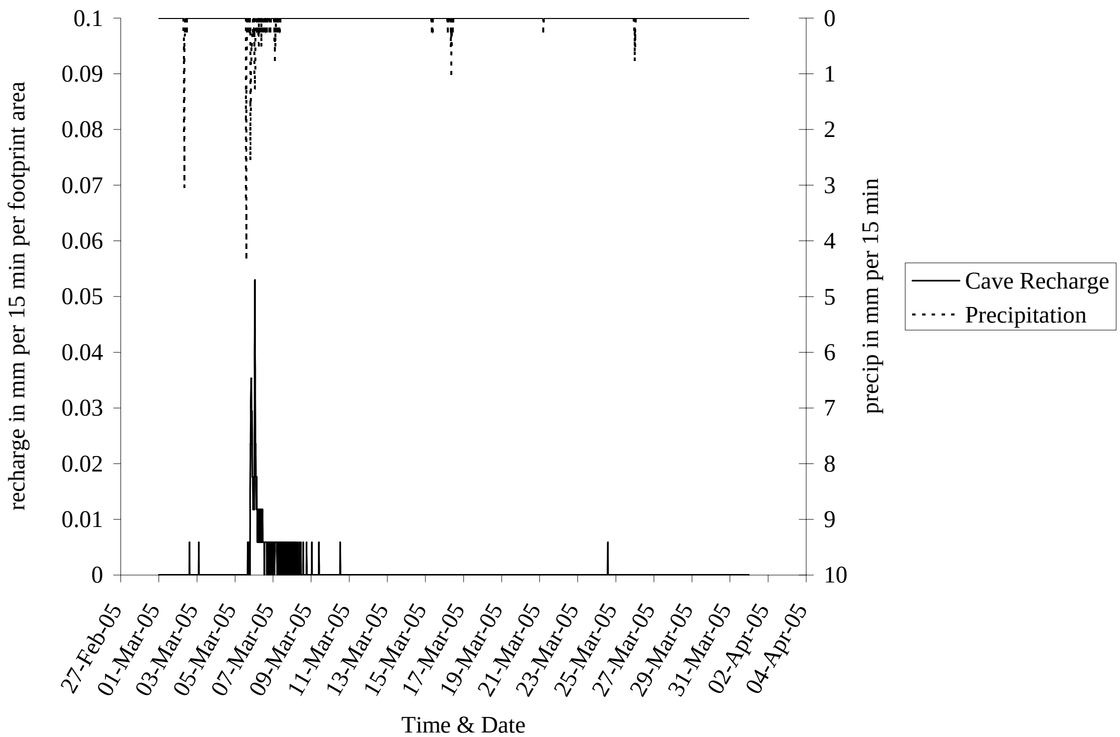


Figure 8. Hydrograph showing precipitation and cave recharge at Bunny Hole for March 2005

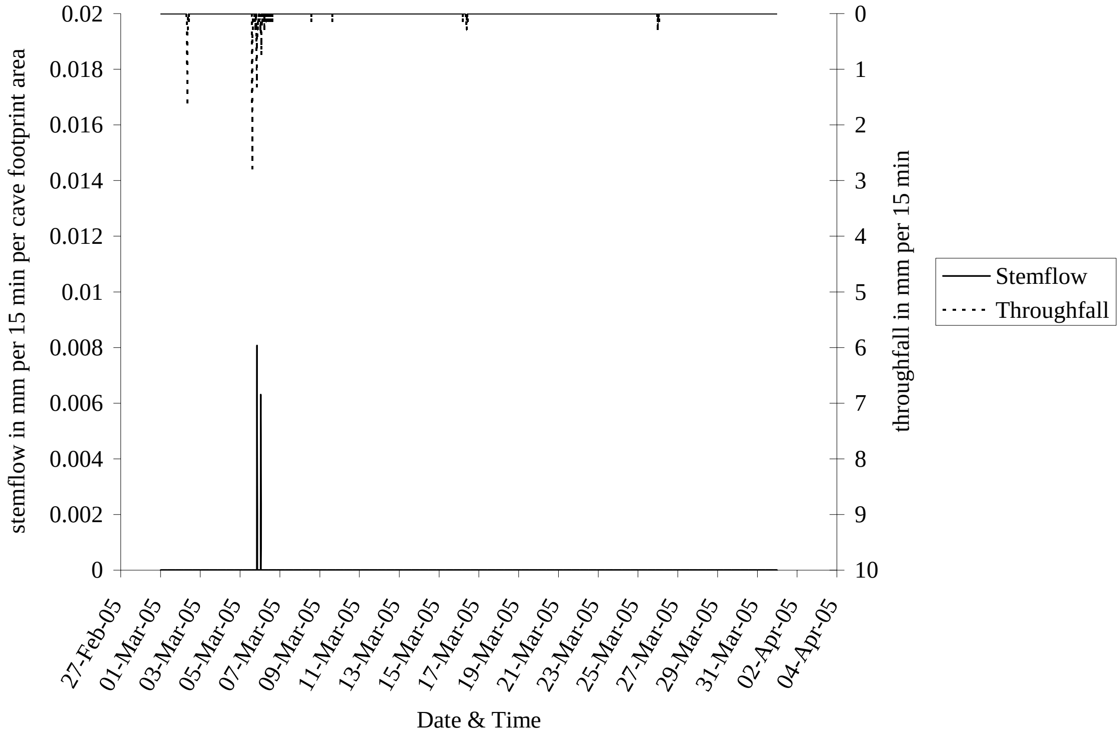


Figure 9. Hydrograph showing stemflow and throughfall at Bunny Hole for March 2005

When comparing November 2004 to the entire year of 2005, an enormous difference can be seen in cave recharge. Approximately four times as much recharge was received during November 2004 as was recorded in all of 2005. Appendix D shows both the yearly water balance and yearly hydrograph for Bunny Hole. This shows that the cave has the ability to accept huge volumes of recharge but does not always exhibit this trait. A possible influential factor could be the thickness of the overburden above the caves and how fractures and bedding planes have been enlarged over time. Other factors could be the intensity and duration of rainfall; was it enough to produce surface runoff? What role does the vegetation play in recharge processes and how did affect observations in the cave?

*Comparison of Natural Events at both Caves*

November 2004 yields a good data set to compare cave responses to natural rainfall events. Due to the extended recession limb of the Headquarters Cave hydrograph and the close proximity of rainfall events to each other, the events could not be looked at individually. What this data illustrated well is the rapid response to rainfall in both caves and the differences in hydrograph recession limbs.

Three events occurred at both cave locations in which we were able to obtain data showing responses to the individual event inside the cave. The first event occurred May 8, 2005 and lasted for approximately three hours. At Headquarters Cave, 31 mm of rain fell while 31.2 mm fell at Bunny Hole. Since May was a dry month, Headquarters Cave and Bunny Hole only received 21 L and 50.8 L of recharge respectively. Three weeks later on June 1, 2005 the second rainfall event occurred producing 24.1 mm at Headquarters Cave and 27.7 mm at Bunny Hole; subsequently, they received 448 L and 237.5 L of recharge. The third event took place on August 10, 2005 yielding 37.8 and 49.5 mm of precipitation at Headquarters Cave and Bunny Hole. Recharge that resulted at the caves from this event was 385 L and 1068.5 L respectively. These data are presented in Table IV.

Table IV. Comparison of individual rainfall events at Headquarters Cave and Bunny Hole

| Headquarters Cave | | | | Bunny Hole | | | |
|---|---|---|---|---|---|---|---|
| | Liters | mm | Percent | | Liters | mm | Percent |
| **5/8/05** | | | | **5/8/05** | | | |
| precipitation | 9386.9 | 31.0 | 100.00 | precipitation | 5304 | 31.2 | 100.00 |
| cave recharge | 21 | 0.1 | 0.22 | cave recharge | 50.8 | 0.1 | 0.29 |
| **6/1/05** | | | | **6/1/05** | | | |
| precipitation | 7311.4 | 24.1 | 100.00 | precipitation | 4709 | 27.7 | 100.00 |
| cave recharge | 448 | 1.5 | 6.13 | cave recharge | 237.5 | 0.4 | 1.55 |
| **8/10/05** | | | | **8/10/05** | | | |
| precipitation | 11465.5 | 37.8 | 100.00 | precipitation | 8420.1 | 49.5 | 100.00 |
| cave recharge | 385 | 1.3 | 3.36 | cave recharge | 1068.5 | 3.29 | 12.69 |

## Rainfall Simulations

The rainfall simulator was set up at Bunny Hole on August 24, 2004 and the initial run commenced the following day. Evaluation of data from the soaker hose test on July 21 and 22, 2004 helped us in determining the exact location that the rainfall simulator should be installed; Figure 10 shows the approximate location of the masts situated above the cave and the approximate area that the rainfall simulator applies water to. A total of seven simulations have been conducted with use of the rainfall simulator applying water above the canopy.

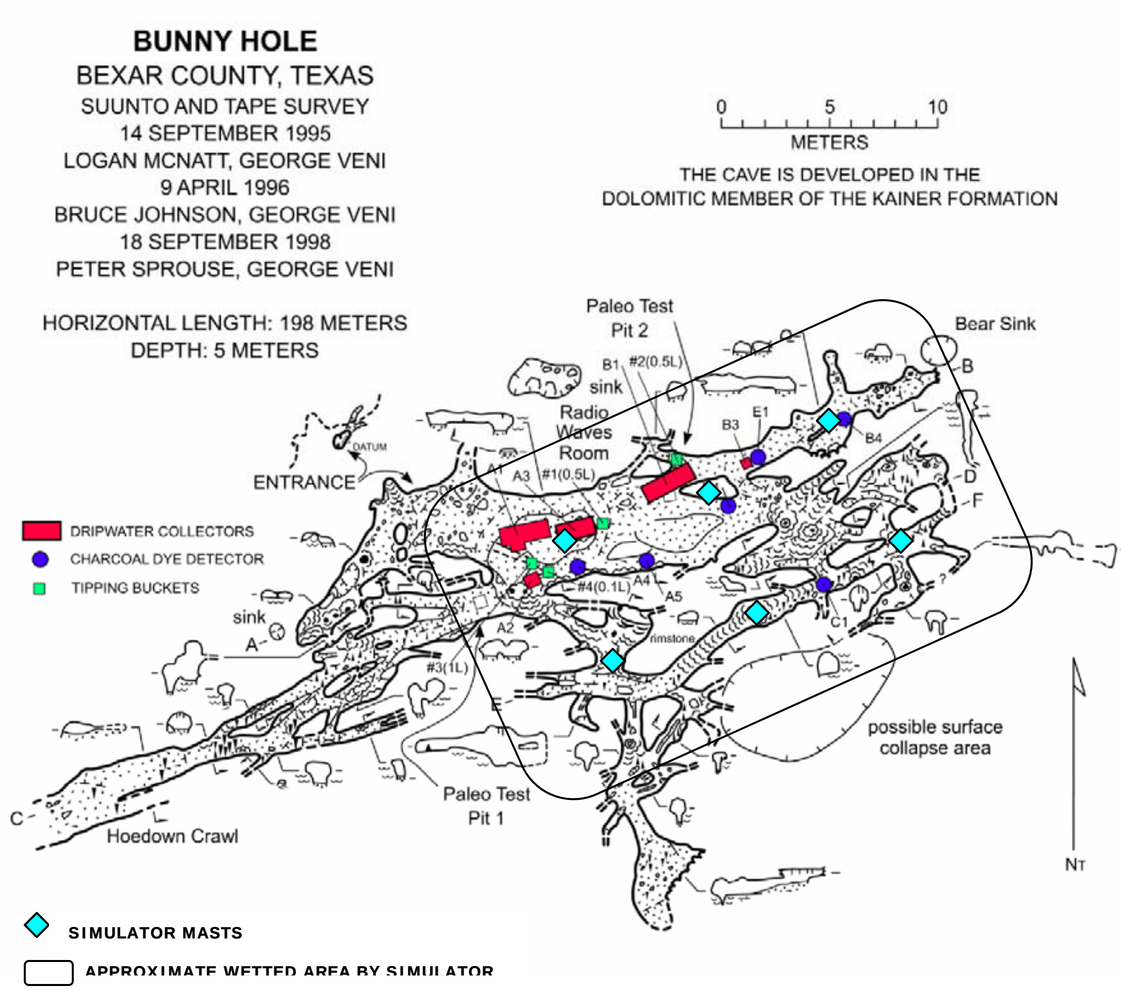


Figure 10. Map of Bunny Hole adapted from Veni G, and Associates to show rainfall simulator mast locations and the approximate area wetted by the rainfall simulator

*Initial Simulations*

The rainfall event produced on August 25, 2004 was mainly used to determine if the equipment was functioning properly; most of it was, but we did have some minor problems. Elapsed time from the start of the simulation to the end was 66 minutes, but water was only applied for 37 minutes. Artificial rainfall was applied at a rate of 57.2

mm/hr during this event; but due to the short duration of the simulation, no surface runoff was generated. Stemflow measurement devices failed to record any data during this simulation; therefore we do not know how much water comprised stemflow. Automatic throughfall also malfunctioned, but manual throughfall was collected. Table V shows the water budget for this simulation.

Table V. August 25, 2004 rainfall simulation water budget

| **Simulation Total** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 14744.2 | 35.3 | 100.0 |
| Stemflow | | | |
| Automatic Throughfall | | | |
| Manual Throughfall | 10909.8 | 26.1 | 74.5 |
| [a] Water Reaching Surface | 10909.8 | 26.1 | 74.5 |
| Surface Runoff | | | |
| Cave Recharge | 958.3 | 1.7 | 6.5 |
| Canopy Interception | 3834.4 | 9.2 | 25.5 |
| Storage/Subsurface Flow/ET | 9951.5 | 24.4 | 68.0 |

[a] Water reaching surface is manual throughfall plus stemflow

July 6, 2005 was the date of the next rainfall simulation. This event spanned 136 minutes and was held at a continuous rainfall rate of 22.2 mm/hr for the duration of the event. All data collection systems functioned properly during this event. Data are presented below in Figure 11 and Table VI.

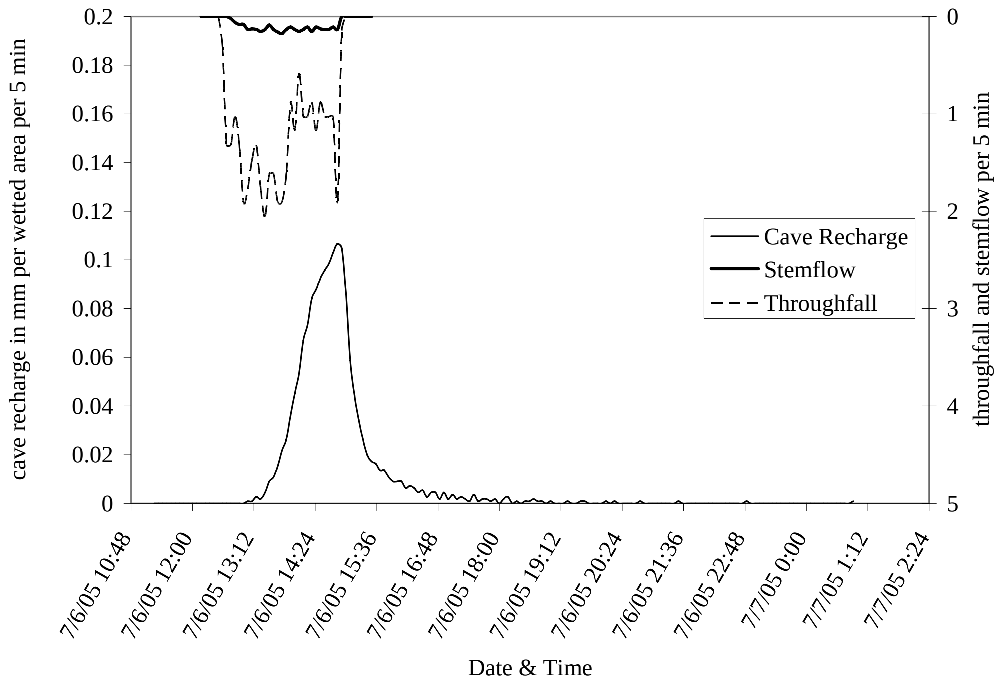


Figure 11. Hydrograph from July 6, 2005 simulation showing throughfall and stemflow on the top axis and cave recharge on the bottom axis in mm per wetted area in 5 minute intervals

Table VI. July 6, 2005 rainfall simulation water budget

| **Simulation Total** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 27853.1 | 50.4 | 100.0 |
| Stemflow Oak | 1199.9 | 2.2 | 4.3 |
| Stemflow Juniper | 550.7 | 1.0 | 2.0 |
| Stemflow Total | 1750.0 | 3.2 | 6.3 |
| Automatic Throughfall | 20452.5 | 37.0 | 72.9 |
| Manual Throughfall | 19568.1 | 35.4 | 74.5 |
| [a] Water Reaching Surface | 21318.1 | 38.6 | 80.8 |
| Surface Runoff | 0.0 | 0.0 | 0.0 |
| Cave Recharge | 1474.2 | 2.7 | 5.3 |
| Canopy Interception | 6535.0 | 11.8 | 19.2 |
| Storage/Subsurface Flow | 19843.9 | 35.9 | 75.5 |

[a] Water reaching surface is manual throughfall plus stemflow

*Standard Simulations*

On July 13 and 14, 2005 paired simulations were conducted on consecutive days in an effort to illustrate the effects of moisture content on the vadose zone above Bunny Hole. Soils and fractured rock were allowed to drain for one week after the July 6, 2005 simulation and no measurable rainfall occurred during this time. Application was done in three intervals varying in length and intensity for each run. The theory behind this approach is to create several different intensities and durations of rainfall that will produce varying results in stemflow, throughfall, surface runoff, and recharge.

Conditions at the site prior to water application on July 13, 2005 were relatively dry. Run 1 of the July 13 simulation applied water at a rate of 20.8 mm per hour and lasted 1 hour. Run 2 spanned 2 hours and applied artificial rainfall at 5.7 mm per hour while Run 3 lasted 45 minutes and applied water at a rate of 27.25 mm per hour. Table VII depicts the water budget for each run and the total rainfall simulation while Figure 12 shows the event hydrograph.

A nearly identical simulation was conducted the following day, July 14 2005. A total of 18 hours elapsed from the end of the first simulation to the beginning of this simulation. Run 1 of this simulation applied 21.2 mm of rainfall during one hour. Run 2 of the simulation applied 11.3 mm of water at a rate of 5.65 mm per hour and extended for 2 hours. Run 3 lasted 45 minutes and applied 21.6 mm of rainfall at a rate of 28.8 mm per hour. Wet conditions created by the rainfall simulation the day before allowed much more water to make it to the ground and become surface runoff or recharge as a result. A detailed water balance for each individual run and the entire simulation can be seen in Table VIII and the hydrograph in Figure 13 shows responses to the event.

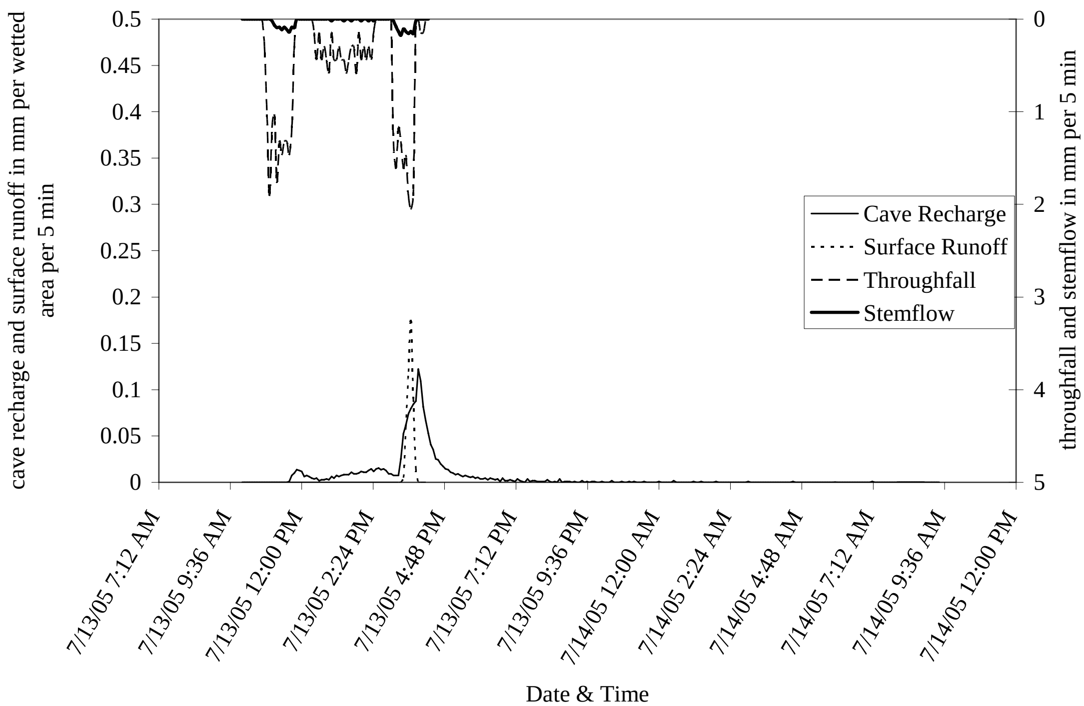


Figure 12. Hydrograph from July 13, 2005 simulation showing throughfall and stemflow on the top axis and surface runoff and cave recharge on the bottom axis in mm per wetted area in 5 minute intervals

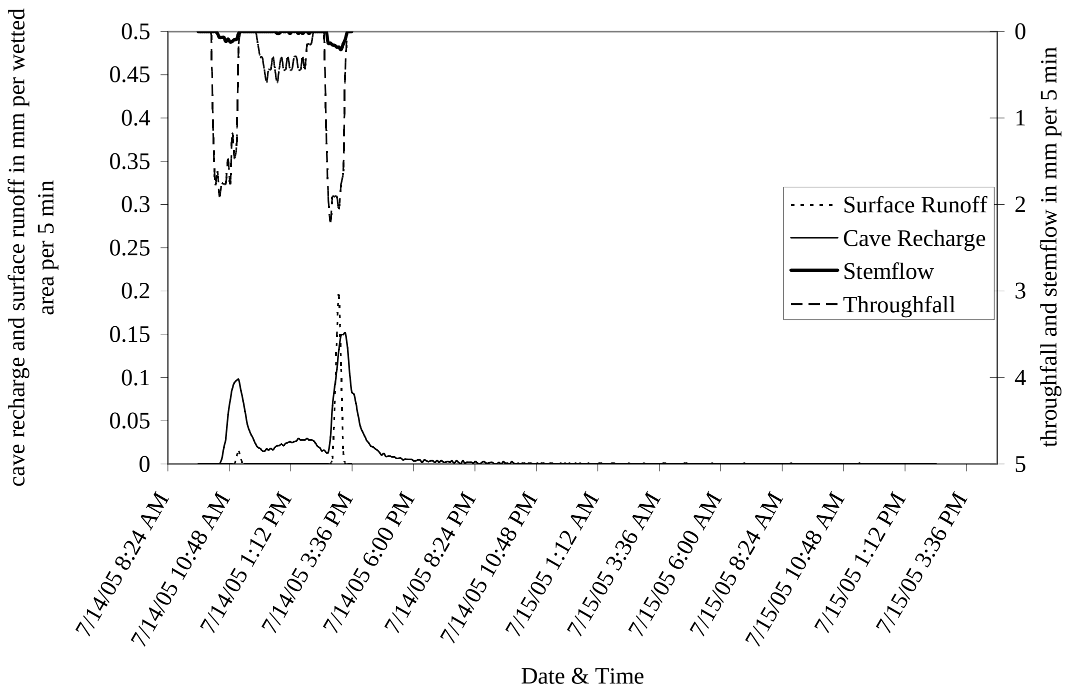


Figure 13. Hydrograph from July 14, 2005 simulation showing throughfall and stemflow on the top axis and surface runoff and cave recharge on the bottom axis in mm per wetted area in 5 minute intervals

Table VII. July 13, 2005 standard simulation water budgets

| **Run 1** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 11500.1 | 20.8 | 100.0 |
| Stemflow Total | 500.4 | 0.9 | 4.4 |
| Automatic Throughfall | 6818.2 | 12.3 | 59.3 |
| Manual Throughfall | 9010.2 | 16.3 | 78.4 |
| [a] Water Reaching Surface | 9510.6 | 17.2 | 82.8 |
| Surface Runoff | 0.0 | 0.0 | 0.0 |
| Cave Recharge | 77.5 | 0.1 | 0.7 |
| Canopy Interception | 1989.5 | 3.6 | 17.2 |
| Storage/Subsurface Flow | 9433.1 | 17.1 | 82.1 |
| **Run 2** | Liters | mm | Percent |
| Water Applied | 6298.9 | 11.4 | 100.0 |
| Stemflow Total | 67.9 | 0.1 | 1.1 |
| Automatic Throughfall | 5032.5 | 9.1 | 79.9 |
| Manual Throughfall | 3648.3 | 6.6 | 57.9 |
| [a] Water Reaching Surface | 3716.2 | 6.7 | 59.0 |
| Surface Runoff | 0.0 | 0.0 | 0.0 |
| Cave Recharge | 272.5 | 0.5 | 4.3 |
| Canopy Interception | 2582.7 | 4.7 | 41.0 |
| Storage/Subsurface Flow | 3443.7 | 6.2 | 54.7 |
| **Run 3** | Liters | mm | Percent |
| Water Applied | 12037.6 | 21.8 | 100.0 |
| Stemflow Total | 618.5 | 1.1 | 5.1 |
| Automatic Throughfall | 8116.9 | 14.7 | 67.4 |
| Manual Throughfall | 9562.9 | 17.3 | 79.4 |
| [a] Water Reaching Surface | 10181.4 | 18.4 | 84.5 |
| Surface Runoff | 570.4 | 1.0 | 4.7 |
| Cave Recharge | 1168.2 | 2.1 | 9.7 |
| Canopy Interception | 1856.2 | 3.4 | 15.5 |
| Storage/Subsurface Flow | 8442.8 | 15.3 | 70.1 |
| **Simulation Total** | Liters | mm | Percent |
| Water Applied | 29836.6 | 54.0 | 100.0 |
| Stemflow Oak | 781.0 | 1.4 | 2.6 |
| Stemflow Juniper | 405.8 | 0.7 | 1.4 |
| Stemflow Total | 1186.8 | 2.1 | 4.0 |
| Automatic Throughfall | 21753.2 | 39.4 | 72.9 |
| Manual Throughfall | 22221.4 | 40.2 | 74.5 |
| [a] Water Reaching Surface | 23408.2 | 42.3 | 78.5 |
| Surface Runoff | 570.4 | 1.0 | 1.9 |
| Cave Recharge | 1518.2 | 2.7 | 5.1 |
| Canopy Interception | 6428.4 | 11.7 | 21.5 |
| Storage/Subsurface Flow | 21319.6 | 38.6 | 71.5 |

[a] Water reaching surface is manual throughfall plus stemflow

Table VIII. July 14, 2005 standard simulation water budgets

| **Run 1** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 11719.6 | 21.2 | 100 |
| Stemflow | 474.5 | 0.9 | 4.1 |
| Automatic Throughfall | 10551.9 | 19.1 | 90 |
| Manual Throughfall | 10447.4 | 18.9 | 89.1 |
| [a] Water Reaching Surface | 10921.9 | 19.8 | 93.2 |
| Surface Runoff | 32.7 | 0.1 | 0.3 |
| Cave Recharge | 908.7 | 1.6 | 7.75 |
| Canopy Interception | 797.7 | 1.4 | 6.8 |
| Storage/Subsurface Flow | 9980.5 | 18.1 | 85.1 |
| **Run 2** | Liters | mm | Percent |
| Water Applied | 6249.7 | 11.3 | 100 |
| Stemflow | 67.9 | 0.1 | 1.1 |
| Automatic Throughfall | 5194.8 | 9.4 | 83.1 |
| Manual Throughfall | 3731.2 | 6.8 | 59.7 |
| [a] Water Reaching Surface | 3799.1 | 6.9 | 60.8 |
| Surface Runoff | 0 | 0 | 0 |
| Cave Recharge | 509.67 | 0.92 | 8.16 |
| Canopy Interception | 2450.6 | 4.4 | 39.2 |
| Storage/Subsurface Flow | 3289.43 | 5.98 | 52.64 |
| **Run 3** | Liters | mm | Percent |
| Water Applied | 11924 | 21.6 | 100 |
| Stemflow | 763.4 | 1.4 | 6.4 |
| Automatic Throughfall | 9334.4 | 16.9 | 78.3 |
| Manual Throughfall | 10093.6 | 18.3 | 84.7 |
| [a] Water Reaching Surface | 10857 | 19.7 | 91.1 |
| Surface Runoff | 602.1 | 1.1 | 5.1 |
| Cave Recharge | 1890.3 | 3.4 | 15.85 |
| Canopy Interception | 1067 | 1.9 | 8.9 |
| Storage/Subsurface Flow | 8364.6 | 15.2 | 70.1 |
| **Simulation Total** | Liters | mm | Percent |
| Water Applied | 29893.4 | 54.1 | 100 |
| Stemflow Oak | 769.7 | 1.4 | 2.6 |
| Stemflow Juniper | 536.2 | 1.0 | 1.8 |
| Stemflow Total | 1305.8 | 2.4 | 4.4 |
| Automatic Throughfall | 25081.1 | 45.4 | 83.9 |
| Manual Throughfall | 24321.9 | 44 | 81.4 |
| [a] Water Reaching Surface | 25627.7 | 46.4 | 85.8 |
| Surface Runoff | 634.8 | 1.1 | 2.1 |
| Cave Recharge | 3308.7 | 6.0 | 11.07 |
| Canopy Interception | 4265.7 | 7.7 | 14.2 |
| Storage/Subsurface Flow | 21684.2 | 39.3 | 72.6 |

[a] Water reaching surface is manual throughfall plus stemflow

A similar event was conducted two weeks later on July 28, 2005. Several natural rainfall events totaling 50 mm occurred during this two week period. Conditions prior to the rainfall simulation were wet due to an 11.2 mm event that occurred approximately 5 hours before the beginning of the simulation. This was not enough precipitation to cause recharge into the cave, but the soil and fractured rock appeared to be relatively wet and the tree canopy did retain some of the rainfall.

Run 1 of the event applied a depth of 21.3 mm of water over the plot area in 1 hour. Run 2 applied 8.6 mm of water at 4.3 mm per hours during a 2 hour time period. Run 3 lasted for 45 minutes and applied 18.1 mm of precipitation at a rate of 24.1 mm per hour. The detailed water balance can be seen below in Table IX and the hydrograph in Figure 14 visually represents these data.

Data from this simulation resulted in more water reaching the surface than was actually applied and negative values for canopy interception. When all simulations are averaged together, a more reasonable valuation for each component is indicated. Table X shows all three data sets from Tables VII, VIII, and IX averaged together with standard errors (S.E.) calculated in mm.

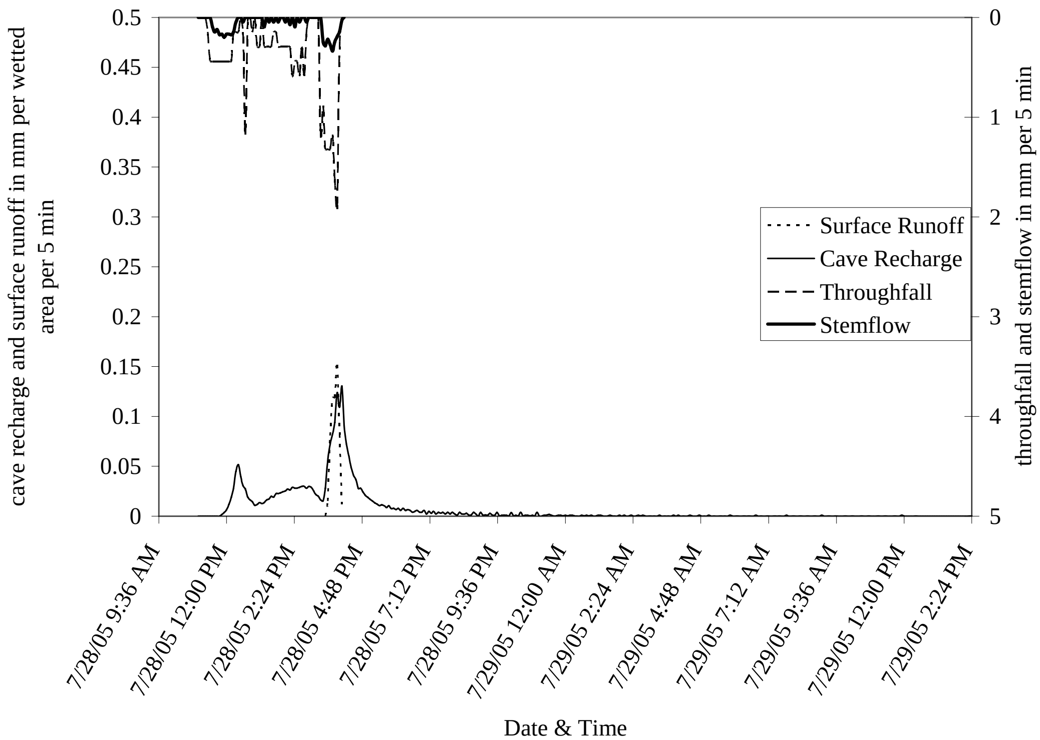


Figure 14. Hydrograph from July 28, 2005 simulation showing throughfall and stemflow on the top axis and surface runoff and cave recharge on the bottom axis in mm per wetted area in 5 minute intervals

Table IX. July 28, 2005 standard simulation water budgets

| **Run 1** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 11768.8 | 21.3 | 100 |
| Stemflow | 906.1 | 1.6 | 7.7 |
| Automatic Throughfall | 3490.2 | 6.3 | 29.7 |
| Manual Throughfall | 10502.6 | 19 | 89.2 |
| [a] Water Reaching Surface | 11408.7 | 20.6 | 96.9 |
| Surface Runoff | 0 | 0 | 0 |
| Cave Recharge | 290.2 | 0.5 | 2.47 |
| Canopy Interception | 360.1 | 0.7 | 3.1 |
| Storage/Subsurface Flow | 11118.5 | 20.1 | 94.4 |
| **Run 2** | Liters | mm | Percent |
| Water Applied | 4731.8 | 8.6 | 100 |
| Stemflow | 298.5 | 0.5 | 6.3 |
| Automatic Throughfall | 3896.1 | 7 | 82.3 |
| Manual Throughfall | 4698.5 | 8.5 | 99.3 |
| [a] Water Reaching Surface | 4997 | 9 | 105.6 |
| Surface Runoff | 0 | 0 | 0 |
| Cave Recharge | 599.2 | 1.1 | 12.66 |
| Canopy Interception | -265.2 | -0.4 | -5.6 |
| Storage/Subsurface Flow | 4397.8 | 7.9 | 92.9 |
| **Run 3** | Liters | mm | Percent |
| Water Applied | 9993.5 | 18.1 | 100 |
| Stemflow | 1085 | 2 | 10.9 |
| Automatic Throughfall | 6087.6 | 11 | 60.9 |
| Manual Throughfall | 9507.6 | 17.2 | 95.1 |
| [a] Water Reaching Surface | 10592.6 | 19.2 | 106 |
| Surface Runoff | 641.4 | 1.2 | 6.4 |
| Cave Recharge | 1399.7 | 2.5 | 14.01 |
| Canopy Interception | -599.1 | -1.1 | -6 |
| Storage/Subsurface Flow | 8551.5 | 15.5 | 85.6 |
| **Simulation Total** | Liters | mm | Percent |
| Water Applied | 26494.1 | 47.9 | 100 |
| Stemflow Oak | 724.4 | 1.3 | 2.7 |
| Stemflow Juniper | 1565.0 | 2.8 | 5.9 |
| Stemflow Total | 2289.5 | 4.1 | 8.6 |
| Automatic Throughfall | 13474 | 24.4 | 50.9 |
| Manual Throughfall | 24708.8 | 44.7 | 93.3 |
| [a] Water Reaching Surface | 26998.3 | 48.8 | 101.9 |
| Surface Runoff | 641.4 | 1.2 | 2.4 |
| Cave Recharge | 2289.0 | 4.1 | 8.64 |
| Canopy Interception | -504.2 | -0.9 | -1.9 |
| Storage/Subsurface Flow | 24067.9 | 43.5 | 90.9 |

[a] Water reaching surface is manual throughfall plus stemflow

Table X. Standard simulation average water budget

| **Simulation Total** | Liters | mm | Percent | S.E. (mm) |
|---|---|---|---|---|
| Water Applied | 28741.4 | 52.0 | 100.0 | 3.6 |
| Stemflow Oak | 758.4 | 1.4 | 2.6 | 0.1 |
| Stemflow Juniper | 835.7 | 1.5 | 2.9 | 1.1 |
| Stemflow Total | 1594.0 | 2.9 | 5.5 | 1.1 |
| Automatic Throughfall | 20120.8 | 36.4 | 72.9 | 10.8 |
| Manual Throughfall | 23750.7 | 43.0 | 74.5 | 2.4 |
| [a] Water Reaching Surface | 25344.7 | 45.9 | 80.0 | 3.3 |
| Surface Runoff | 615.5 | 1.1 | 2.1 | 0.1 |
| Cave Recharge | 2371.9 | 4.3 | 8.3 | 1.6 |
| Canopy Interception | 3396.6 | 6.1 | 20.0 | 6.4 |
| Storage/Subsurface Flow | 22357.2 | 40.4 | 69.7 | 2.6 |

*Re-created Rainfall Events*

On August 3rd and 4th, a different type of rainfall simulation was conducted. We re-created a natural rainfall event that occurred July 17, 2005 to evaluate the difference in hydrologic response from a similar event applied directly over the cave footprint instead of the entire hillslope as in a natural event. Natural rainfall data was collected from an automatic rain gauge that recorded data on 15 minute intervals. This enabled us to accurately replicate the amount of rainfall that was applied within a 15 minute window; however, the intensity and exact duration of the natural event was unknown due to the 15 minute resolution natural rainfall data. 16.25 mm of rainfall occurred July 15th and 16th and partially saturated the system.

The natural rainfall event produced 21.33 mm of precipitation and lasted approximately 330 minutes with the last 45 minutes receiving 0.7 mm of precipitation. Our rainfall simulator is not capable of producing small rainfall intensities such as those occurring in the last 45 minutes; therefore we cut the simulation short by 45 minutes.

The re-created simulations lasted a total of 285 minutes with water applied for only 145 of those minutes in order to mimic the natural rainfall event.

The first re-created event occurred August 3, 2005 under dry conditions and applied 22 mm of water. The second event was conducted August 4, 2005 under wet conditions and 22.2 mm of water was applied. Table XI shows the water budget for each of these re-created events as well as the water budget for the naturally occurring event that we duplicated.

Hydrographs (Figure 15, 16, and 17) from these three events reveal similar patterns in hydrologic response to the rainfall events. Throughfall data was not collected during the natural event due to equipment failure and precipitation data was not available during the re-created rainfall events because the rain gauge is outside of the wetted area. Comparison of natural precipitation to simulated throughfall shows similar patterns and depths/intensities on the second day of simulation when conditions are similar to the natural event. Data from the re-created event showed stemflow response that mimics patterns in the throughfall and cave recharge hydrographs. The response on day two is higher and is a result of the semi-saturated conditions from the previous day's simulation. Cave response also varies as a result of moisture conditions. In both simulated events, cave response resembles the hydrograph from the natural event.

Table XI. Natural event and re-created rainfall simulation water budgets

| **August 3, 2005** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 12170.1 | 22 | 100 |
| Stemflow Oak | 124.5 | 0.2 | 1.0 |
| Stemflow Juniper | 29.0 | 0.1 | 0.2 |
| Stemflow Total | 153.5 | 0.3 | 1.3 |
| Automatic Throughfall | 7305.2 | 13.2 | 60 |
| Manual Throughfall | 7959.9 | 14.4 | 65.4 |
| [a] Water Reaching Surface | 8113.4 | 14.7 | 66.7 |
| Surface Runoff | 0 | 0 | 0 |
| Cave Recharge | 153.3 | 0.3 | 1.3 |
| Canopy Interception | 4056.7 | 7.3 | 33.3 |
| Storage/Subsurface Flow | 7960.1 | 14.4 | 65.4 |

| **August 4, 2005** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 12257.2 | 22.2 | 100 |
| Stemflow Oak | 203.8 | 0.4 | 1.7 |
| Stemflow Juniper | 72.5 | 0.1 | 0.6 |
| Stemflow Total | 276.2 | 0.5 | 2.3 |
| Automatic Throughfall | 10551.9 | 19.1 | 86.1 |
| Manual Throughfall | 9231.3 | 16.7 | 75.3 |
| [a] Water Reaching Surface | 9507.5 | 17.2 | 77.6 |
| Surface Runoff | 0 | 0 | 0 |
| Cave Recharge | 841.5 | 1.5 | 6.9 |
| Canopy Interception | 2749.7 | 5 | 22.4 |
| Storage/Subsurface Flow | 8666.0 | 15.7 | 70.7 |

| **July 17, 2005** | Liters | mm | Percent |
|---|---|---|---|
| Water Applied | 11653.5 | 21.1 | 100 |
| Stemflow Oak | 34.0 | 0.1 | 0.3 |
| Stemflow Juniper | 58.0 | 0.1 | 0.5 |
| Stemflow Total | 91.9 | 0.2 | 0.8 |
| Automatic Throughfall | 8733.9 | 15.8 | 74.9 |
| Manual Throughfall | 0 | 0 | 0 |
| [a] Water Reaching Surface | 8825.7 | 16 | 75.7 |
| Surface Runoff | 0 | 0 | 0 |
| Cave Recharge | 450.5 | 0.8 | 3.9 |
| Canopy Interception | 2827.8 | 5.1 | 24.3 |
| Storage/Subsurface Flow | 8375.2 | 15.2 | 71.9 |

[a] Water reaching surface is manual throughfall plus stemflow except for the natural simulation; it is automatic throughfall plus stemflow

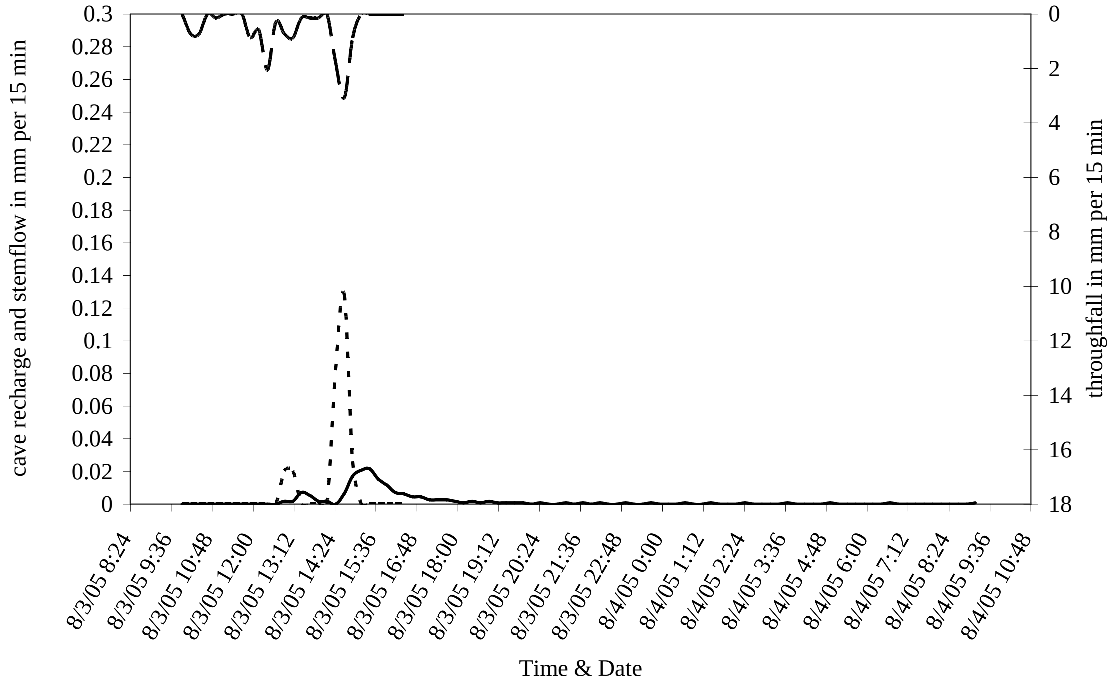


Figure 15. Hydrograph showing throughfall, stemflow, and cave recharge in mm per wetted area in 15 minute intervals for the re-created event on August 3, 2005

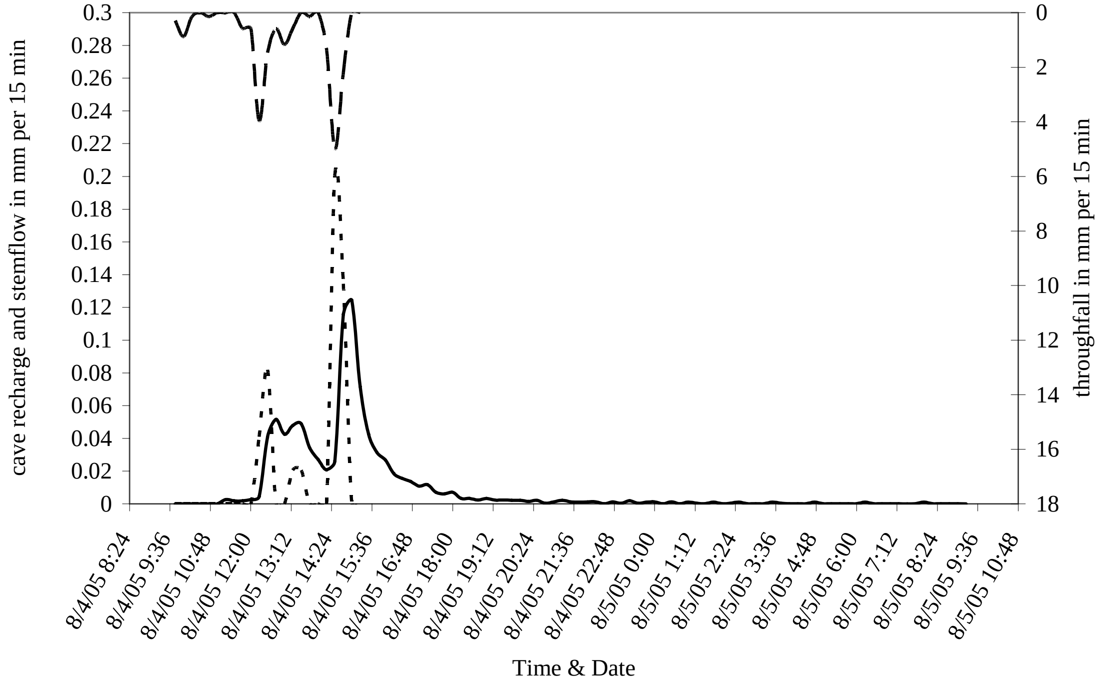


Figure 16. Hydrograph showing throughfall, stemflow, and cave recharge in mm per wetted area in 15 minute intervals for the re-created event on August 4, 2005

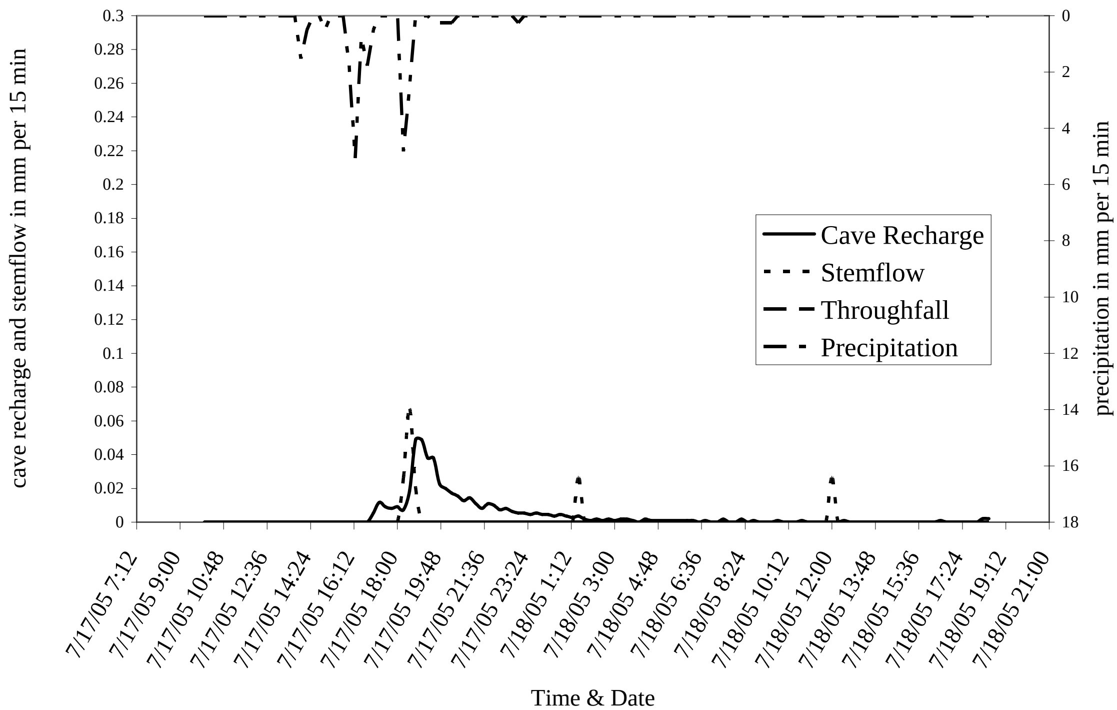


Figure 17. Hydrograph showing precipitation, stemflow, and cave recharge in mm per wetted area in 15 minute intervals for the natural event on July 17, 2005

*Simulation Averages*

Overall, 7 rainfall simulations have taken place. Two of these were initial simulations that applied water at a continuous rate, three where standard simulations that applied water in three intervals at varying rates, and the final two were events that replicated rainfall from a natural event. Table XII presents data from all of these runs as an average from the seven events and gives the S.E. for each component in mm. Component data from an event was not included if no data was not recorded for that event. For example, surface runoff only occurred in three of the seven events; therefore, the surface runoff was averaged over three events, not seven.

Table XII. Average water budget for all simulated events

| **Simulation Total** | Liters | mm | Percent | S.E. (mm) |
|---|---|---|---|---|
| Water Applied | 21892.7 | 39.6 | 100.0 | 14.3 |
| Stemflow Oak | 633.9 | 1.1 | 2.9 | 0.8 |
| Stemflow Juniper | 526.5 | 1.0 | 2.4 | 1.0 |
| Stemflow Total | 1160.3 | 2.1 | 5.3 | 9.2 |
| Automatic Throughfall | 16436.3 | 37.0 | 72.9 | 11.7 |
| Manual Throughfall | 16988.7 | 35.4 | 74.5 | 17.5 |
| [a] Water Reaching Surface | 18149.0 | 37.5 | 79.8 | 18.5 |
| Surface Runoff | 615.5 | 1.1 | 2.8 | 3.3 |
| Cave Recharge | 1506.2 | 2.7 | 6.9 | 8.3 |
| Canopy Interception | 3743.6 | 2.1 | 20.2 | 4.7 |
| Storage/Subsurface Flow | 16027.3 | 33.7 | 70.1 | 12.8 |

# DISCUSSION

## Moisture Conditions

Results from rainfall simulations, soaker hose experiments, and monitoring of natural rainfall events have re-affirmed that antecedent moisture conditions play a vital role in the amount of water moving into, stored in, and transmitted by soil and fractured rock into underlying caves. The ability of vegetation to intercept precipitation, generate stemflow, and allow throughfall is also affected by moisture conditions. Owens et al. (2006) found that it is not until after 11 mm of have fallen that direct throughfall reaches 50% in an Ashe juniper community. At this point, stemflow accounts for 2% of the water budget and interception by the canopy and litter accounted for about 48%. Castillo et al. (2003) found that surface runoff generation was affected by antecedent soil moisture conditions by medium and low intensity rainfall events (< 50 mm/hr), but is independent of soil moisture conditions for high intensity events in a semiarid area of Spain dominated by Needle grass (*Stipa tenacissima)*, thyme brush species (*Thymus vulgaris*, *Teucrium capitatum*, *Fumana ericoides*), and Aleppo pine *(Pinus halepensis)*.

## Interception

Thurow and Hester (1997) suggest that interception may be a function of rainfall intensity and duration and is species-specific. An interception study in Ashe juniper (Owens et al., 2006) corroborates that rainfall intensity and duration dictate interception. Their study found that interception rates ranged from 12-96% depending on storm size and averaged 42% over a three year period. Natural data collected at Bunny Hole show that during 2005, interception accounted for 39.56% and ranged from 13.5-93.5% for monthly periods (Table III and XIII). Data from rainfall simulations are also consistent with the range of data collected by Owens et al. (2006). Tables V, VI, VII, VIII, X, and XI show interception values for rainfall simulations and individual runs during the simulation ranging from 6.8-41% of the water applied.

**Throughfall and Stemflow**

Combined measurements of natural and simulated throughfall and stemflow from Bunny Hole have shown that throughfall accounts for 59.96% of the annual water budget while stemflow totals 0.48% (Table XIII). Owens et al. (2006) found that average water reaching the ground (throughfall and stemflow) over a three year period was 58% of ambient moisture reached the surface while stemflow ranged from 0.8% in Hays County at the Freeman Ranch to 5.2% in Medina County at the Peters Ranch. Stemflow recorded at Bunny Hole is somewhat lower than results from Owens et al. (2006). Tree structure, canopy density, and species composition could be the cause of this variation; canopy cover at Bunny Hole is not as dense as other areas and is almost equally mixed between Live oak and Ashe juniper. Owens et al. (2006) found that the branching pattern and shaggy bark of Ashe juniper can cause stemflow to be deposited as throughfall before reaching the tree trunk. Individual events at Bunny Hole produced stemflow values that were much higher than the yearly average, but were still low when

Table XIII. Water budget at Bunny Hole for October 2004 through December 2005

| **Totals** | Liters | mm | Percent | S.E. (mm) |
|---|---|---|---|---|
| precipitation | 154207 | 907.1 | 100.00 | 77.9 |
| stemflow Oak | 1358.334 | 8.0 | 0.88 | 0.7 |
| stemflow Juniper | 1594.032 | 9.4 | 1.03 | 0.7 |
| stemflow total | 2952.3234 | 17.4 | 1.91 | 1.4 |
| throughfall | 48456.8 | 285.0 | 31.42 | 22.8 |
| water reaching surface | 102797.88 | 604.7 | 66.7 | 24.1 |
| cave recharge | 25051.8 | 147.4 | 16.25 | 84.1 |
| [a] interception | 90602 | 533.0 | 58.75 | 87.2 |
| storage/subsurface flow/ET | 77746.077 | 457.3 | 50.4 | 33.3 |

[a] Interception values are estimates derived by subtracting stemflow and throughfall from precipitation and its accuracy depends on the accuracy of the other measures

compared other studies. Stemflow ranged from 1.1-10.9% for individual runs during rainfall simulations while Sorenson (2004) reported stemflow numbers as high as 23.6% and Porter (2005) found average stemflow to be 25.74%. Tree structure and canopy density can be attributed for higher stemflow in these cases.

Stemflow measurements from live oak and Ashe juniper revealed slight differences in the amount of water transmitted via stemflow for each species. Natural data showed stemflow of 9.4 mm in the Ashe juniper while live oak produced 8 mm. Under simulated conditions, Ashe juniper yielded an average stemflow of 1 mm per event with a standard error of 1 mm while live oak averaged 1.1 mm of stemflow per event and a standard error of 0.8 mm.

**Recharge**

Recharge volumes compared between Bunny Hole and Headquarters Cave shows variable reactions to rainfall events of similar intensity and duration. Yearly totals at Bunny Hole measured 3.6% or 14.4 mm of the total rainfall while Headquarters Cave collected 14.13% or 68.4 mm of the total. Bunny Hole experienced a significant amount of problems with cave drip collectors in the first half of 2005; estimates have been made that at most 60% of the yearly recharge was collected. Assuming this is correct, yearly recharge at Bunny Hole would increase to 5.04% or 20.15 mm of the total annual rainfall.

Recharge at Bunny Hole and Headquarters Cave is considered diffuse recharge and is defined by White (2002) as rainfall directly onto the karst surface and from there entering the aquifer as infiltration through the soil and fracture matrix permeability of the underlying carbonate rock. Other studies have estimated values of diffuse recharge for several areas across the Edwards Aquifer recharge zone. Hauwert et al. (2005) determined diffuse recharge for two large internal drainage basins in the Barton Springs segment of the Edwards Aquifer to be 34% of the total rainfall or 355.3 mm. A study conducted by Dugas et al. (1998) in the Seco Creek watershed about 70 miles west of San Antonio estimated average annual recharge to be about 30% or 326.8 mm of total precipitation over their 5 year study based on ET and surface runoff measurements. Results from water balance studies in the Flatrock watershed in Seco Creek conducted by Huang and Wilcox (2005) reveal that approximately 18% or 169 mm of precipitation account for diffuse recharge annually. A recharge study conducted in Kinney County, approximately 130 miles west of San Antonio conducted by Mace and Anaya (2004) estimated diffuse recharge into the Edwards and Edwards-Trinity Aquifers recharge zones to be 63.8 mm per year.

Bunny Hole and Headquarters Cave generally recorded much lower yearly recharge than the estimates from the studies mentioned with the exception of the Mace and Anaya (2004) study. Our study only measures recharge into the caves and is not able to accurately quantify how much water moves off-site via lateral subsurface flow or is stored in the soil or fracture matrix around the cave; therefore, recharge is really higher than we have estimated. Similar studies that have used rainfall simulation to evaluate the water budget on Edwards Plateau rangelands have been able to quantify lateral subsurface flow by excavating a trench at the downhill end of their plot. Porter (2005) and Taucer (2006) both conducted studies on the Honey Creek State Natural Area about 20 miles north of Camp Bullis. They found average lateral subsurface flow from rainfall simulations to be 32.8% and 56.7% respectively. Sorenson (2004) found that lateral subsurface flow averaged 86.2% during his rainfall simulations at the Sonora, TX Agricultural Experiment Station. In comparison, water budgets from Bunny Hole show a component for storage/lateral subsurface flow/ET. Averaged over the seven rainfall simulations, this accounted for about 71.2% of water the total water budget. We do not know how much of this was actually lateral subsurface flow, but it is within the range of numbers found by Sorenson (2004), Porter (2005), and Taucer (2006).

**Cave Responses**

For individual events the size and duration of the event in combination with antecedent moisture conditions is the determining factor for cave recharge. Short high intensity events such as the one occurring August 10, 2005 (Appendices A and C) generate more recharge for Bunny Hole than they do at Headquarters Cave. Well defined recharge locations such as sinkholes located directly above Bunny Hole enhance the cave's ability to accept water in these intense events. When surface runoff does occur, these sinkholes provide discreet flow paths that can transmit large volumes of water into the cave. Headquarters Cave does not have these well defined features and the water must make its way through soil and fractured rock to enter the cave. Events of longer duration yield more recharge for Headquarters Cave than for Bunny Hole. More water is stored in the cave's overburden and allowed to gradually drain into the cave; the rainfall event that occurred June 1, 2005 portrayed this trait (Appendices A and C).

On a monthly and yearly basis, Headquarters Cave shows the ability to accept more recharge than does Bunny Hole. Residual moisture is stored above Headquarters Cave much longer and in larger volumes than it is above Bunny Hole; but once that moisture has drained it takes longer for it to be replenished. Hydrographs and water budgets from the much drier months of September and October of 2005 (Appendices A and C) show that residual moisture draining into the cave is a significant source of cave recharge at Headquarters Cave while at Bunny Hole the only recharge it received was short responses to rainfall. Inversely, Headquarters Cave exhibited almost no response to individual events and only received recharge from dwindling residual moisture.

**Simulated Events**

Standard rainfall simulations conducted in July 2005 and shown in Figures 12, 13, and 14 and Tables VII, VIII, and IX yield a wide range of values for each component. This range in recorded numbers is caused by moisture conditions before the simulation began. Interception, stemflow, throughfall, surface runoff, and recharge where lowest for the July 13th simulation. The July 14th simulation resulted in the highest values for these same parameters with the exception of surface runoff; it was highest during the July 28th simulation and was due to a short intense rainfall event approximately 5 hours prior to the beginning of the simulation saturating the soil.

One of the most important findings from these standard simulations is that we were able to create surface runoff and develop a threshold rainfall intensity that will generate surface runoff under an Ashe juniper canopy. In order for this to happen, the soil had to be well saturated and a significant rate of rainfall had to be applied to the cave footprint. In two of the three standard simulations, surface runoff did not occur until the end of Run 3 when rainfall was applied at a rate of 29 mm per hour. During the July 28th simulation surface runoff occurred as a result of 21.3 mm per hour rainfall applied in Run 1. This was a result of a 45 minute natural rainfall event saturating the soil with 10.7 mm of rainfall 5 hours prior to the start of the simulation. As stated by Castillo et al. (2003) this low to medium intensity event was affected by antecedent moisture conditions and thus surface runoff was generated quicker. Although the simulation on July 13th saturated the soil for the simulation on July 14th, about 18 hours elapsed between events and allowed much of the stored moisture to drain out of the soil and into the fracture matrix leaving adequate space for water to enter the soil and fractured rock. Based on these data, we feel that under saturated conditions, the threshold for creating surface runoff is a rate of about 28 mm per hour falling continuously for at least 20 minutes. Simulated rainfall that was measured as generated runoff during this study averaged 3.4%; this is lower than the 5% annual runoff that is suggested by Dugas et al. (1998) and Wilcox (2002). As stated by Wilcox (2002), spatial scale can play an important role in runoff generation.

**Re-created Events**

Our efforts to re-create the rainfall event that occurred on July 17, 2005 also proved to us that antecedent moisture conditions are the main driver of hydrologic responses above and inside the cave. Small rainfall events prior to the July 17 event created damp conditions during the natural rainfall. Conditions during our re-created rainfall events were dry for the initial simulation on August 3rd and wet for August 4th. Results presented in Table XI show that throughfall, interception, recharge and estimated storage/subsurface flow were lowest on August 3rd and highest on August 4th. The lowest stemflow reading occurred during the natural event, but is most likely due to differences between actual rainfall rates and intensities and those that were re-created. This test did not provide definitive evidence that more water will recharge into the cave as a result of a natural event than if the same size event was applied directly above the footprint of the cave. This natural event was not large enough to yield data that would determine if it would contribute more recharge than an identical simulated event. One hypothesis is that larger events that produce surface runoff would drastically increase the amount of recharge received by the caves; especially at Bunny Hole due to the discreet recharge locations, but to date we do not have any such data to prove this hypothesis.

# CONCLUSIONS

The main objective of this project was to develop a detailed water budget that incorporates direct upland recharge measurements on a juniper rangeland in the Edwards Plateau. Finding from this study show average throughfall to be 59.96%, stemflow accounted for 0.48%, canopy interception was 39.56%, and cave recharge measured 4.28%; all of which agree with other studies conducted on the Edwards Plateau. Average surface runoff was 0%; this is lower than results from other studies, but the scale of observation can be a determining factor in the percentage of runoff generated. During simulated rainfall events, average throughfall was 74.5%, stemflow measured 5.3%, canopy interception accounted for 20.2%, cave recharge totaled 6.9%, and surface runoff was 2.8%. Differences between natural and simulated events can be attributed to rainfall dynamics; much of the natural rainfall occurred as events that produced less than 5 mm of precipitation. Simulated events were much larger than this producing a minimum of 22 mm.

Water from simulations and natural events accounted for is the water that reached the surface, what was intercepted by the tree canopy, and what recharged into the cave. Water that we are not able to account for is the difference in the volume of water that made it to the surface and what was recorded as recharge inside the caves. There are three places that this unaccounted for water can go, one is that some of the moisture is stored in the soil or fractured rock, the second is that the water is transported off site via lateral subsurface flow, and the third is that it is transpired by plants accessing the soil or rock water. Estimates for ET across the Edwards Plateau average about 65% and we estimate that soil storage is rather small due to the small amount of soils. From this, we have guessed that from simulated rainfall events, lateral subsurface flow could be at most 40% of the water applied. During natural events, we have estimated that lateral subsurface flow only accounts for up to 26% of the water that falls on the cave footprint.

Evaluation of both natural and simulated data from both sites reveals differences in the way caves respond to rainfall. Bunny Hole rapidly receives water once rainfall begins, usually within 15 minutes, while Headquarters Cave takes much longer to respond if it does at all. Numerous short high intensity storms that generate recharge at Bunny Hole do not yield a response inside Headquarters Cave. Discreet recharge features above Bunny Hole provide direct flow paths into solutionally enlarged fractures and bedding planes; Headquarters Cave exhibits recharge from similar features and fractured parent material with less solutional development. Examination of hydrographs from each cave re-affirm this; Bunny Hole quickly responds and quickly ceases to respond to rainfall events, Headquarters Cave takes more time to respond, but continues to receive drip waters for a much longer period of time after the rainfall event. Event size and duration affects how the caves will respond. Bunny Hole generates a more vivid response from short high intensity events while Headquarters Cave shows more activity from longer duration events with either high or low intensity events.

Overall recharge is an important component of the water budget at each location. For some events, little if any recharge occurs, but for others recharge was extremely important. Bunny Hole has exhibited the ability to receive at least 31.23% of monthly rainfall that fell on the footprint of the cave; during the same month, Headquarters Cave collected at least 63.89% of the rainfall that landed on the cave footprint. We believe that there is a larger area than the cave footprints contributing to recharge in these caves from either lateral subsurface flow or surface runoff directed toward the caves. Contrarily, recharge entering the cave is very small compared to the size of the event in some cases. Table IV shows an event occurring May 8, 2005 produced about 31 mm of rainfall at each site yet each cave recharged less than 0.29% of the rainfall. On June 1, 2005 rainfall totaling 24.1 mm at Headquarters Cave and 27 mm at Bunny Hole produced recharge of 6.13% and 1.55% respectively. Despite the lower volume of water applied to the cave, recharge actually increased. Antecedent moisture conditions influenced these differences and can have a significant effect as data from these events illustrated.

This study has illustrated the value and feasibility of rainfall simulation in semi-arid landscapes. The ability to generate desired rates and durations of rainfall where and when you want it is the most important attribute that the simulator has, but it has also proven useful in determining how sensitive cave footprints are to recharge.

This study is the first to employ rainfall simulation above shallow caves to determine a water budget. The ability to capture recharge inside the caves has allowed us to accurately estimate vertical recharge in upland areas as a result of rainfall. Results from this study show the importance of cave recharge in the water budget and highlight their ability to accept large volumes of water and variability that each cave exhibits in receiving recharge. Although annual recharge during 2005 at Bunny Hole and

Headquarters Cave only measured 4.28 and 15.46% respectively, this could be considered a significant volume of recharge in relation to the amount of rainfall that occurs in this region. Individually, each cave is only responsible for a tiny fraction of water that recharges the Edwards Aquifer, but if all of the caves in the area respond similarly, these totals would add up and account for a significant portion of water entering underlying water tables.

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# APPENDIX A

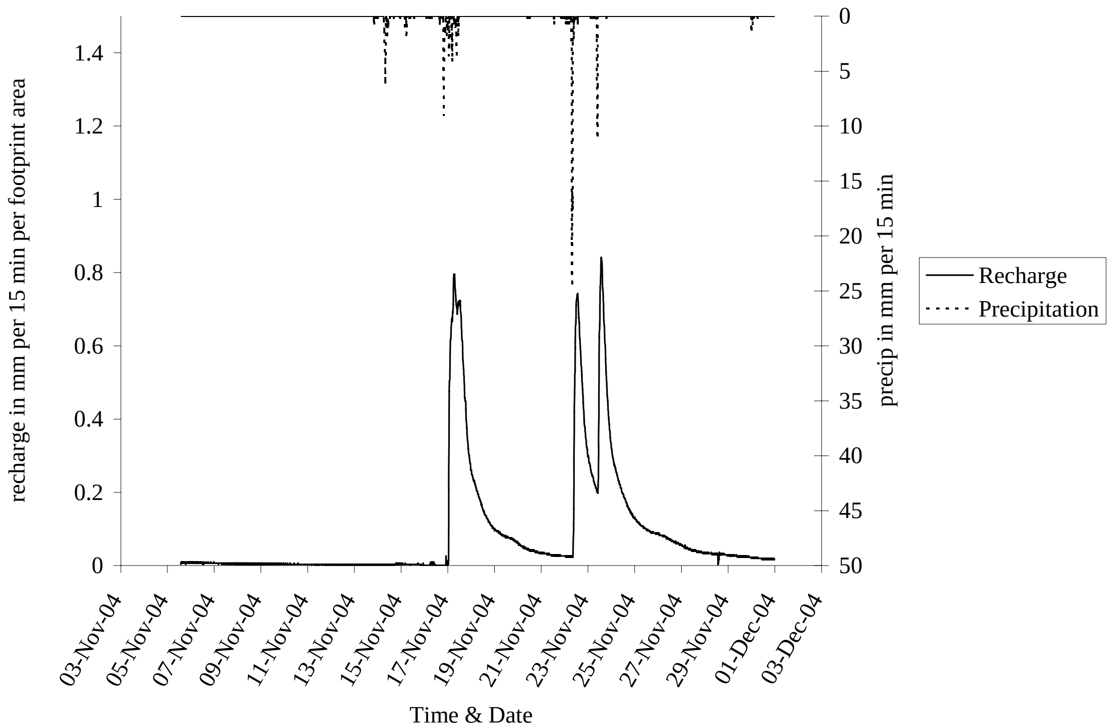


Figure 1A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for November 2004

Table I A. Water budget at Headquarters Cave For November 2004

| **Monthly Totals** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 97959.9 | 323.3 | 100.00 |
| cave recharge | 62591 | 206.6 | 63.89 |

Table II A. Cave recharge by bucket at Headquarters Cave for November 2004

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 62591 | 0 | 0 |
| % of total recharge | 100 | 0 | 0 |

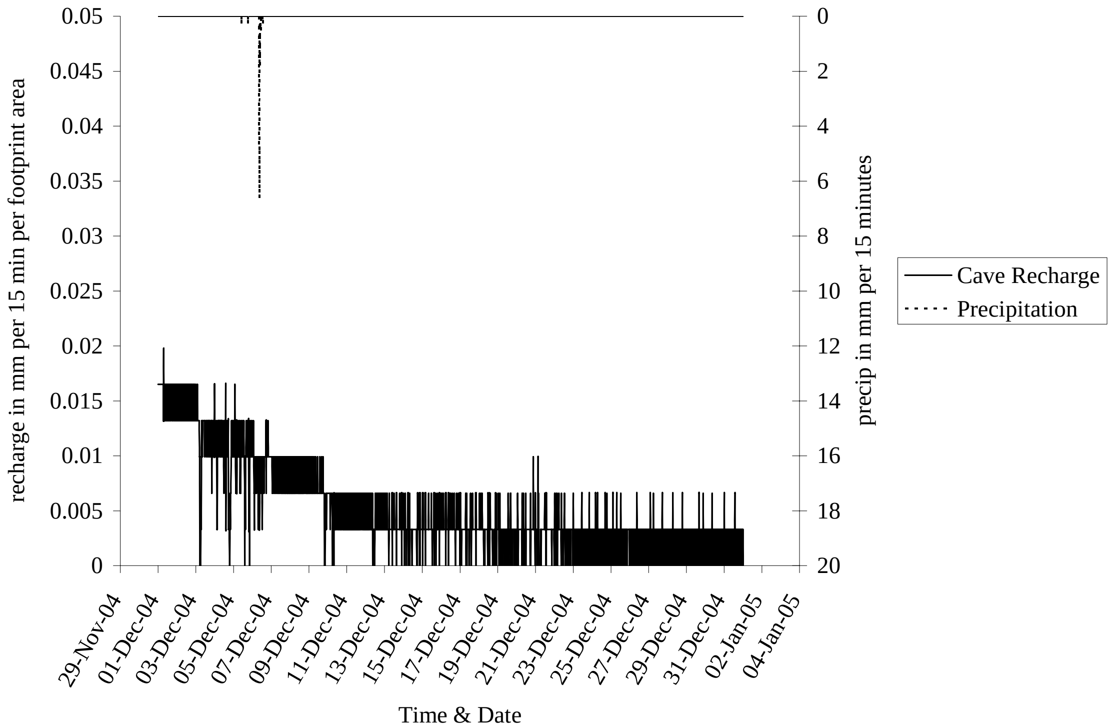


Figure 2A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for December 2004

Table III A. Water budget at Headquarters Cave for December 2004

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 3242.1 | 10.7 | 100.00 |
| cave recharge | 4688 | 15.5 | 144.60 |

Table IV A. Cave recharge by bucket at Headquarters Cave for December 2004

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 4627.00 | 35.00 | 26.00 |
| % of total recharge | 98.70 | 0.75 | 0.55 |

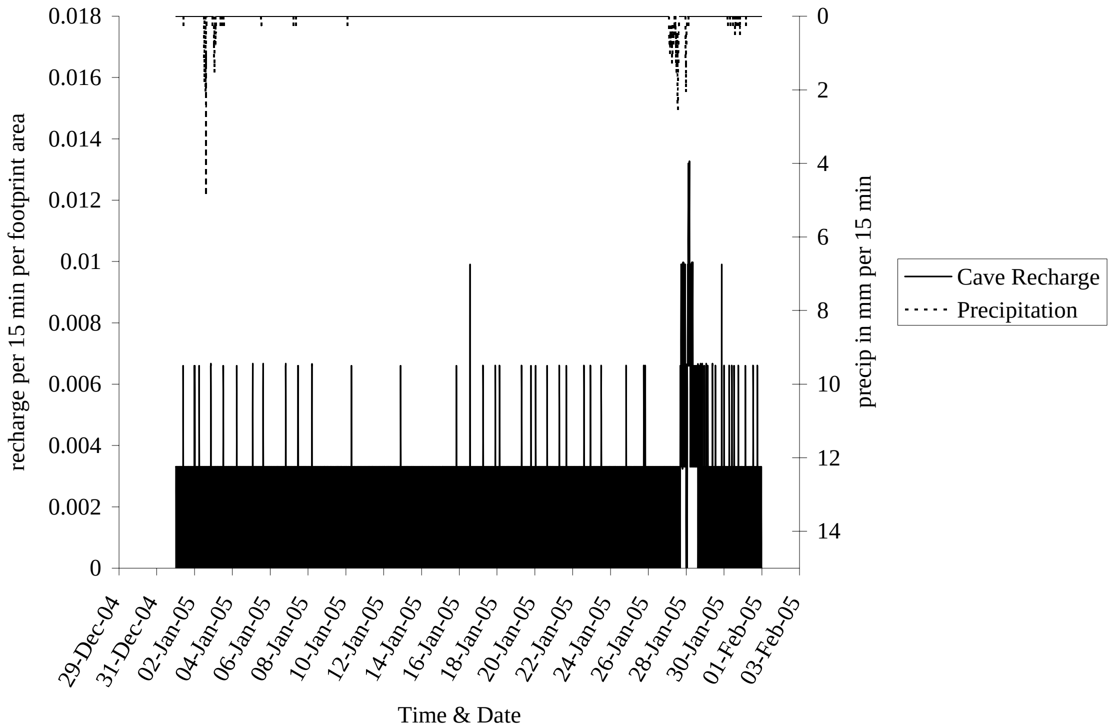


Figure 3A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for January 2005

Table V A. Water budget at Headquarters Cave for January 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 19634.4 | 64.8 | 100.00 |
| cave recharge | 1532 | 5.1 | 7.80 |

Table VI A. Cave recharge by bucket at Headquarters Cave for January 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 1280.00 | 175.00 | 77.00 |
| % of total recharge | 83.55 | 11.42 | 5.03 |

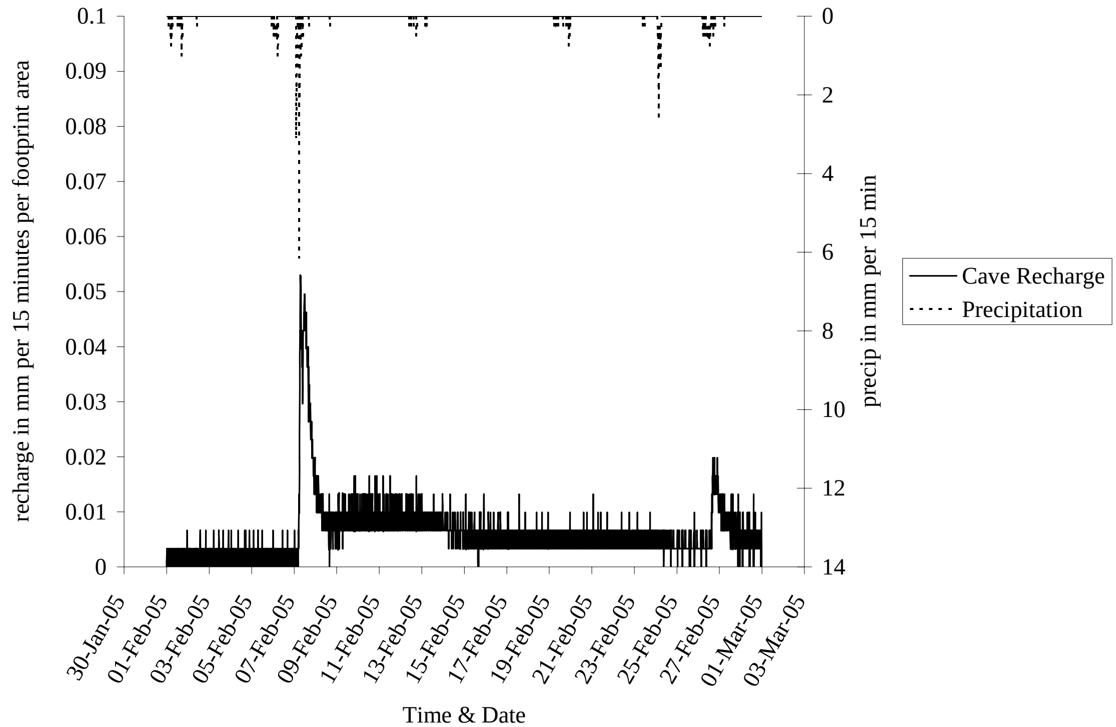


Figure 4A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for February 2005

Table VII A. Water budget at Headquarters Cave for February 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 23634 | 78.0 | 100.00 |
| cave recharge | 4789 | 15.8 | 20.26 |

Table VIII A. Cave recharge by bucket at Headquarters Cave for February 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 3556.00 | 790.00 | 443.00 |
| % of total recharge | 74.25 | 16.50 | 9.25 |

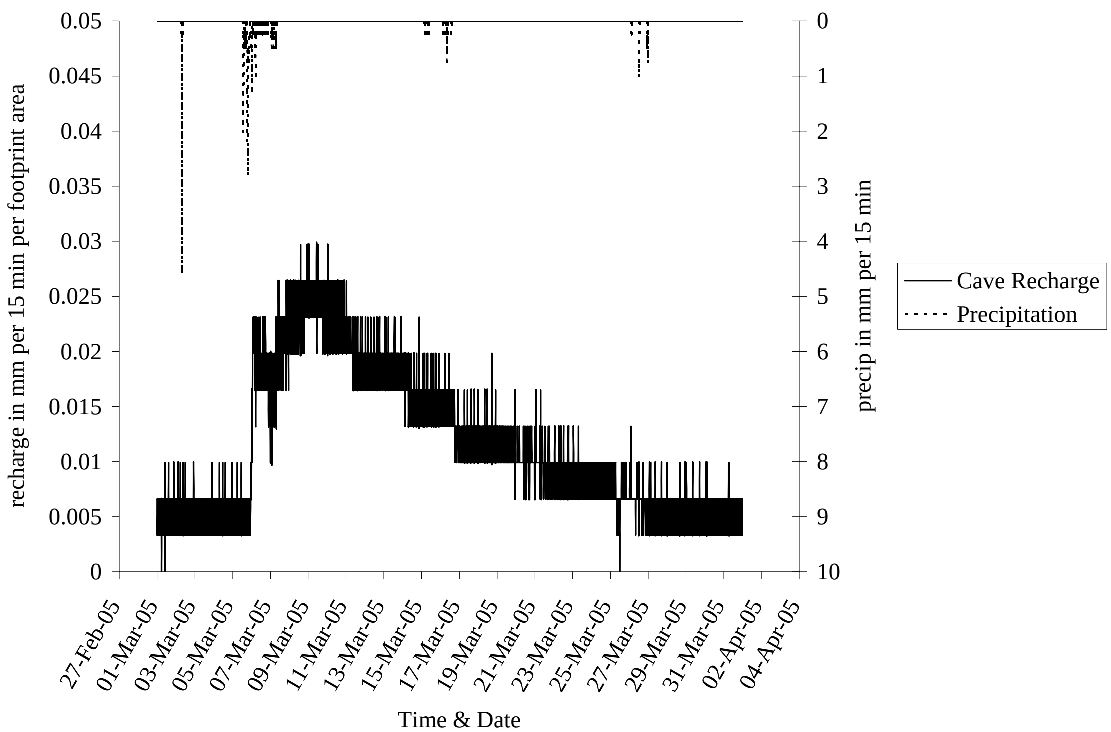


Figure 5A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for March 2005

Table VIII A. Water budget at Headquarters Cave for March 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 14392.5 | 47.5 | 100.00 |
| cave recharge | 10254 | 33.8 | 71.25 |

Table IX A. Cave recharge by bucket at Headquarters Cave for March 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 9305.00 | 584.00 | 365.00 |
| % of total recharge | 90.75 | 5.70 | 3.56 |

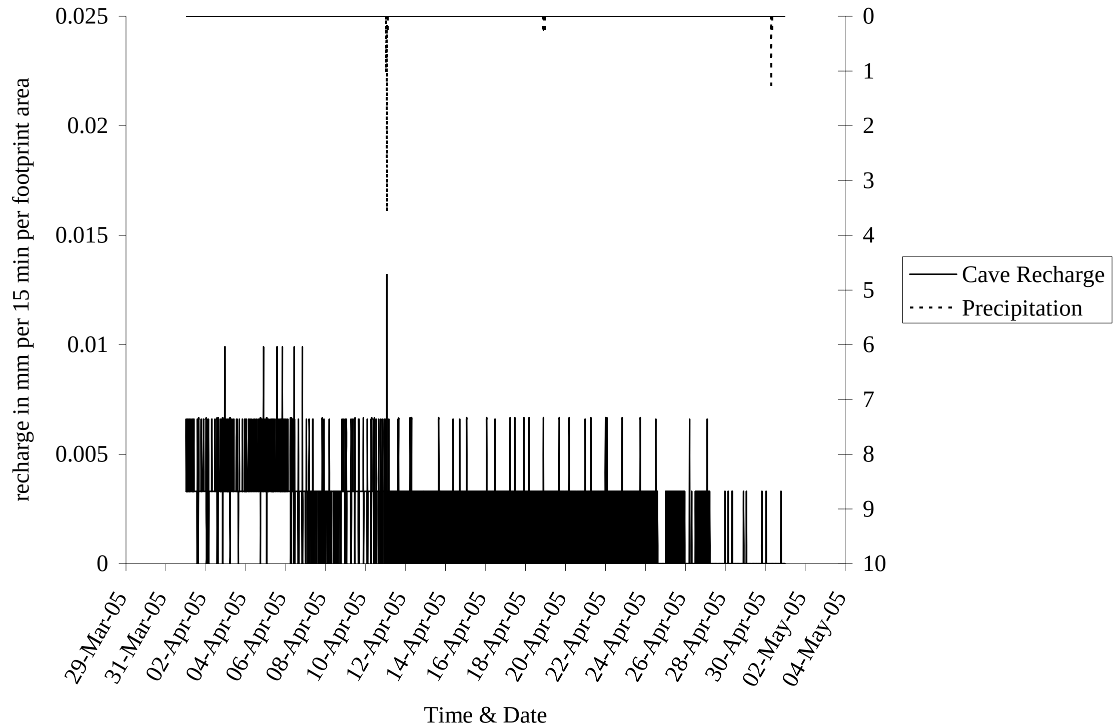


Figure 6A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for April 2005

Table X A. Water budget at Headquarters Cave for April 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 2454.3 | 8.1 | 100.00 |
| cave recharge | 1881 | 6.2 | 76.64 |

Table XI A. Cave recharge by bucket at Headquarters Cave for April 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 1790.00 | 47.00 | 44.00 |
| % of total recharge | 95.16 | 2.50 | 2.34 |

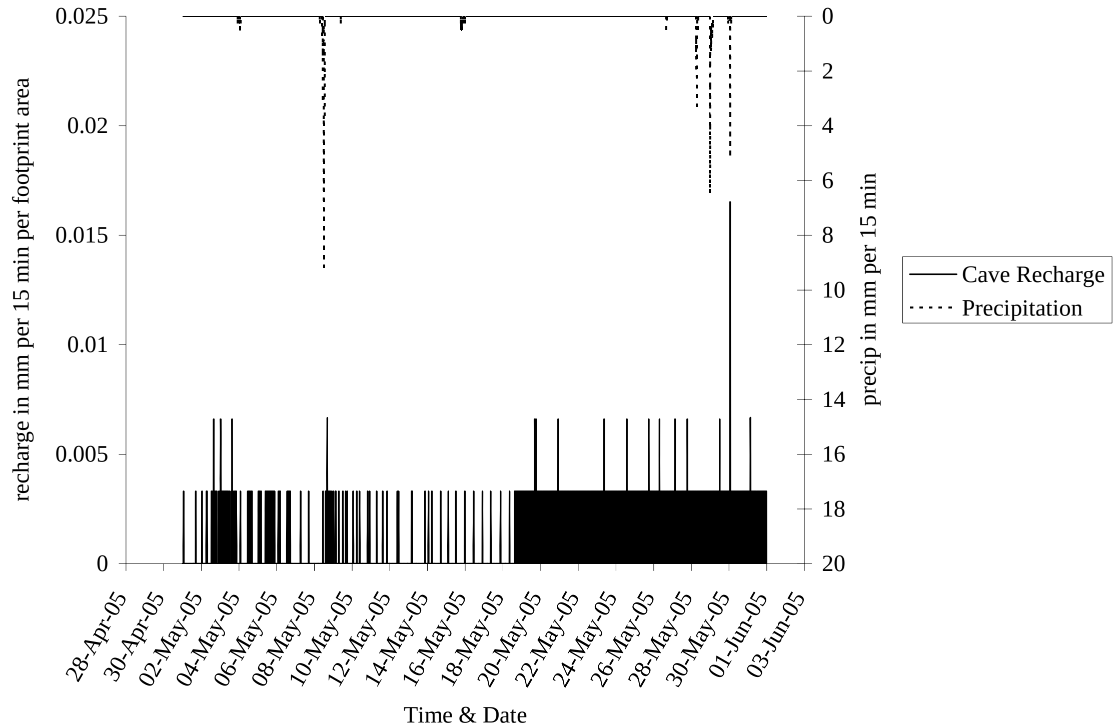


Figure 7A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for May 2005

Table XII A. Water budget at Headquarters Cave for May 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 22937.1 | 75.7 | 100.00 |
| cave recharge | 705 | 2.3 | 3.07 |

Table XIII A. Cave recharge by bucket at Headquarters Cave for May 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 619.00 | 49.00 | 37.00 |
| % of total recharge | 87.80 | 6.95 | 5.25 |

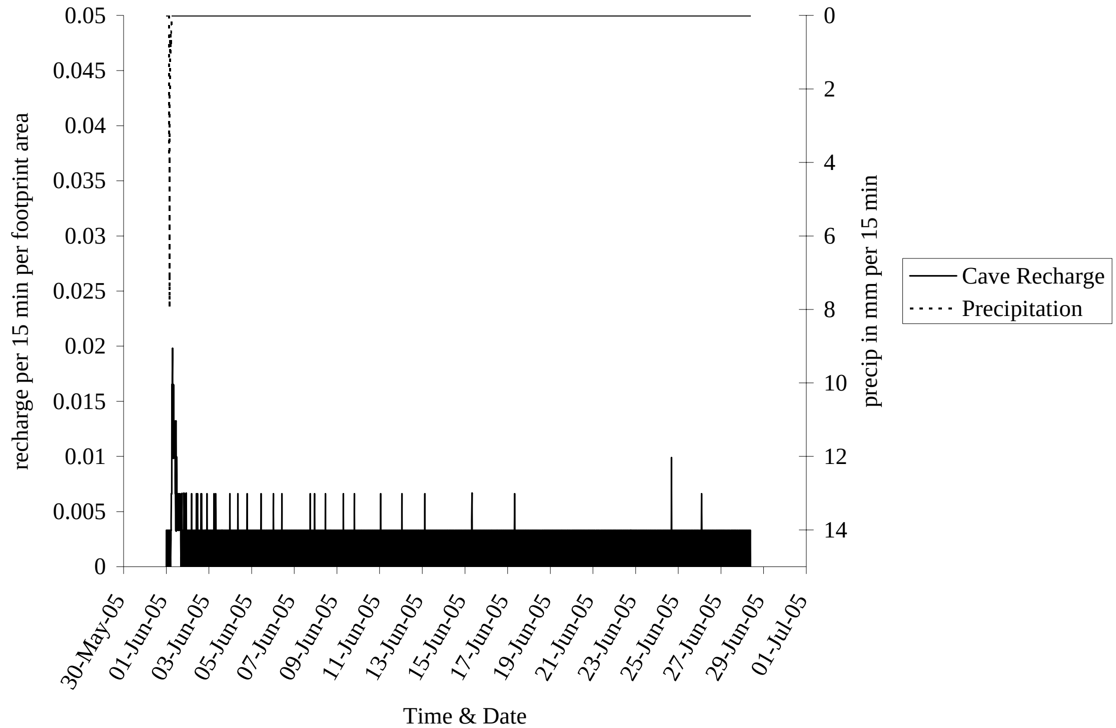


Figure 8A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for June 2005

Table XIV A. Water budget at Headquarters Cave for June 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 7302.3 | 24.1 | 100.00 |
| cave recharge | 1043 | 3.4 | 14.28 |

Table XV A. Cave recharge by bucket at Headquarters Cave for June 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 876.00 | 106.00 | 61.00 |
| % of total recharge | 83.99 | 10.16 | 5.85 |

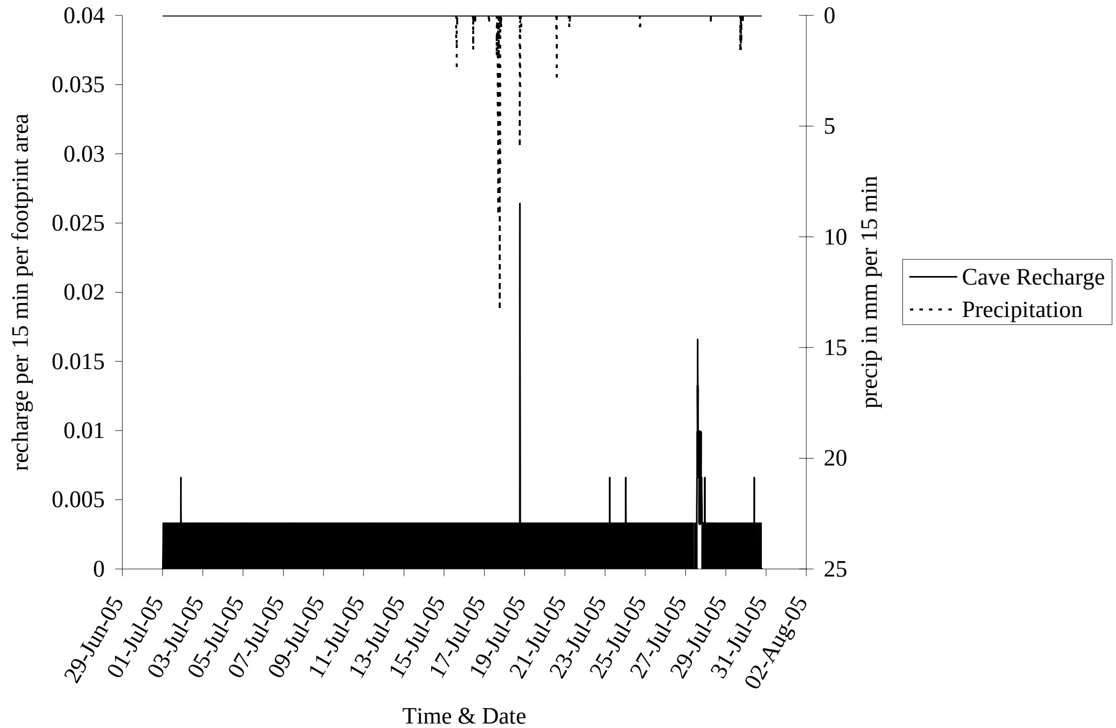


Figure 9A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for July 2005

Table XVI A. Water budget at Headquarters Cave for July 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 20149.5 | 66.5 | 100.00 |
| cave recharge | 915 | 3.0 | 4.54 |

Table XVII A. Cave recharge by bucket at Headquarters Cave for July 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 684.00 | 136.00 | 95.00 |
| % of total recharge | 74.75 | 14.86 | 10.38 |

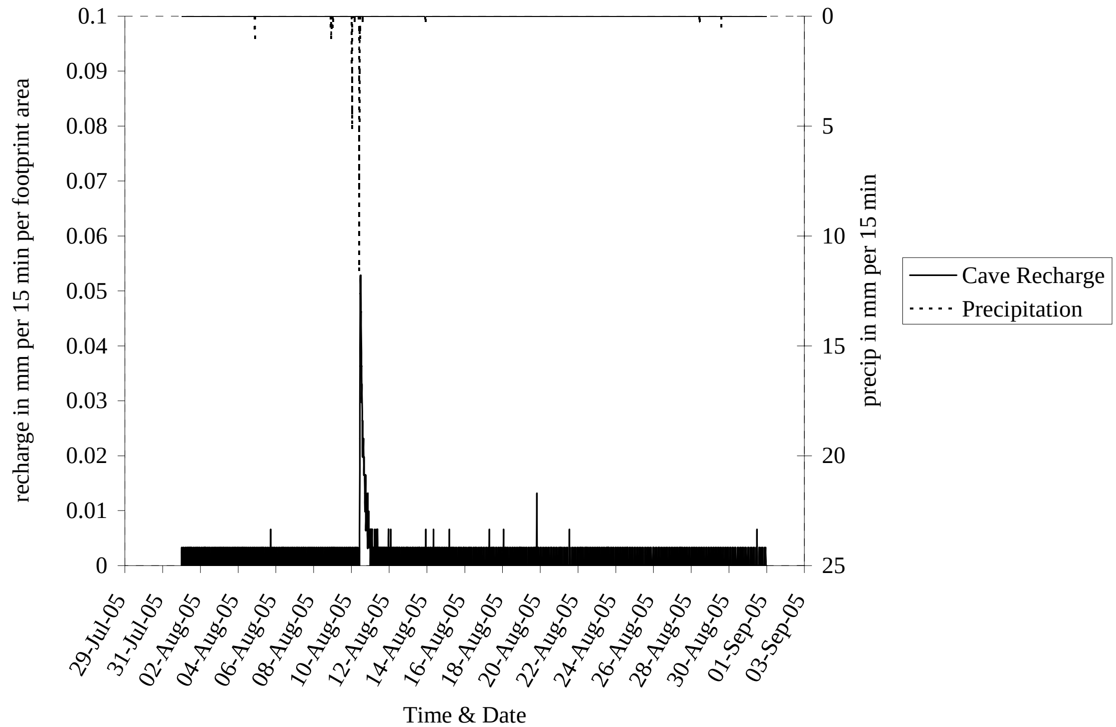


Figure 10A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for August 2005

Table XVIII A. Water budget at Headquarters Cave for August 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 13089.6 | 43.2 | 100.00 |
| Cave recharge | 892 | 2.9 | 6.81 |

Table XIX A. Cave recharge by bucket at Headquarters Cave for August 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 503.00 | 229.00 | 160.00 |
| % of total recharge | 56.39 | 25.67 | 17.94 |

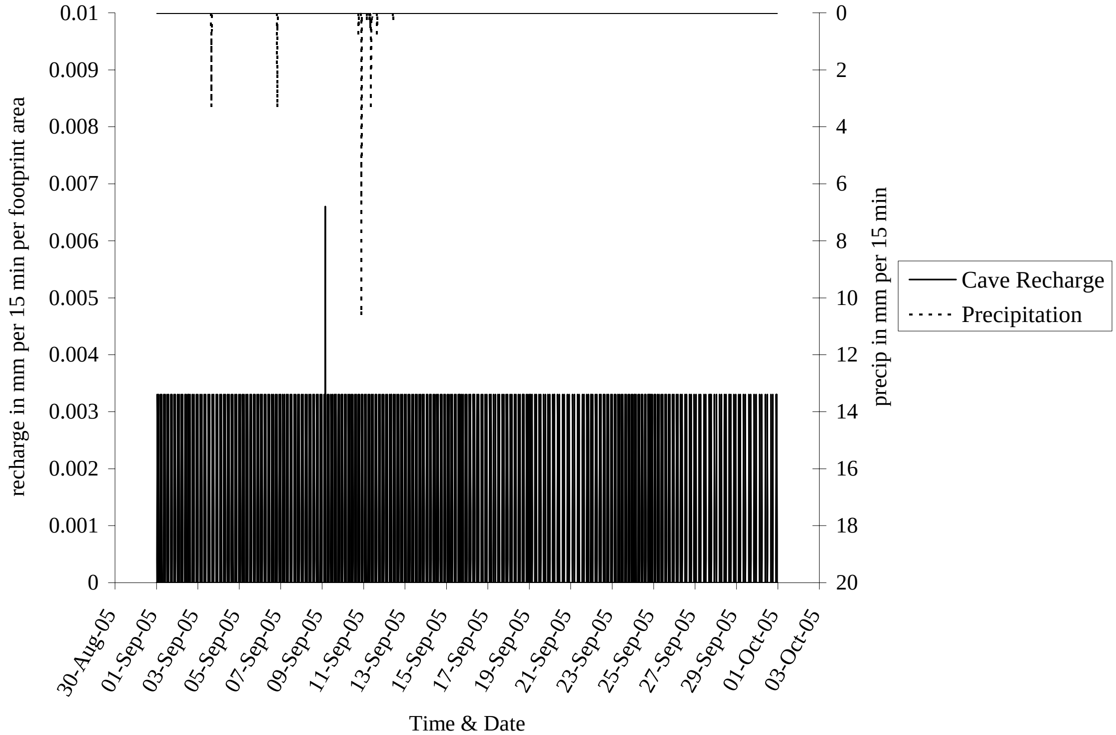


Figure 11A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for September 2005

Table XX A. Water budget at Headquarters Cave for September 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 11695.8 | 38.6 | 100.00 |
| cave recharge | 333 | 1.1 | 2.85 |

Table XXI A. Cave recharge by bucket at Headquarters Cave for September 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 318.00 | 7.00 | 8.00 |
| % of total recharge | 95.50 | 2.10 | 2.40 |

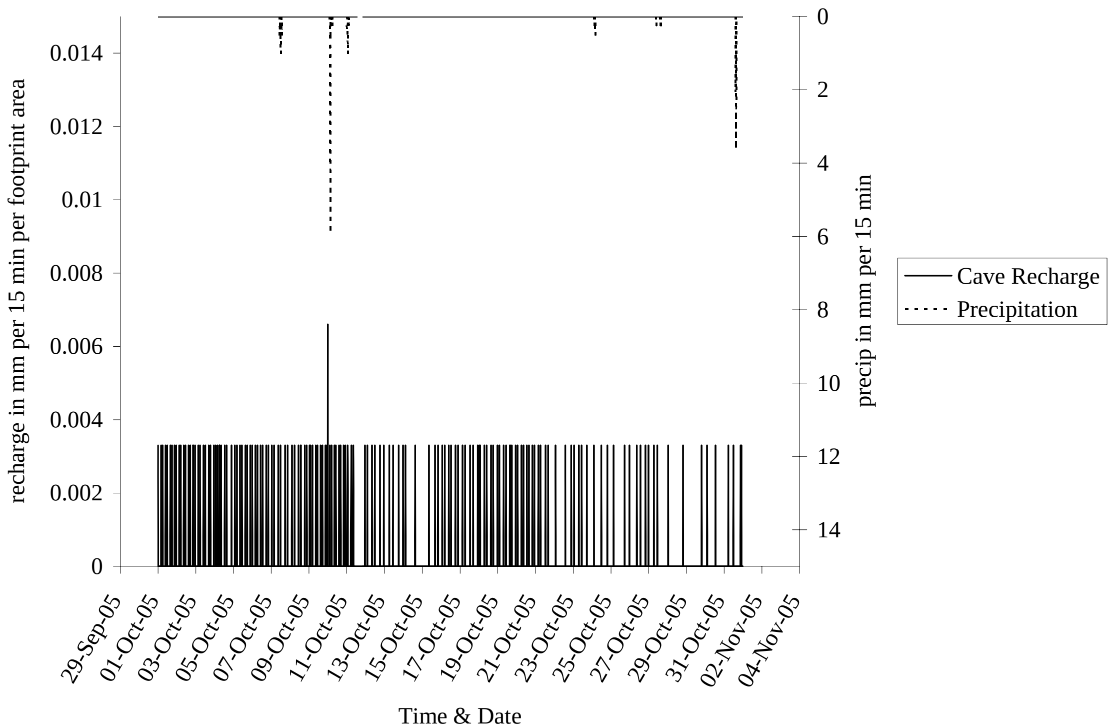


Figure 12A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for October 2005

Table XXII A. Water budget at Headquarters Cave for October 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 8696.1 | 28.7 | 100.00 |
| cave recharge | 161 | 0.5 | 1.85 |

Table XXIII A. Cave recharge by bucket at Headquarters Cave for October 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 146.00 | 3.00 | 12.00 |
| % of total recharge | 90.68 | 1.86 | 7.45 |

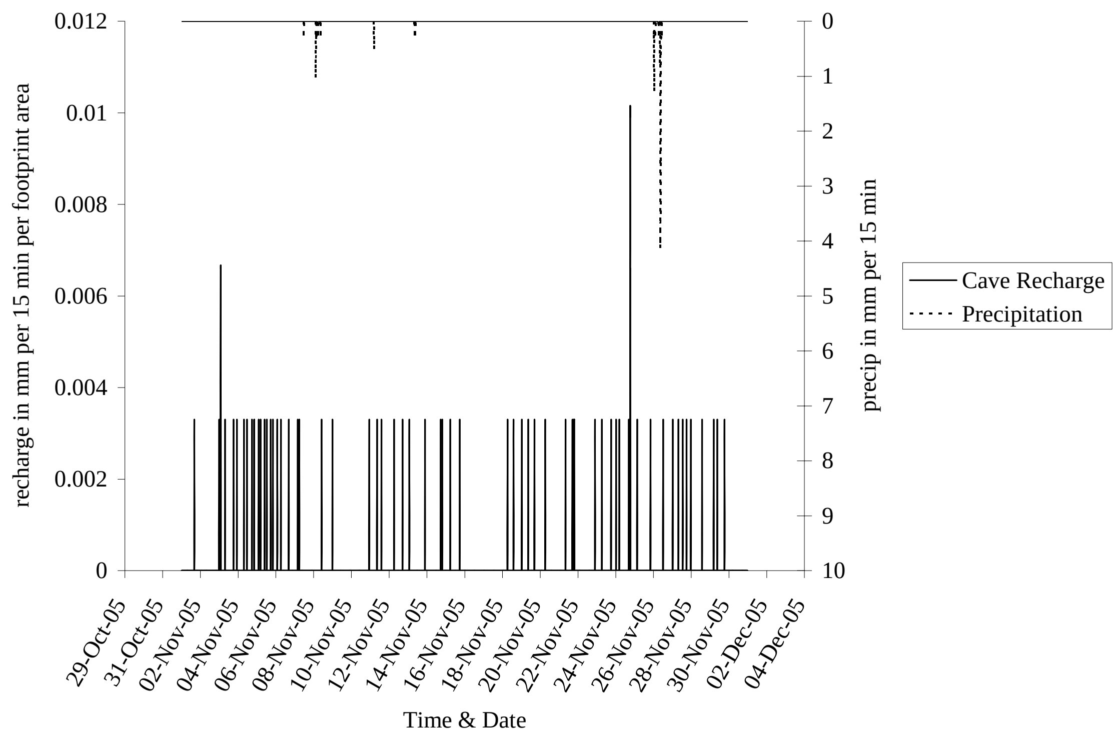


Figure 13A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for November 2005

Table XXIV A. Water budget at Headquarters Cave for November 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 4605.6 | 15.2 | 100.00 |
| cave recharge | 71 | 0.2 | 1.54 |

Table XXV A. Cave recharge by bucket at Headquarters Cave for November 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 52.00 | 6.00 | 13.00 |
| % of total recharge | 73.24 | 8.45 | 18.31 |

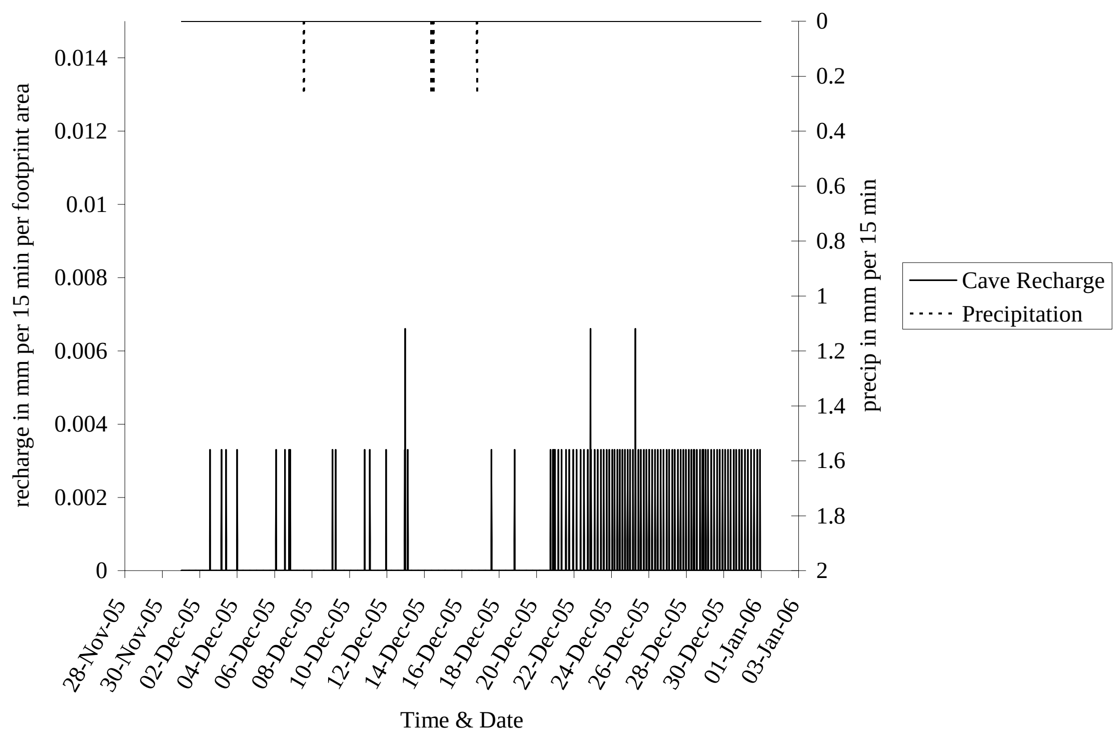


Figure 14A. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for December 2005

Table XXVI A. Water budget at Headquarters Cave for December 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 545.4 | 1.8 | 100.00 |
| cave recharge | 99 | 0.3 | 18.15 |

Table XXVII A. Cave recharge by bucket at Headquarters Cave for December 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 74.00 | 8.00 | 17.00 |
| % of total recharge | 74.75 | 8.08 | 17.17 |

# APPENDIX B

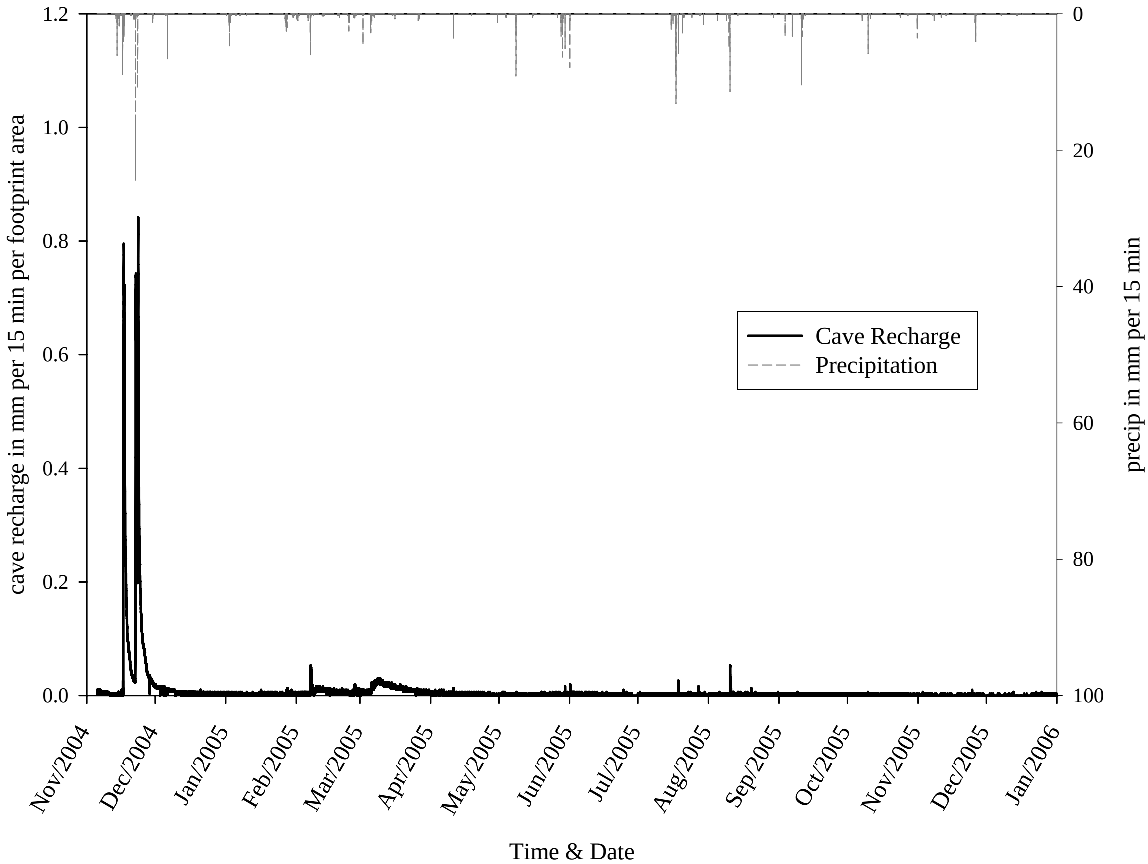


Figure 1B. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for November 2004 through December 2005

Table I B. Water budget at Headquarters Cave for November 2004 through December 2005

| **Yearly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 226653.1 | 748.0 | 100.00 |
| cave recharge | 89953 | 296.9 | 39.69 |

Table II B. Cave recharge by bucket at Headquarters Cave from November 2004 to December 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 86420.00 | 2175.00 | 1358.00 |
| % of total recharge | 96.07 | 2.42 | 1.51 |

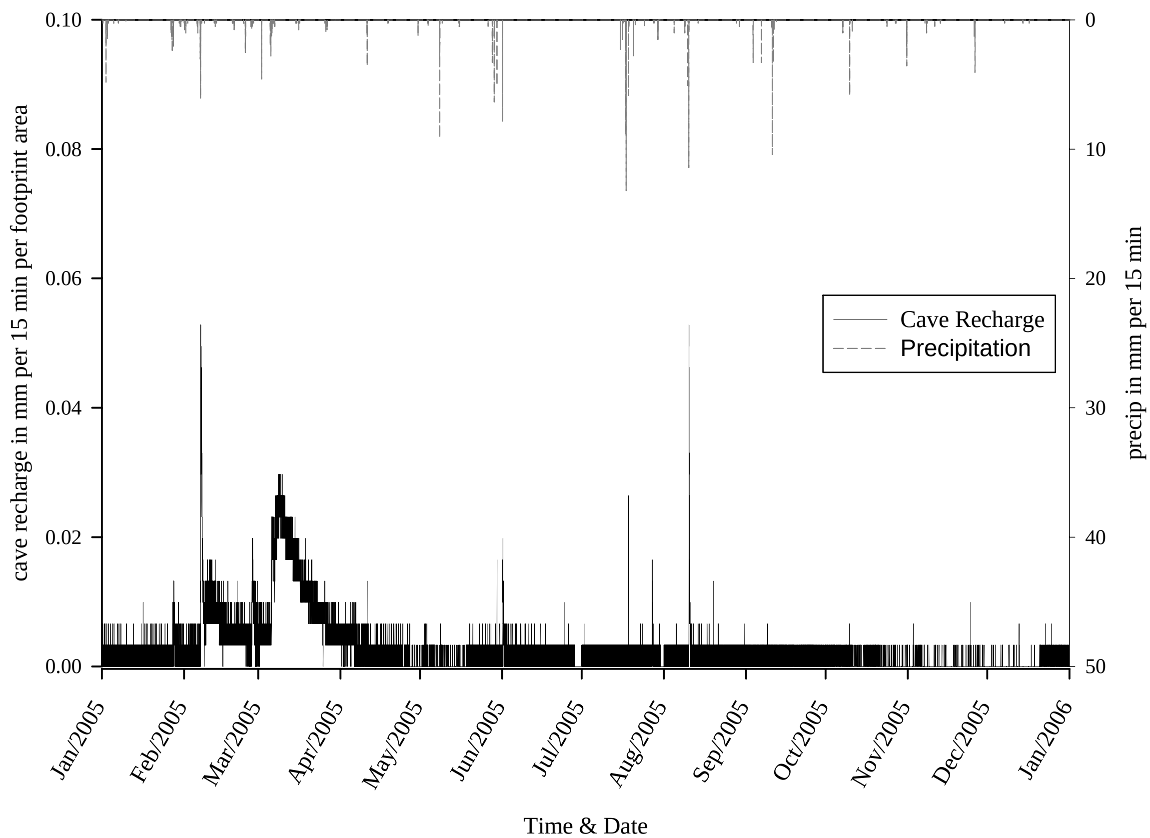


Figure 2B. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Headquarters Cave for January 2005 through December 2005

Table III B. Water budget at Headquarters Cave for 2005

| **Yearly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 146630.8 | 483.9 | 100.00 |
| cave recharge | 22675 | 74.8 | 15.46 |

Table IV B. Cave recharge by bucket at Headquarters Cave from January 2005 to December 2005

| **Tipping Bucket #** | #1 | #2 | #3 |
|---|---|---|---|
| recharge L collected | 19203.00 | 2140.00 | 1332.00 |
| % of total recharge | 84.69 | 9.44 | 5.87 |

# APPENDIX C

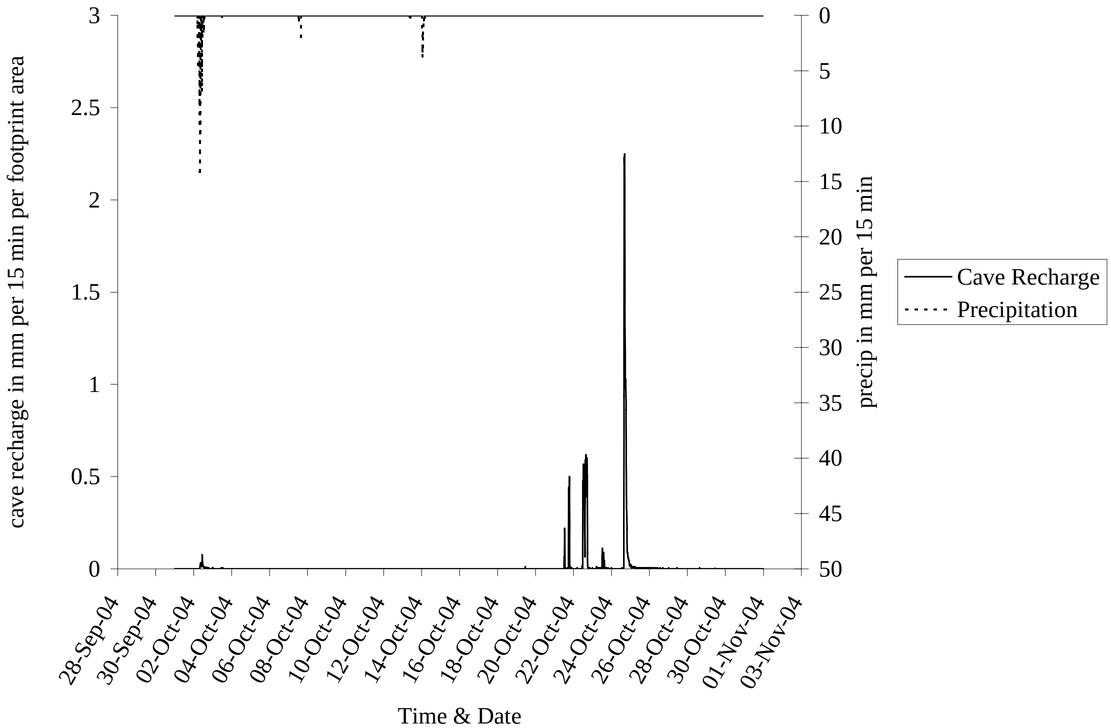


Figure 1C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for October 2004

Table I C. Water budget at Bunny Hole for October 2004

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 16065 | 94.5 | 100.00 |
| stemflow | 25.8 | 0.2 | 0.16 |
| throughfall | 5967 | 35.1 | 37.14 |
| cave recharge | 9747 | 57.3 | 60.67 |
| [a] interception | 10072.2 | 59.2 | 62.70 |

[a] Interception is estimated by subtracting stemflow from throughfall

Table II C. Cave recharge by bucket at Bunny Hole October 2004

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 1049.50 | 218.00 | 4525.00 | 55.70 |
| % of total recharge | 17.95 | 3.73 | 77.37 | 0.95 |

Recharge L are not scaled up to account for uncollected drips

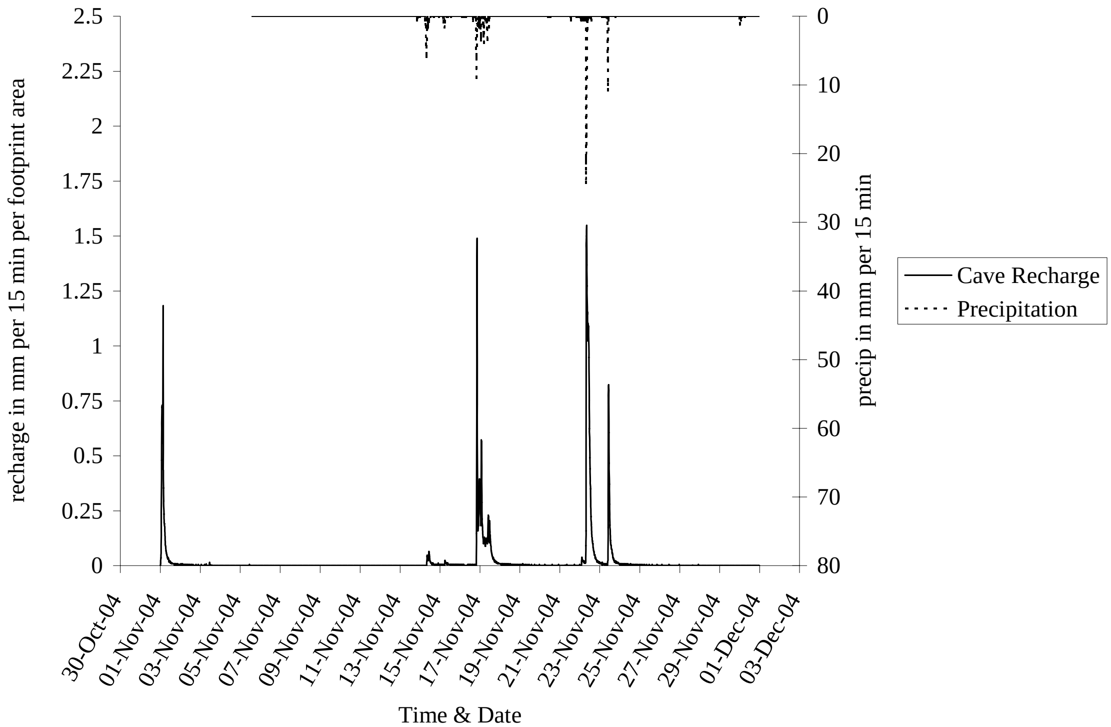


Figure 2C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for November 2004

Table III C. Water budget at Bunny Hole for November 2004

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 54961 | 323.3 | 100.00 |
| stemflow | 77.4 | 0.5 | 0.14 |
| throughfall | 1700 | 10.0 | 3.09 |
| cave recharge | 17166 | 101.0 | 31.23 |
| [a] interception | 53183.6 | 312.8 | 96.77 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table IV C. Cave recharge by bucket at Bunny Hole November 2004

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 2842.50 | 1.50 | 7455.00 | 0.60 |
| % of total recharge | 27.60 | 0.01 | 72.38 | 0.01 |

Recharge L are not scaled up to account for uncollected drips

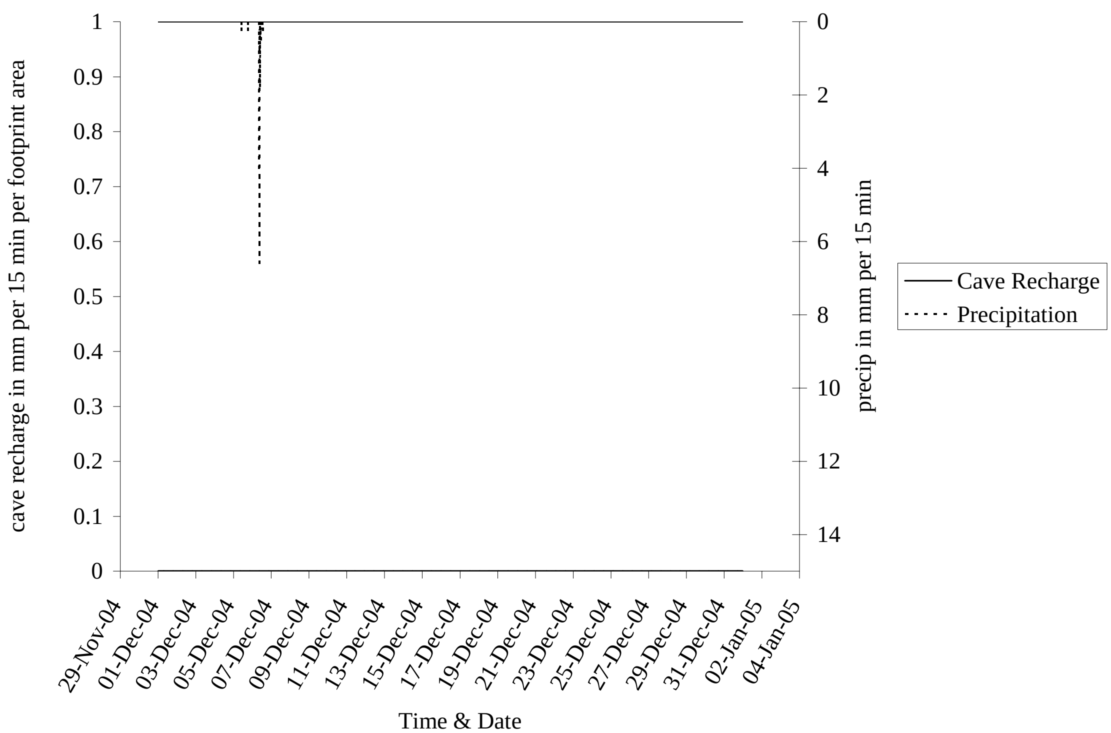


Figure 3C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for December 2004

Table V C. Water budget at Bunny Hole for December 2004

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 1037 | 6.1 | 100.00 |
| stemflow | 0 | 0.0 | 0.00 |
| throughfall | 34 | 0.2 | 3.28 |
| cave recharge | 0 | 0.0 | 0.00 |
| [a] interception | 1003 | 5.9 | 96.72 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table VI C. Cave recharge by bucket at Bunny Hole December 2004

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 0.00 | 0.00 | 0.00 | 0.00 |
| % of total recharge | 0.00 | 0.00 | 0.00 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

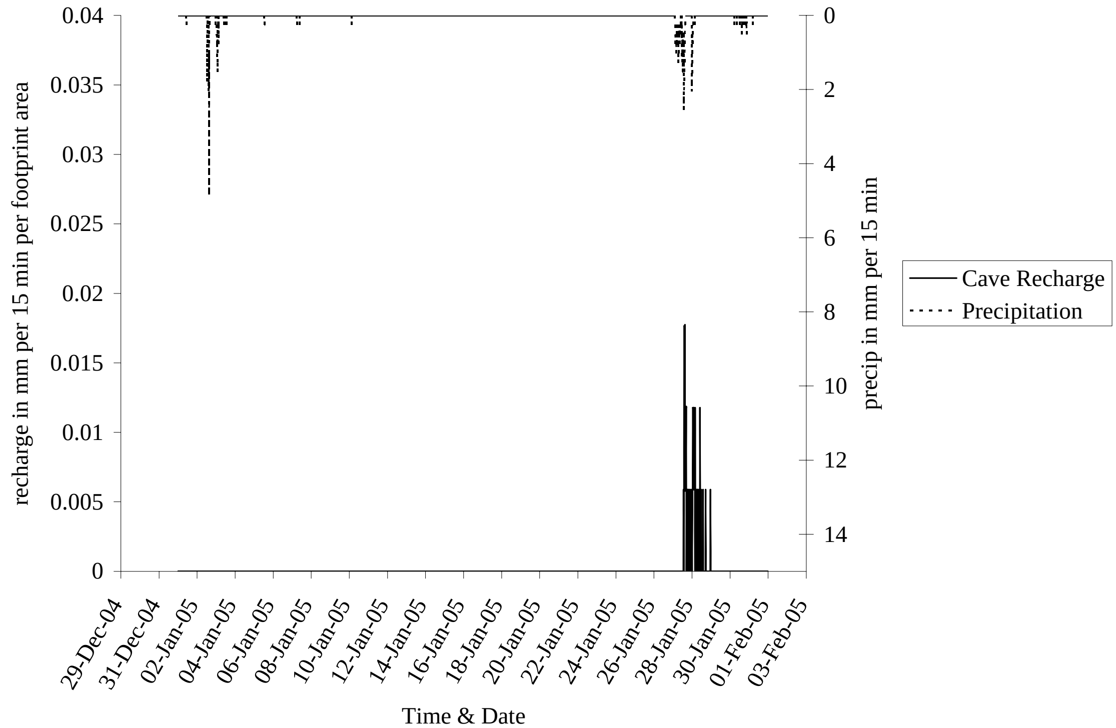


Figure 4C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for January 2005

Table VII C. Water budget at Bunny Hole for January 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 11475 | 67.5 | 100.00 |
| stemflow | 0 | 0.0 | 0.00 |
| throughfall | 0 | 0.0 | 0.00 |
| cave recharge | 67.5 | 0.4 | 0.59 |
| [a] interception | 0 | 0.0 | 0.00 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table VIII C. Cave recharge by bucket at Bunny Hole January 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 13.00 | 0.00 | 55.00 | 0.00 |
| % of total recharge | 19.12 | 0.00 | 80.88 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

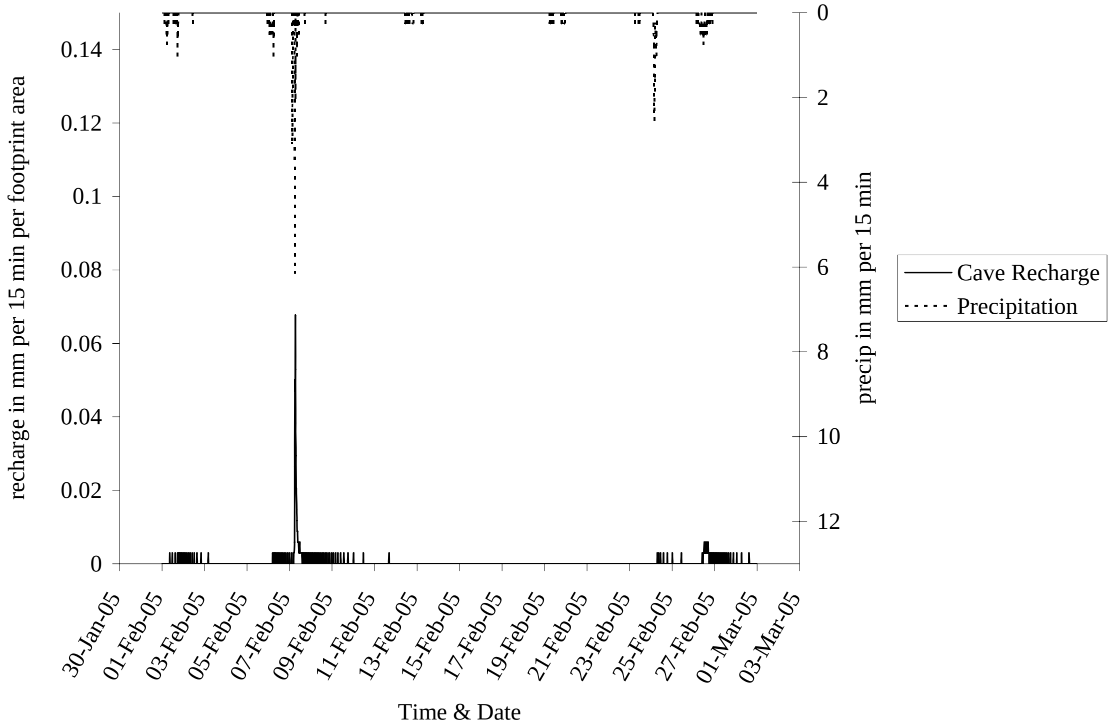


Figure 5C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for February 2005

Table IX C. Water budget at Bunny Hole for February 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 13600 | 80.0 | 100.00 |
| stemflow | 8.9 | 0.1 | 0.07 |
| throughfall | 3077 | 18.1 | 22.63 |
| cave recharge | 291.7 | 1.7 | 2.14 |
| [a] interception | 10520.9 | 61.9 | 77.36 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table X C. Cave recharge by bucket at Bunny Hole February 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 0.00 | 0.00 | 175.00 | 0.00 |
| % of total recharge | 0.00 | 0.00 | 100.00 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

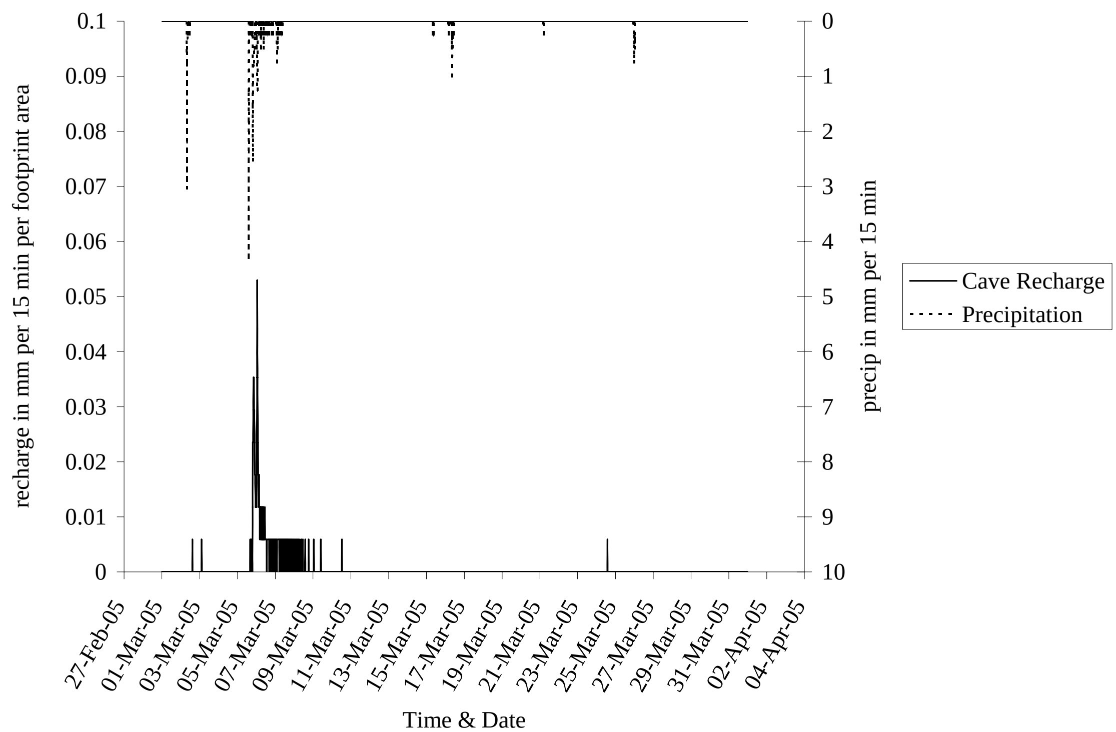


Figure 6C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for March 2005

Table XI C. Water budget at Bunny Hole for March 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 8024 | 47.2 | 100.00 |
| stemflow | 2.4 | 0.0 | 0.03 |
| throughfall | 4012 | 23.6 | 50.00 |
| cave recharge | 486.7 | 2.9 | 6.07 |
| [a] interception | 4009.6 | 23.6 | 49.97 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XII C. Cave recharge by bucket at Bunny Hole March 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 0.00 | 0.00 | 292.00 | 0.00 |
| % of total recharge | 0.00 | 0.00 | 100.00 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

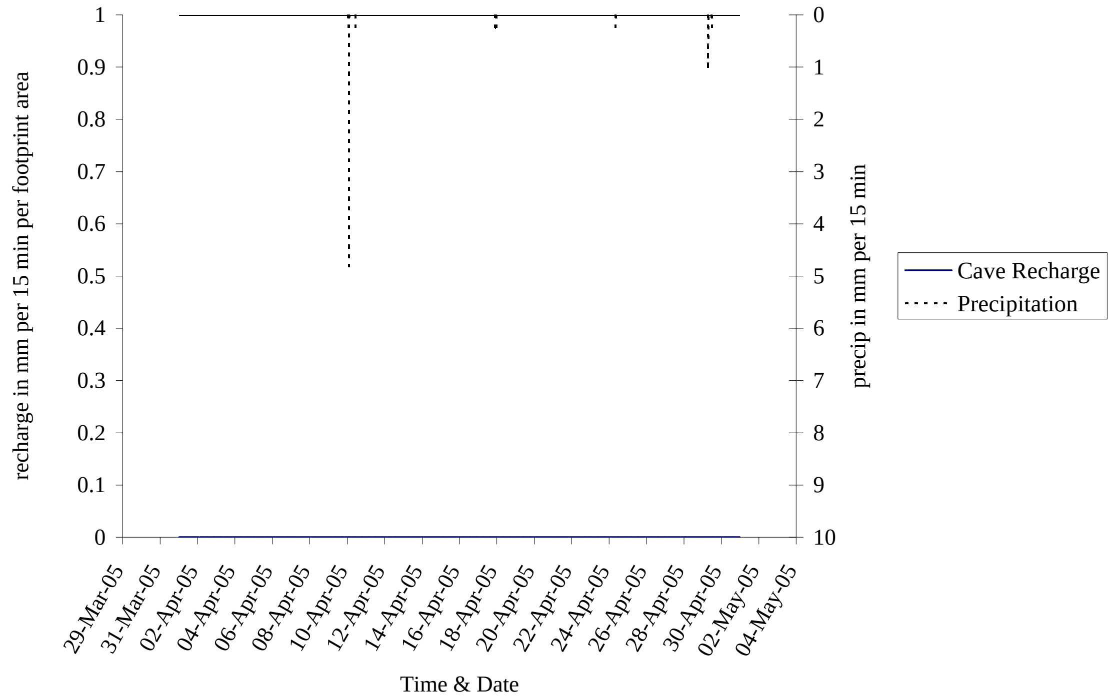


Figure 7C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for April 2005

Table XIII C. Water budget at Bunny Hole for April 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 1462 | 8.6 | 100.00 |
| stemflow | | | |
| throughfall | 578 | 3.4 | 39.53 |
| cave recharge | 0 | 0.0 | 0.00 |
| [a] interception | 892.5 | 5.3 | 61.05 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XIV C. Cave recharge by bucket at Bunny Hole April 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 0.00 | 0.00 | 0.00 | 0.00 |
| % of total recharge | 0.00 | 0.00 | 0.00 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

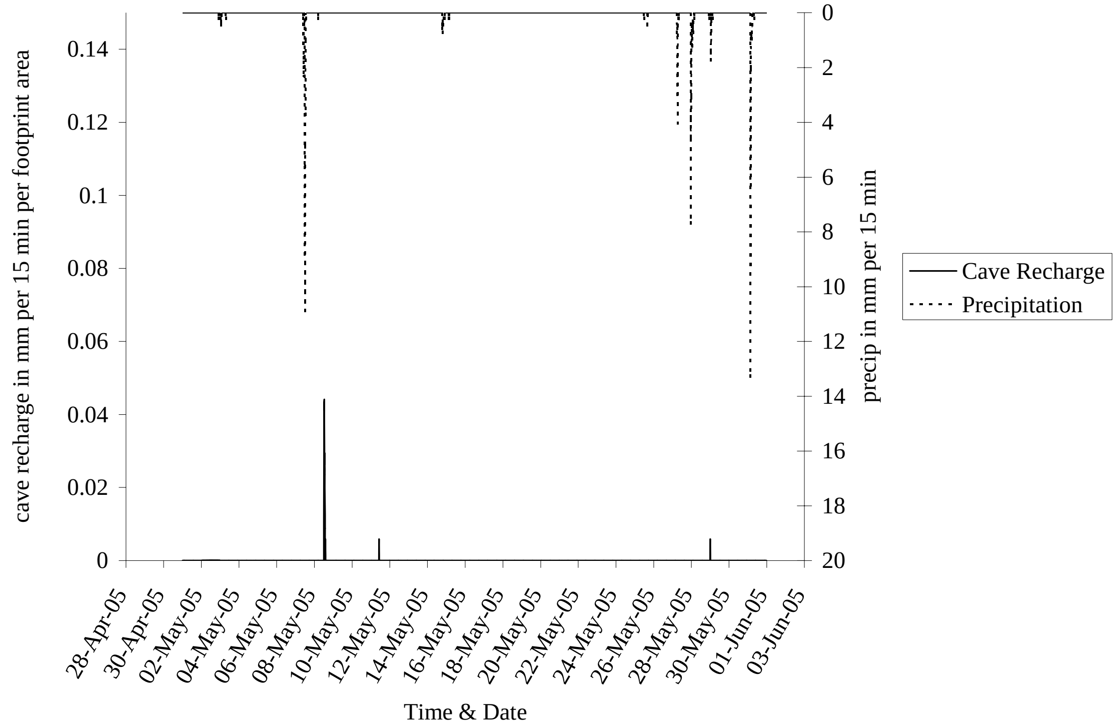


Figure 8C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for May 2005

Table XV C. Water budget at Bunny Hole for May 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 17782 | 104.6 | 100.00 |
| stemflow | 65.6 | 0.4 | 0.37 |
| throughfall | 14246 | 83.8 | 80.11 |
| cave recharge | 54.2 | 0.3 | 0.30 |
| [a] interception | 3470.4 | 20.4 | 19.52 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XVI C. Cave recharge by bucket at Bunny Hole May 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 2.00 | 1.50 | 29.00 | 0.00 |
| % of total recharge | 6.15 | 4.62 | 89.23 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

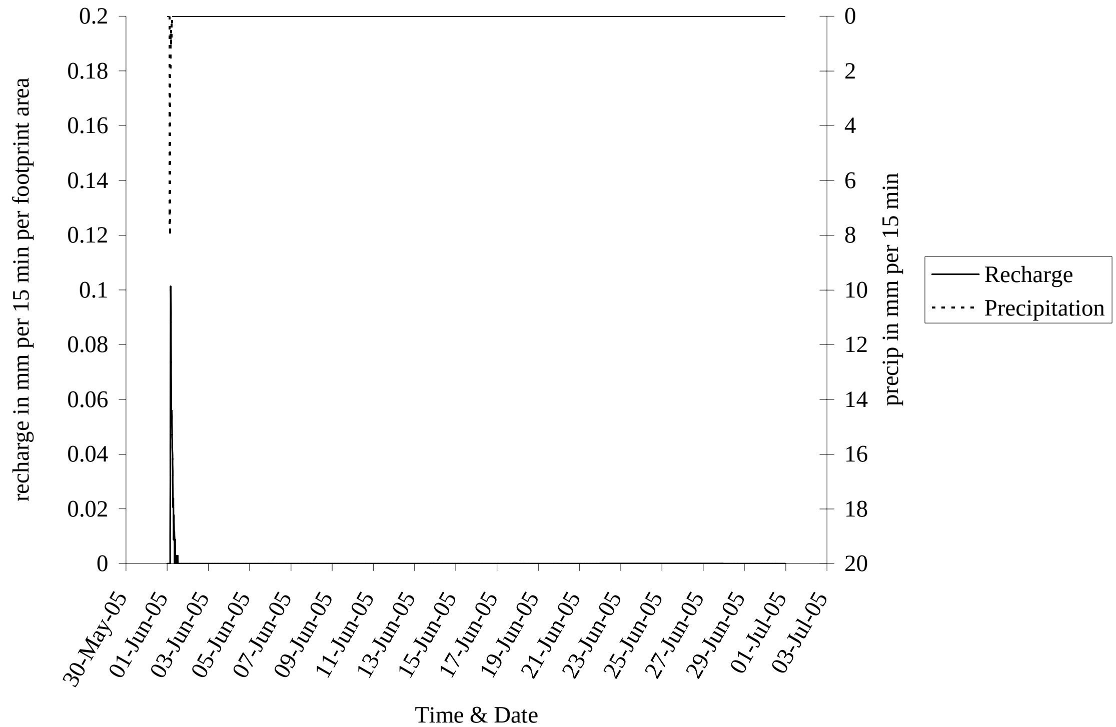


Figure 9C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for June 2005

Table XVII C. Water budget at Bunny Hole
For June 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 4709 | 27.7 | 100.00 |
| stemflow | 30.6 | 0.2 | 0.65 |
| throughfall | 0 | 0.0 | 0.00 |
| cave recharge | 237.5 | 1.4 | 5.04 |
| [a] interception | 0 | 0.0 | 0.00 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XVIII C. Cave recharge by bucket at Bunny Hole June 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 25.00 | 28.50 | 89.00 | 0.00 |
| % of total recharge | 16.67 | 19.00 | 59.33 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

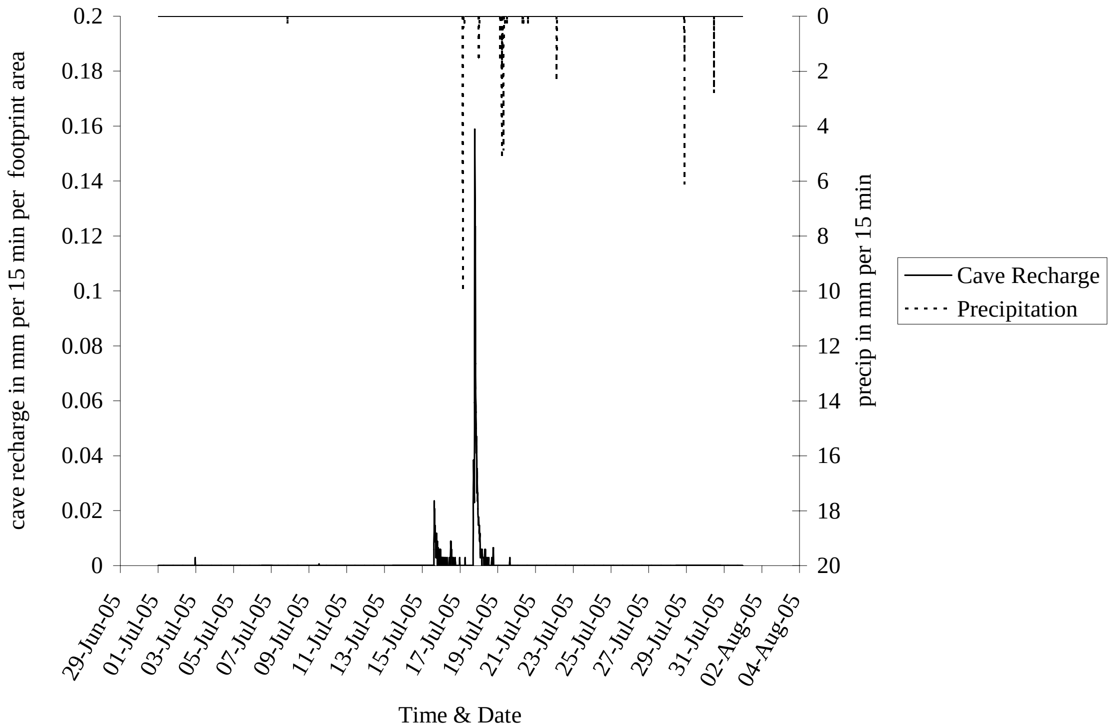


Figure 10C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for July 2005

Table XIX C. Water budget at Bunny Hole for July 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 9673 | 56.9 | 100.00 |
| stemflow | 18 | 0.1 | 0.19 |
| throughfall | 1530 | 9.0 | 15.82 |
| cave recharge | 660.3 | 3.9 | 6.83 |
| [a] interception | 8131.8 | 47.8 | 84.07 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table X. Cave recharge by bucket at Bunny Hole July 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 110.00 | 130.00 | 155.00 | 1.20 |
| % of total recharge | 27.76 | 32.81 | 39.12 | 0.30 |

Recharge L are not scaled up to account for uncollected drips

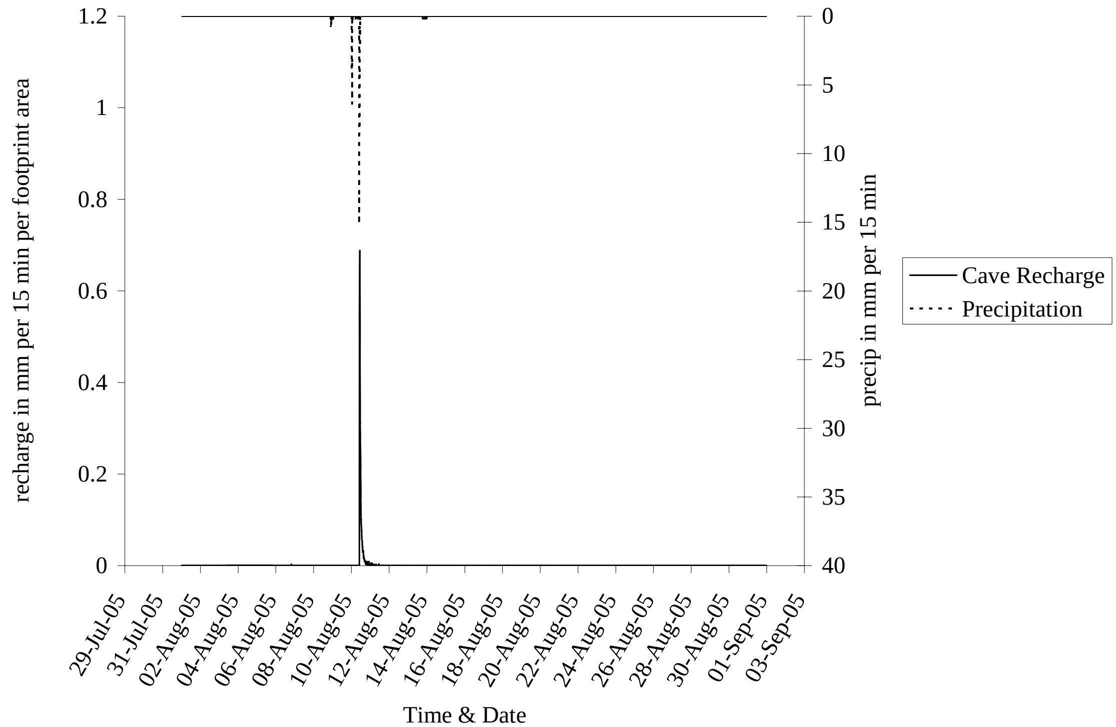


Figure 11C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for August 2005

Table XXI C. Water budget at Bunny Hole for August 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 8891 | 52.3 | 100.00 |
| stemflow | 64.4 | 0.4 | 0.72 |
| throughfall | 4811 | 28.3 | 54.11 |
| cave recharge | 1069.7 | 6.3 | 12.03 |
| [a] interception | 4015.6 | 23.6 | 45.16 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XXI. Cave recharge by bucket at Bunny Hole August 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 396.00 | 128.00 | 117.00 | 0.80 |
| % of total recharge | 61.70 | 19.94 | 18.23 | 0.12 |

Recharge L are not scaled up to account for uncollected drips

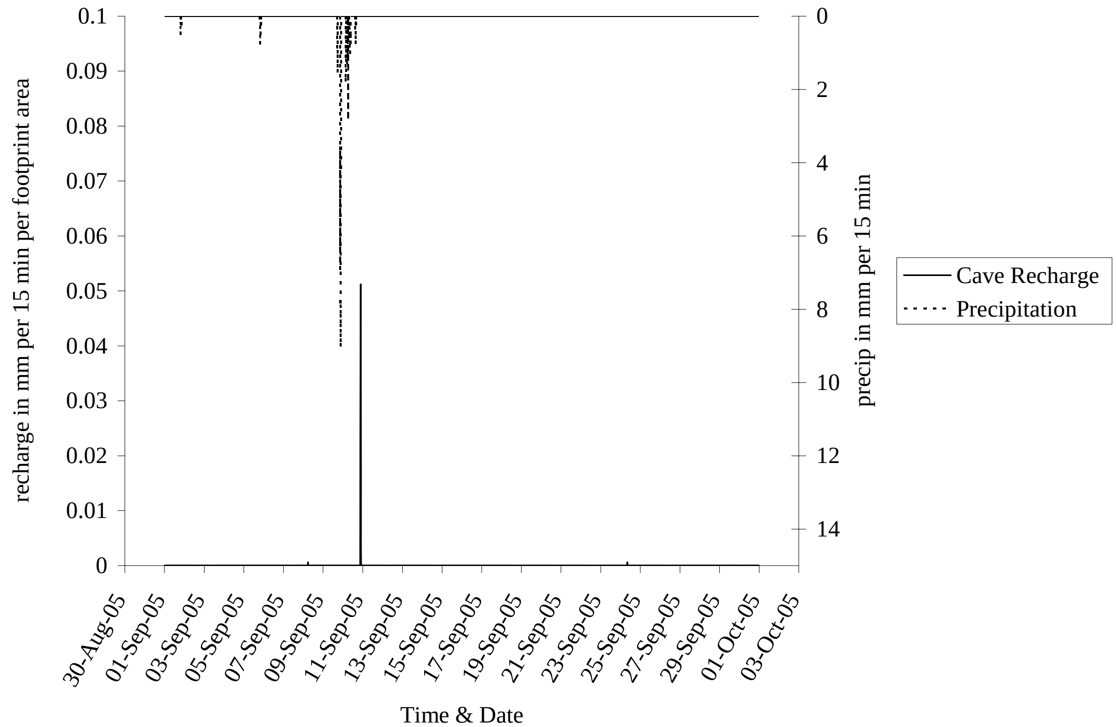


Figure 12C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for September 2005

Table XXIII C. Water budget at Bunny Hole for September 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 7684 | 45.2 | 100.00 |
| stemflow | 41.3 | 0.2 | 0.54 |
| throughfall | 4267 | 25.1 | 55.53 |
| cave recharge | 31 | 0.2 | 0.40 |
| [a] interception | 3375.7 | 19.9 | 43.93 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XXIV C. Cave recharge by bucket at Bunny Hole September 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 13.00 | 0.00 | 55.00 | 0.00 |
| % of total recharge | 19.12 | 0.00 | 80.88 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

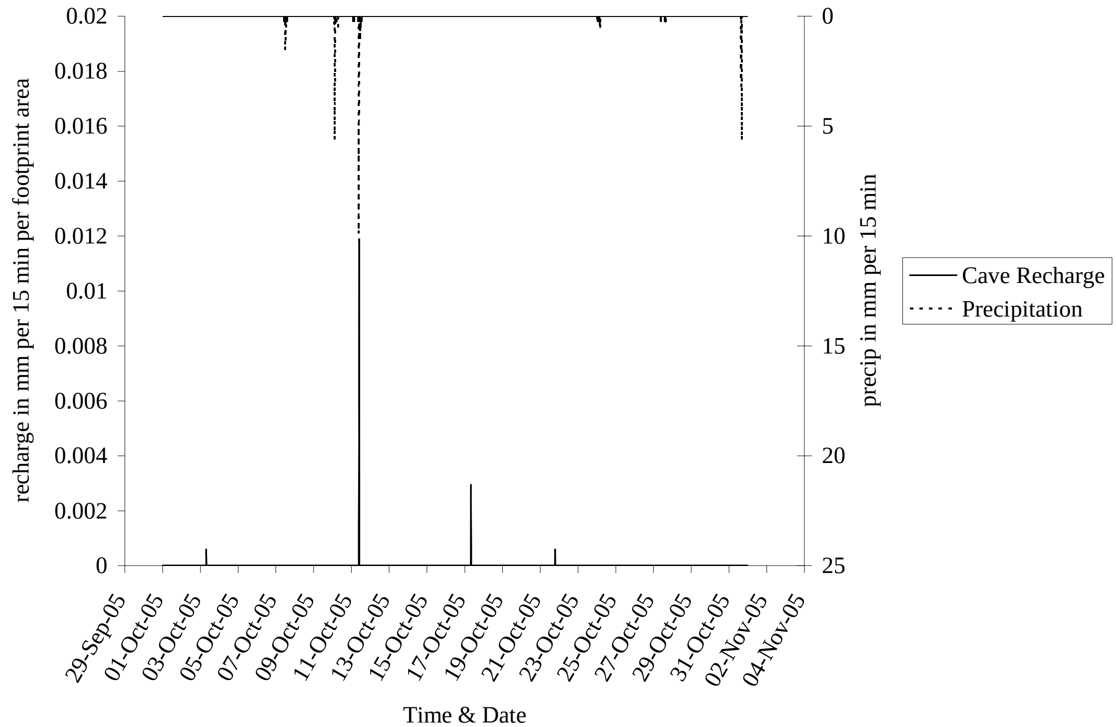


Figure 13C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for October 2005

Table XXV C. Water budget at Bunny Hole for October 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 8126 | 47.8 | 100.00 |
| stemflow | 54.1 | 0.3 | 0.67 |
| throughfall | 6970 | 41.0 | 85.77 |
| cave recharge | 6.2 | 0.0 | 0.08 |
| [a] interception | 1098.5 | 6.5 | 13.52 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XXVI C. Cave recharge by bucket at Bunny Hole October 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 1.00 | 0.50 | 2.00 | 0.20 |
| % of total recharge | 27.03 | 13.51 | 54.05 | 5.41 |

Recharge L are not scaled up to account for uncollected drips

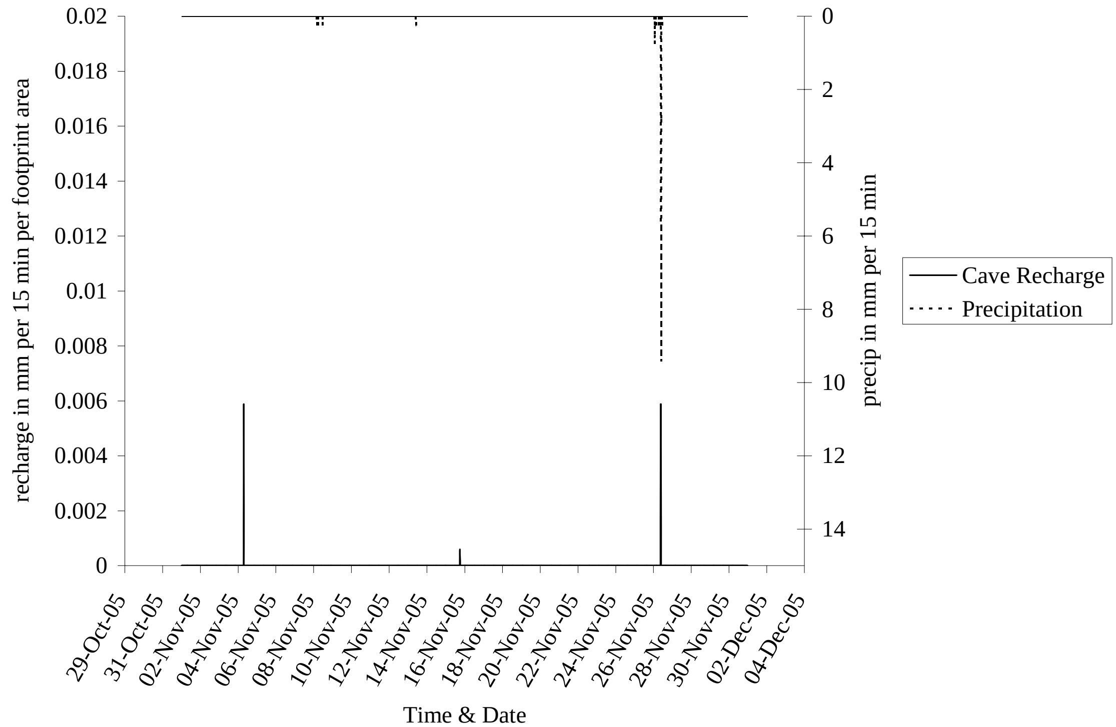


Figure 14C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for November 2005

Table XXVII C. Water budget at Bunny Hole for November 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 2805 | 16.5 | 100.00 |
| stemflow | 37.2 | 0.2 | 1.33 |
| throughfall | 1241 | 7.3 | 44.24 |
| cave recharge | 5.2 | 0.0 | 0.19 |
| [a] interception | 1521.7 | 9.0 | 54.25 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XXVIII C. Cave recharge by bucket at Bunny Hole November 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 1.00 | 0.00 | 2.00 | 0.10 |
| % of total recharge | 32.26 | 0.00 | 64.52 | 3.23 |

Recharge L are not scaled up to account for uncollected drips

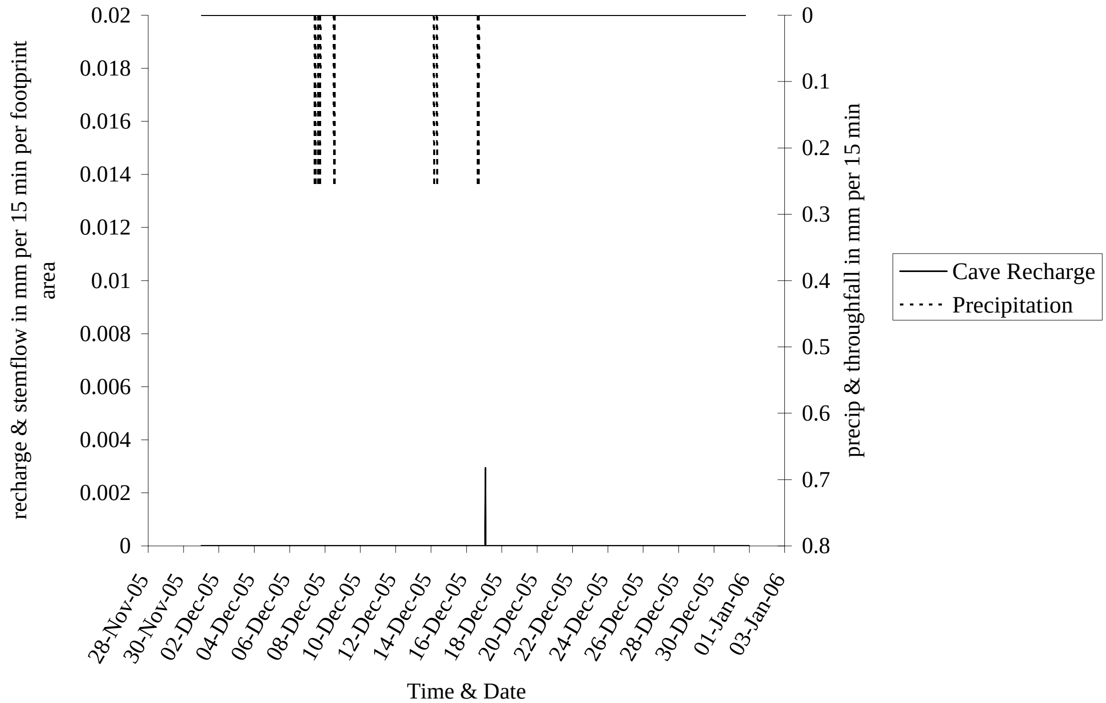


Figure 15C. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for December 2005

Table XXIX C. Water budget at Bunny Hole for December 2005

| **Monthly Total** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 431.8 | 2.5 | 100.00 |
| stemflow | 2.4 | 0.0 | 0.56 |
| throughfall | 25.5 | 0.2 | 5.91 |
| cave recharge | 0.8 | 0.0 | 0.19 |
| [a] interception | 403.9 | 2.4 | 93.54 |

[a] Interception is estimated by subtracting stemflow and throughfall from precipitation

Table XXX C. Cave recharge by bucket at Bunny Hole December 2005

| **Tipping Bucket #** | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| recharge L collected | 0.00 | 0.00 | 0.50 | 0.00 |
| % of total recharge | 0.00 | 0.00 | 100.00 | 0.00 |

Recharge L are not scaled up to account for uncollected drips

# APPENDIX D

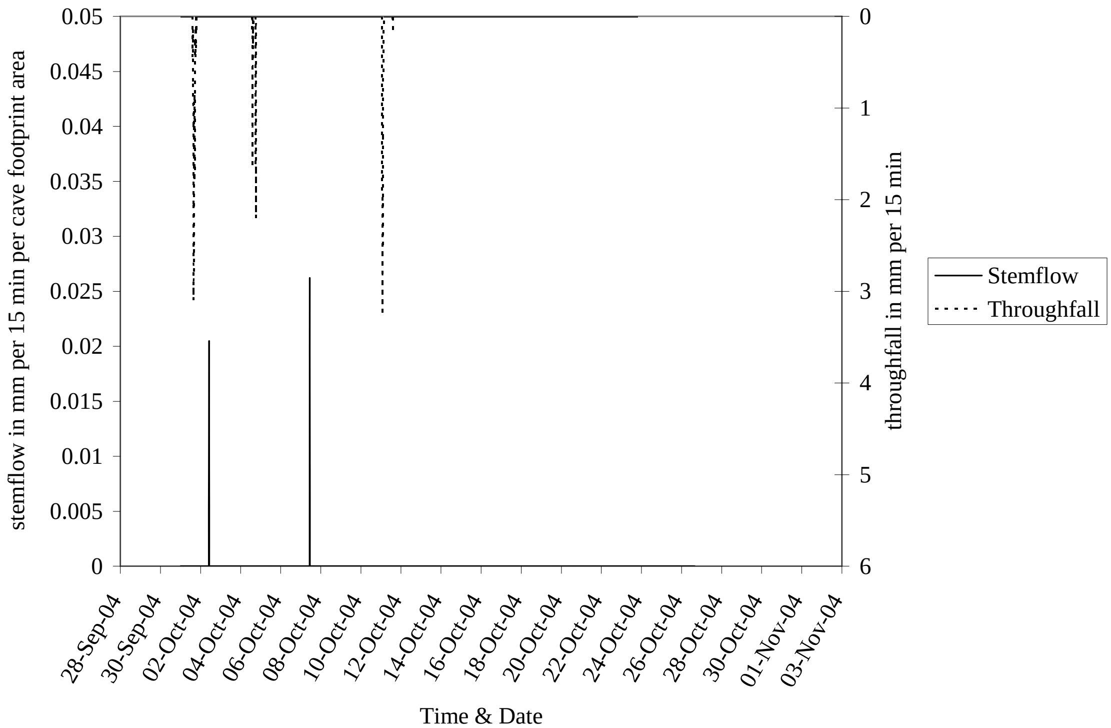


Figure 1D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in October 2004

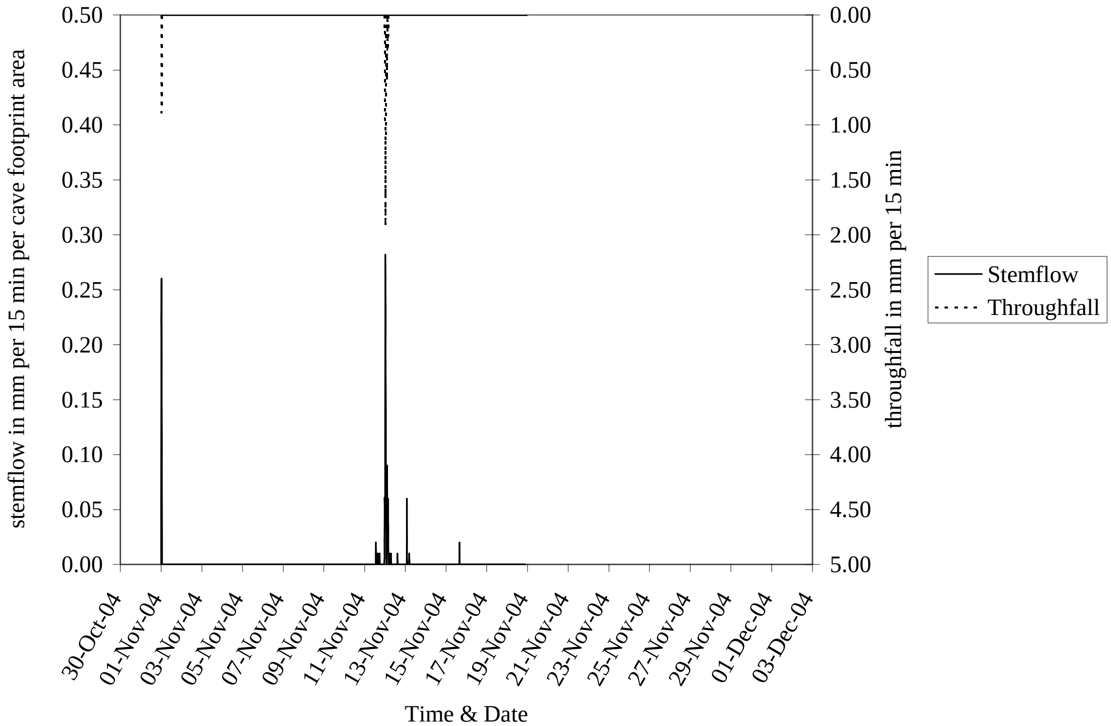


Figure 2D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in November 2004

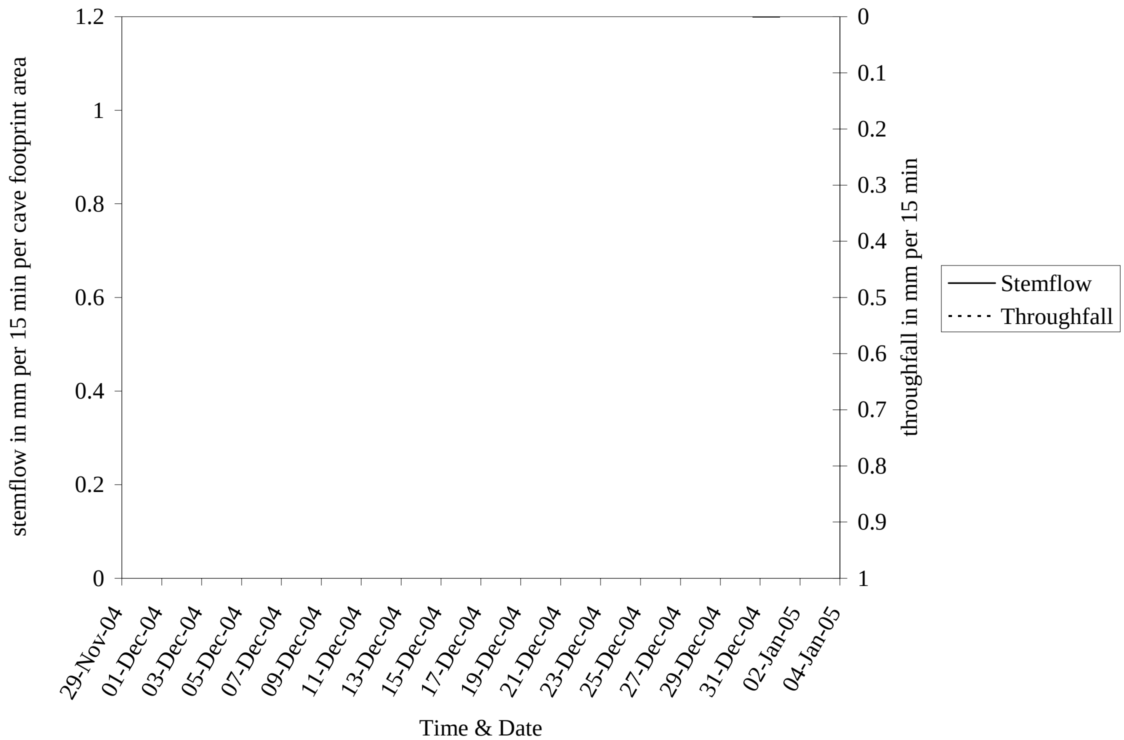


Figure 3D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in December 2004

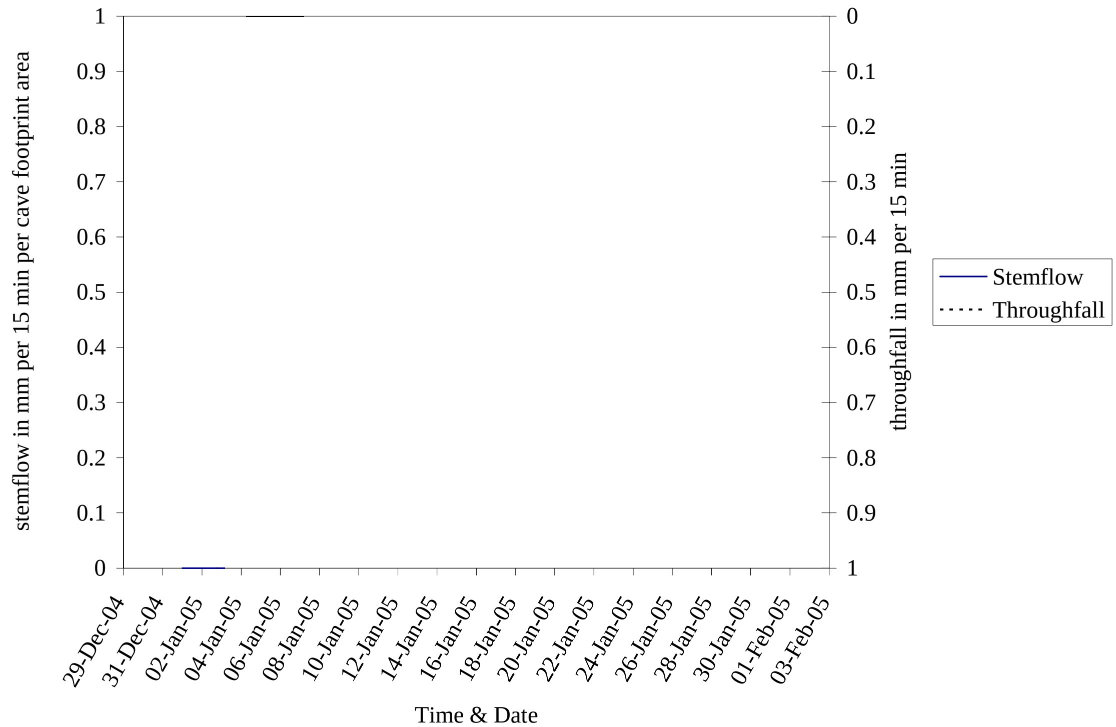


Figure 4D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in January 2005

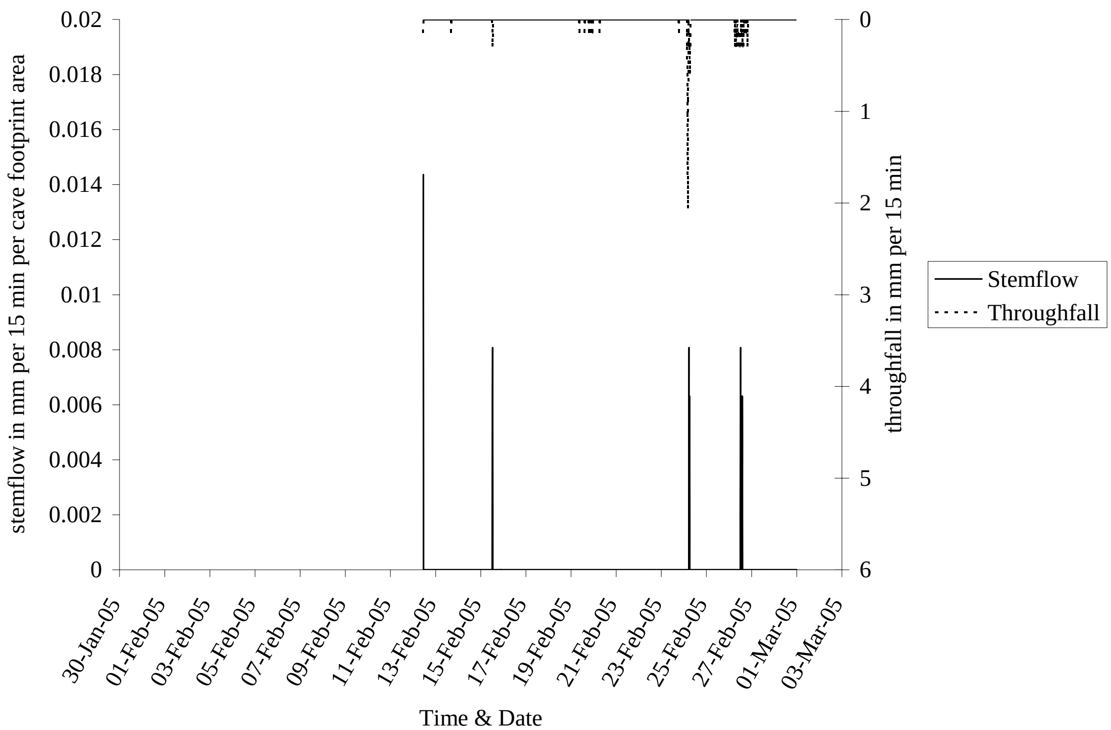


Figure 5D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in February 2005

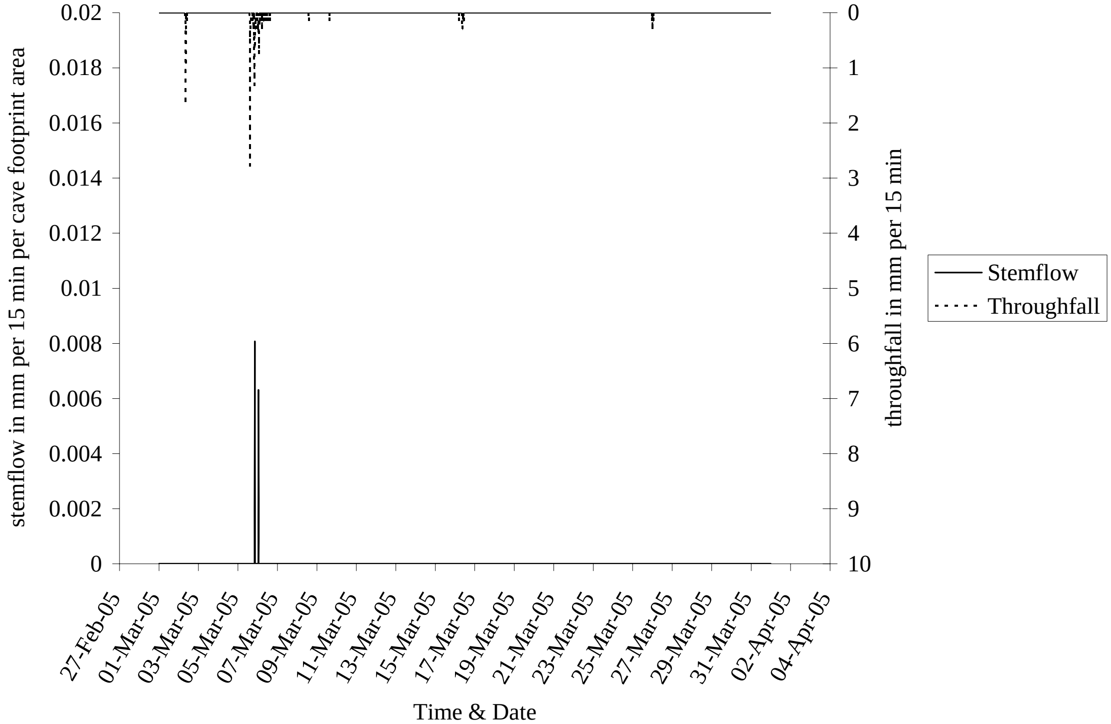


Figure 6D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in March 2005

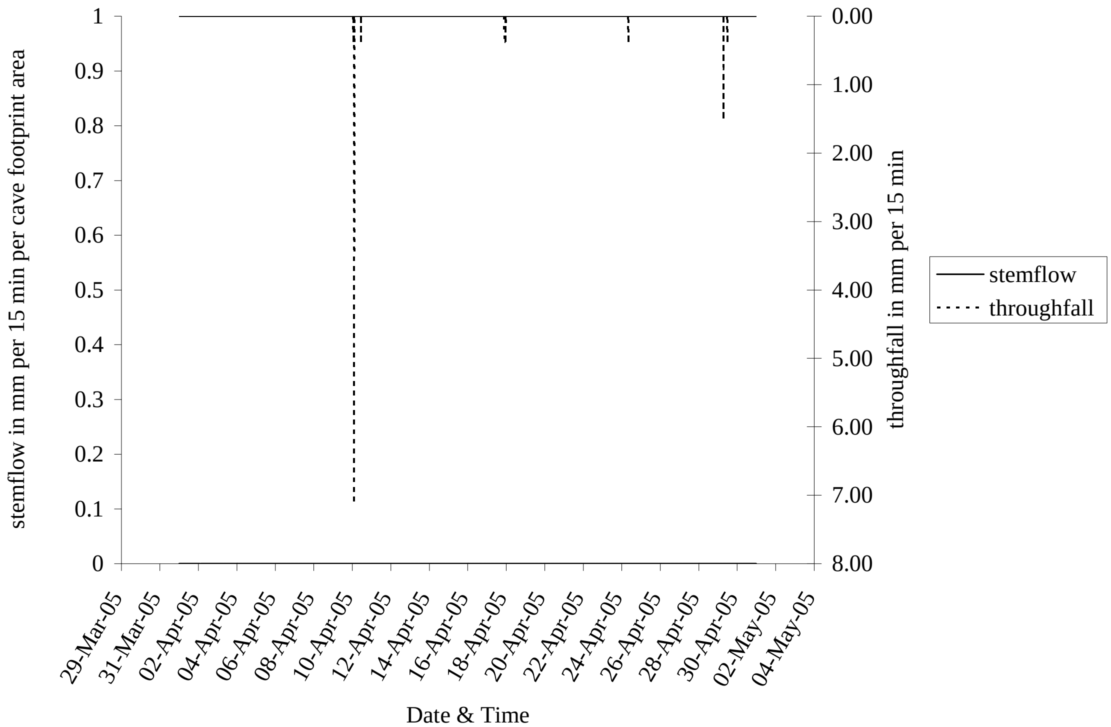


Figure 7D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in April 2005

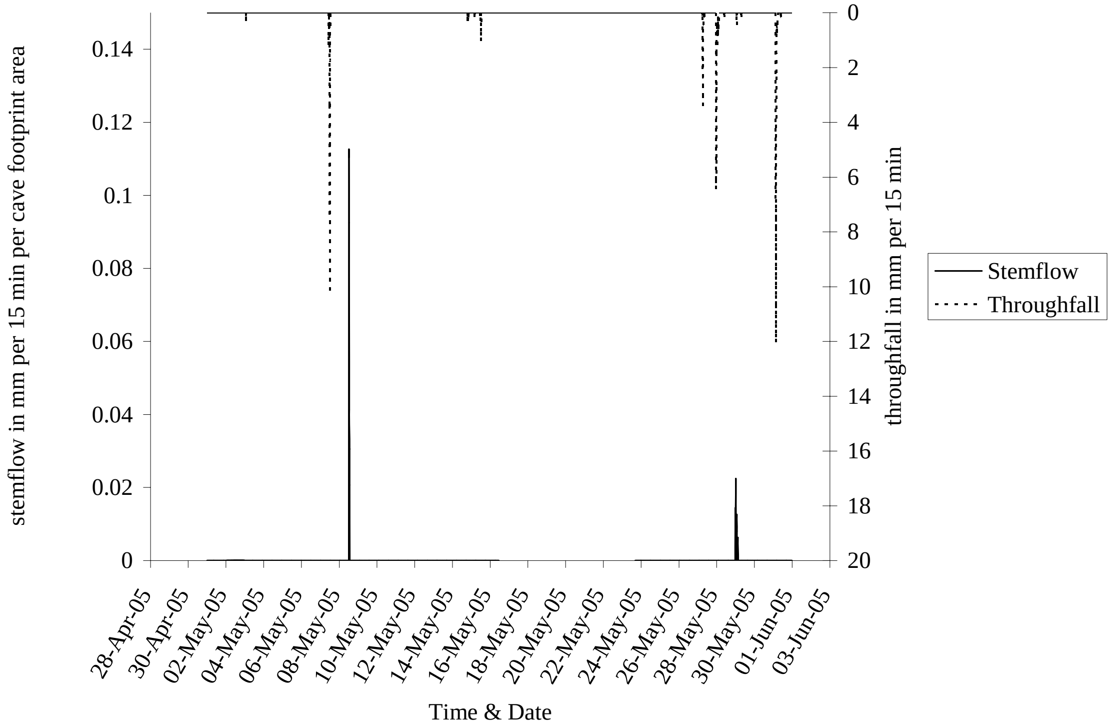


Figure 8D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in May 2005

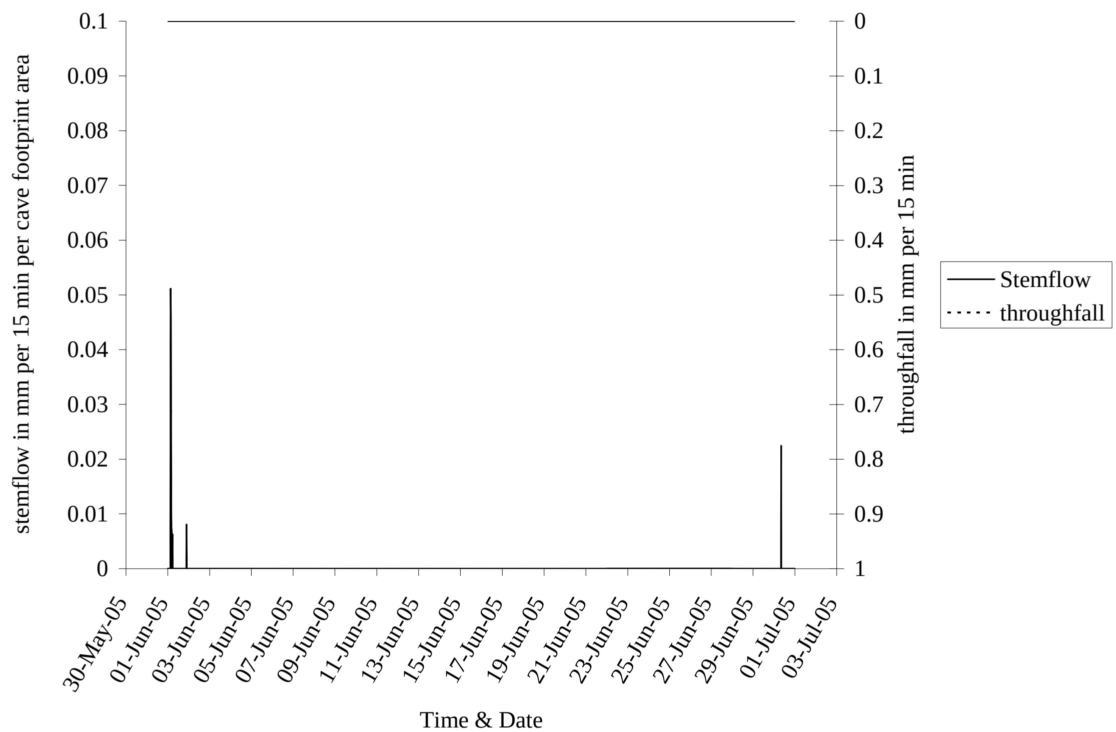


Figure 9D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in June 2005

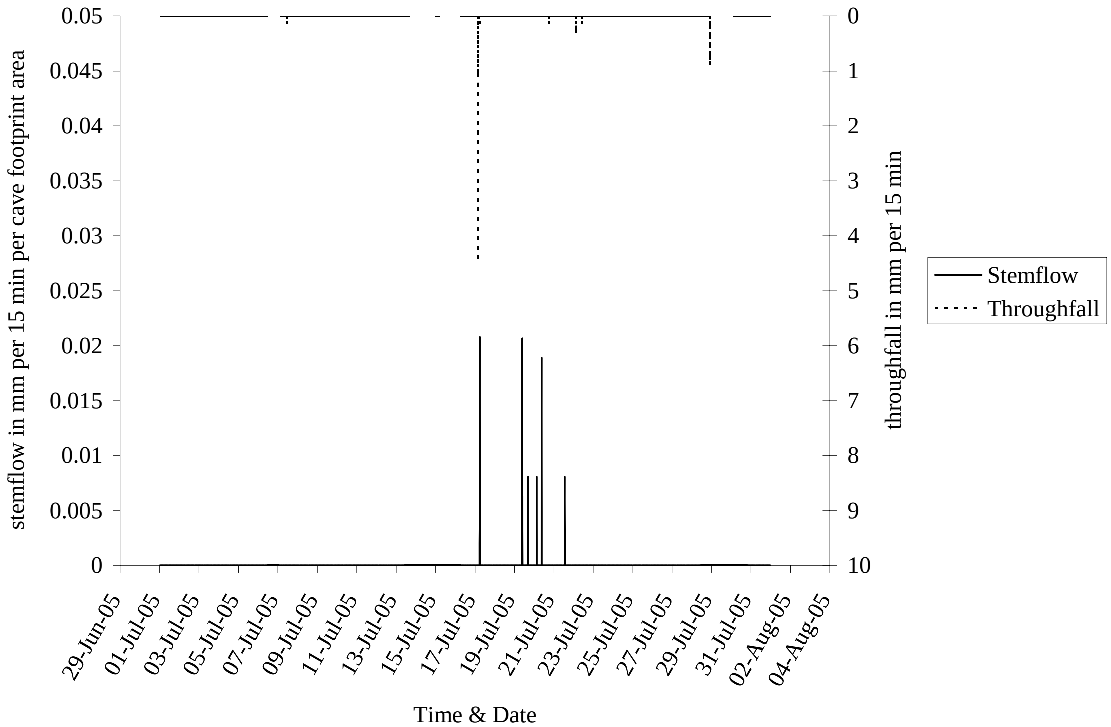


Figure 10D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in July 2005

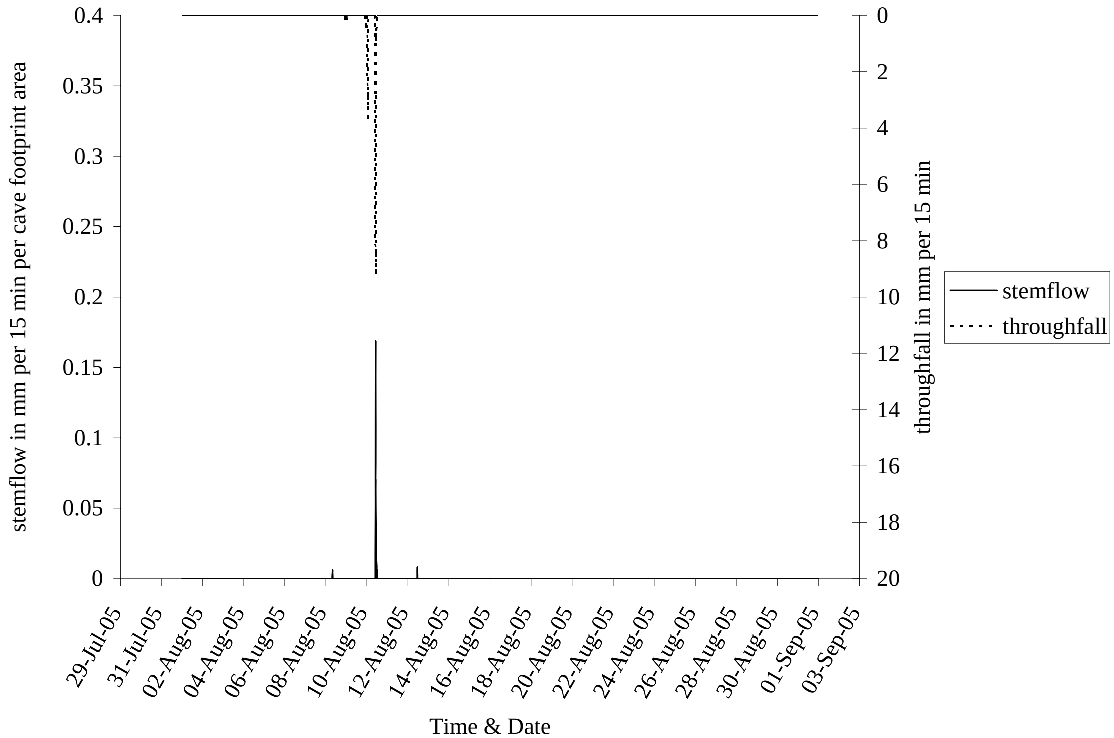


Figure 11D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in August 2005

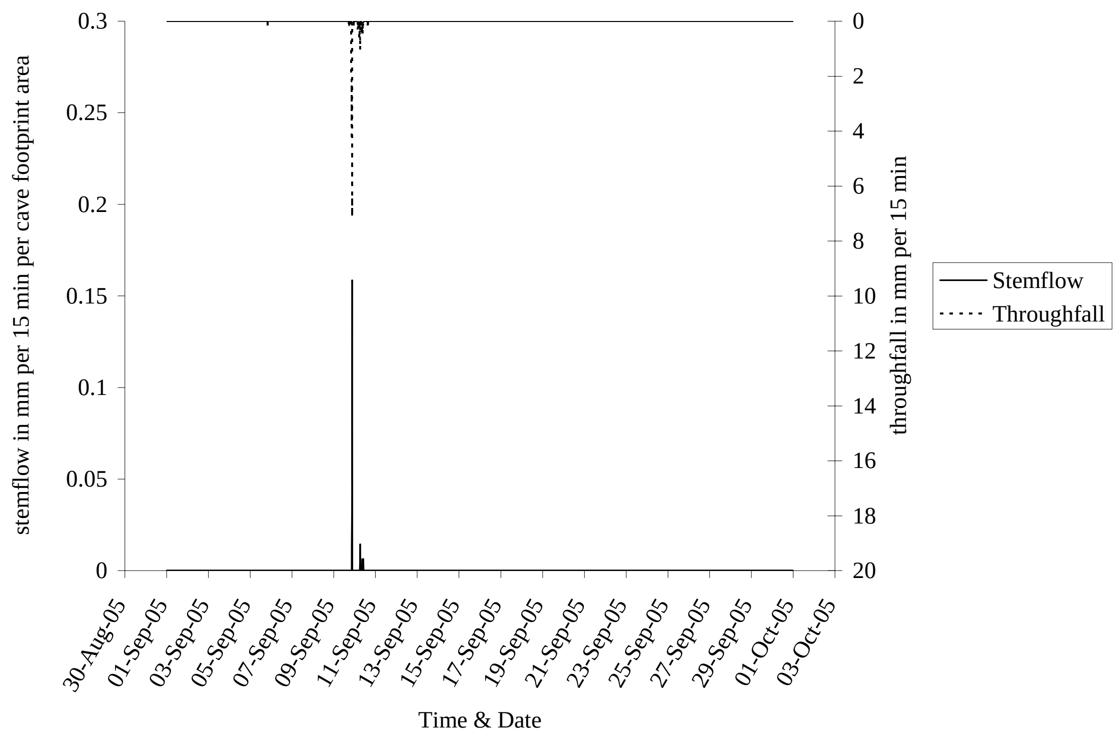


Figure 12D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in September 2005

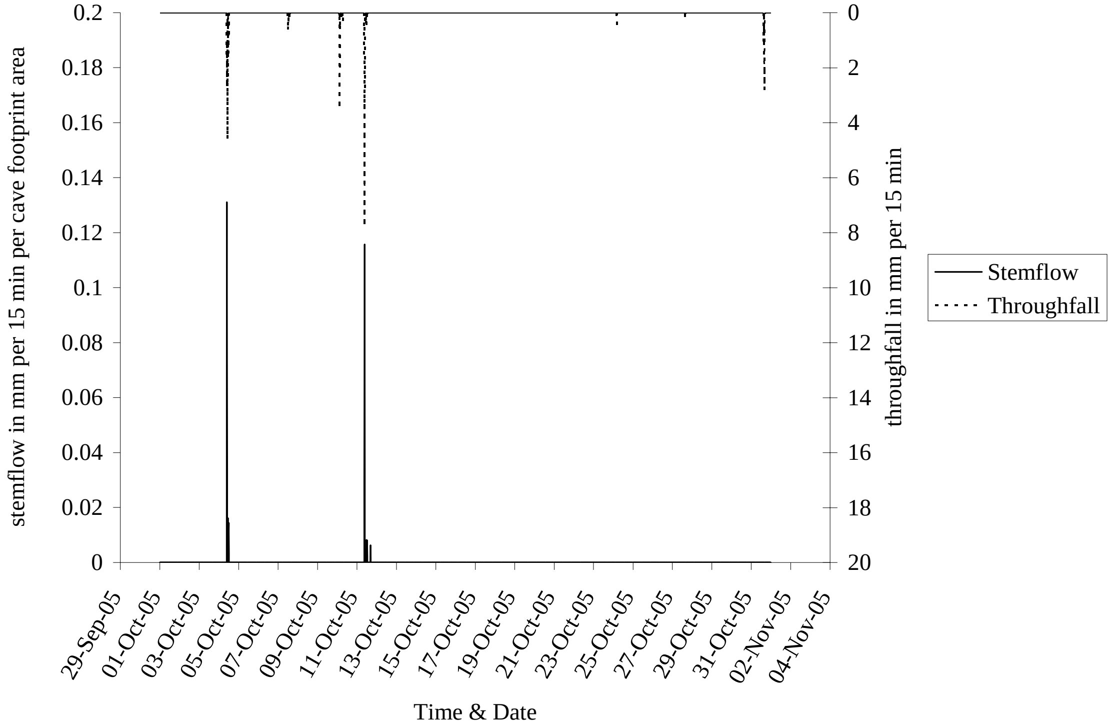


Figure 13D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in October 2005

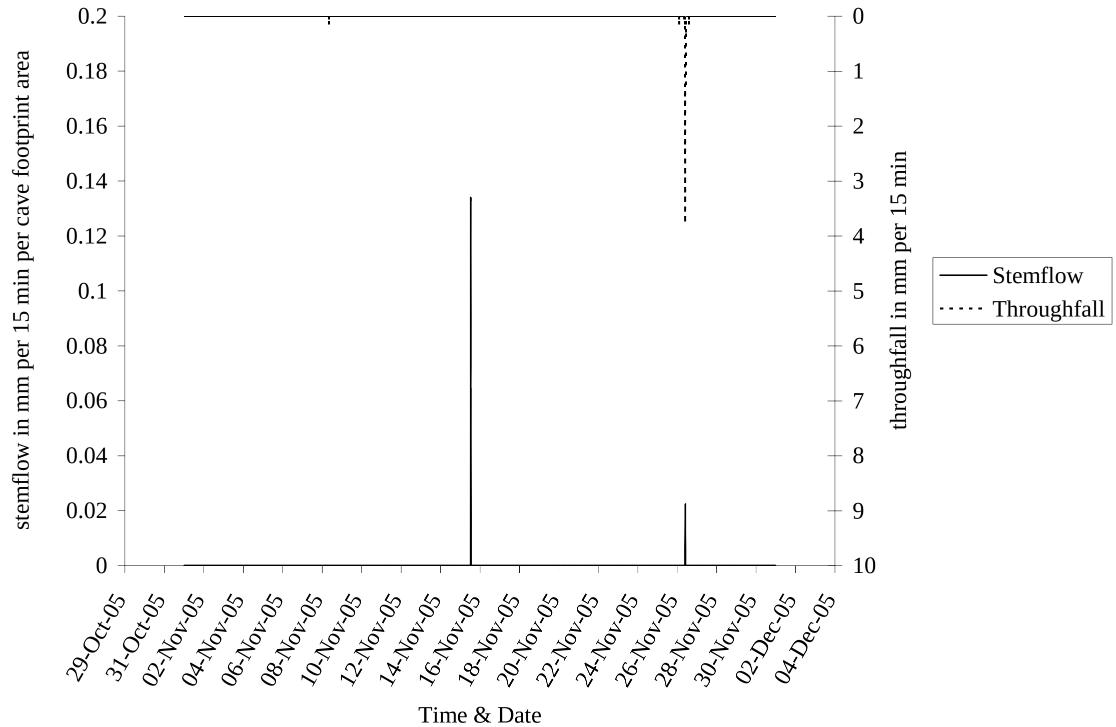


Figure 14D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in November 2005

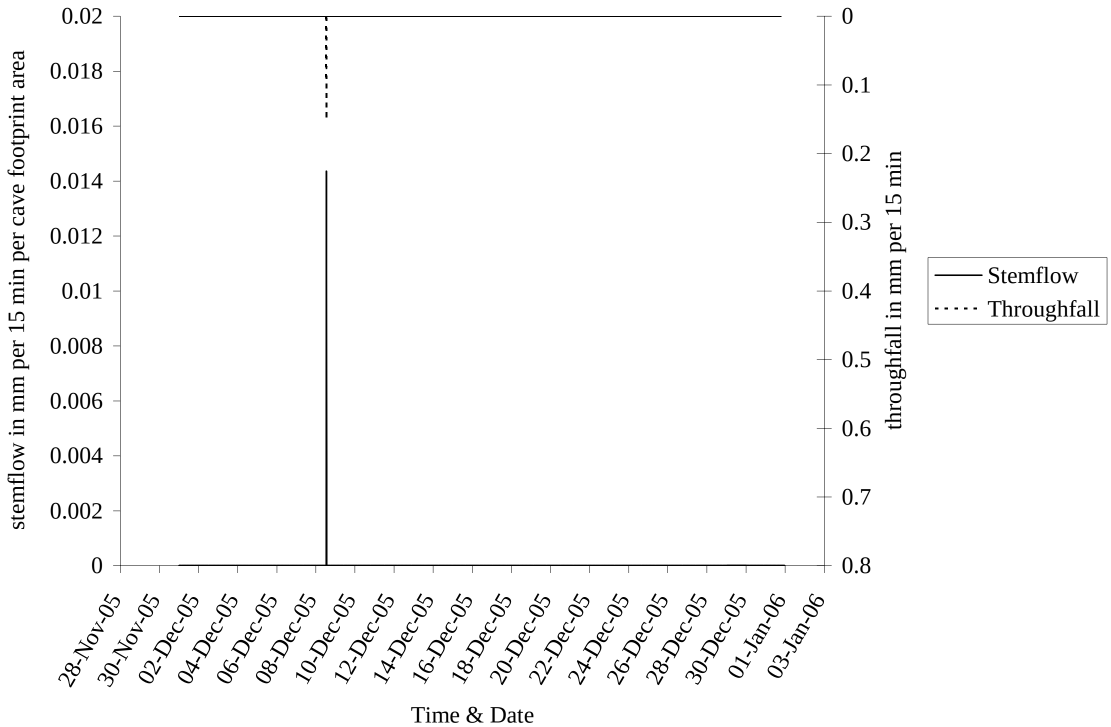


Figure 15D. Hydrograph of throughfall versus stemflow in mm per cave footprint area at Bunny Hole in December 2005

# APPENDIX E

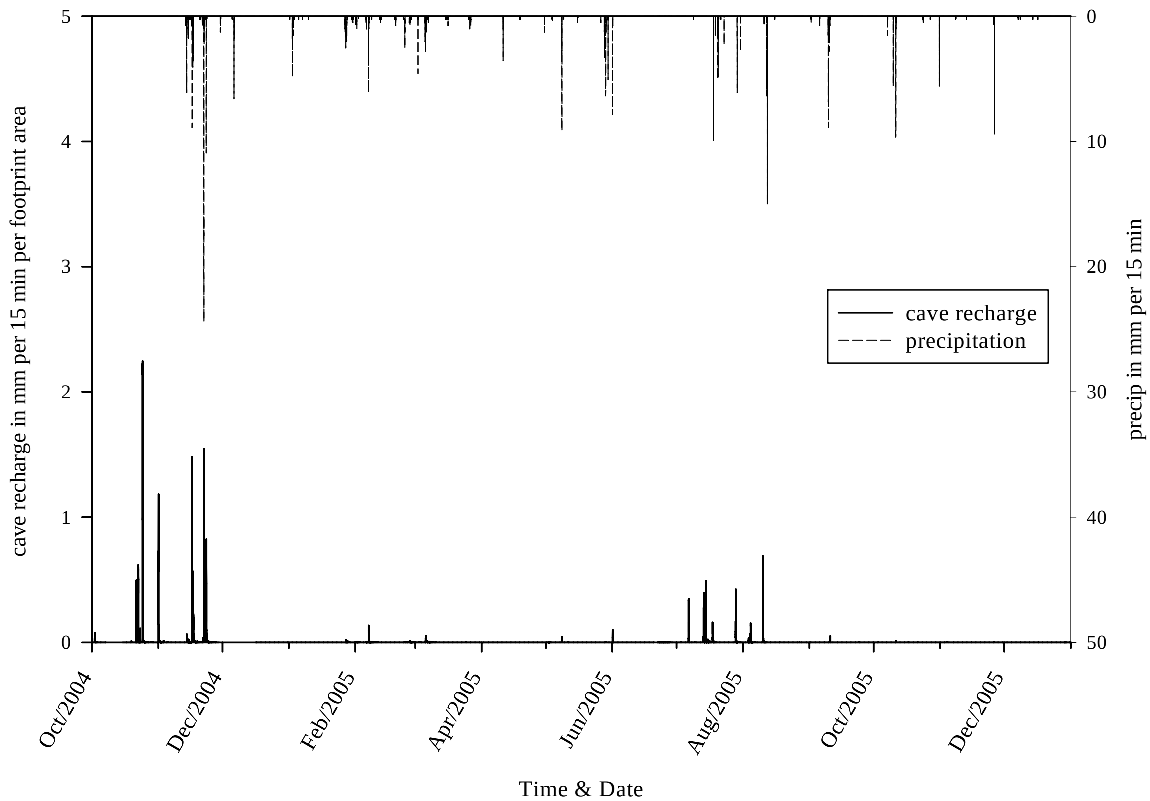


Figure 1E. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for October 2004 to December 2005

Table I E. Water budget at Bunny Hole for October 2004 through December 2005

| **Totals** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 154207 | 907.1 | 100.00 |
| stemflow | 428.1 | 2.5 | 0.28 |
| throughfall | 48456.8 | 285.0 | 31.42 |
| water reaching surface | 105322.1 | 619.6 | 68.3 |
| cave recharge | 25051.8 | 147.4 | 16.25 |
| [a] interception | 90602 | 533.0 | 58.75 |
| storage/subsurface flow/ET | 80270.3 | 472.2 | 52.1 |

[a] Interception values are estimates derived by subtracting stemflow and throughfall from precipitation and its accuracy depends on the accuracy of the other measures.

This budget includes all data collected; numerous gaps exist

Cave recharge numbers are low due to equipment failure throughout the year

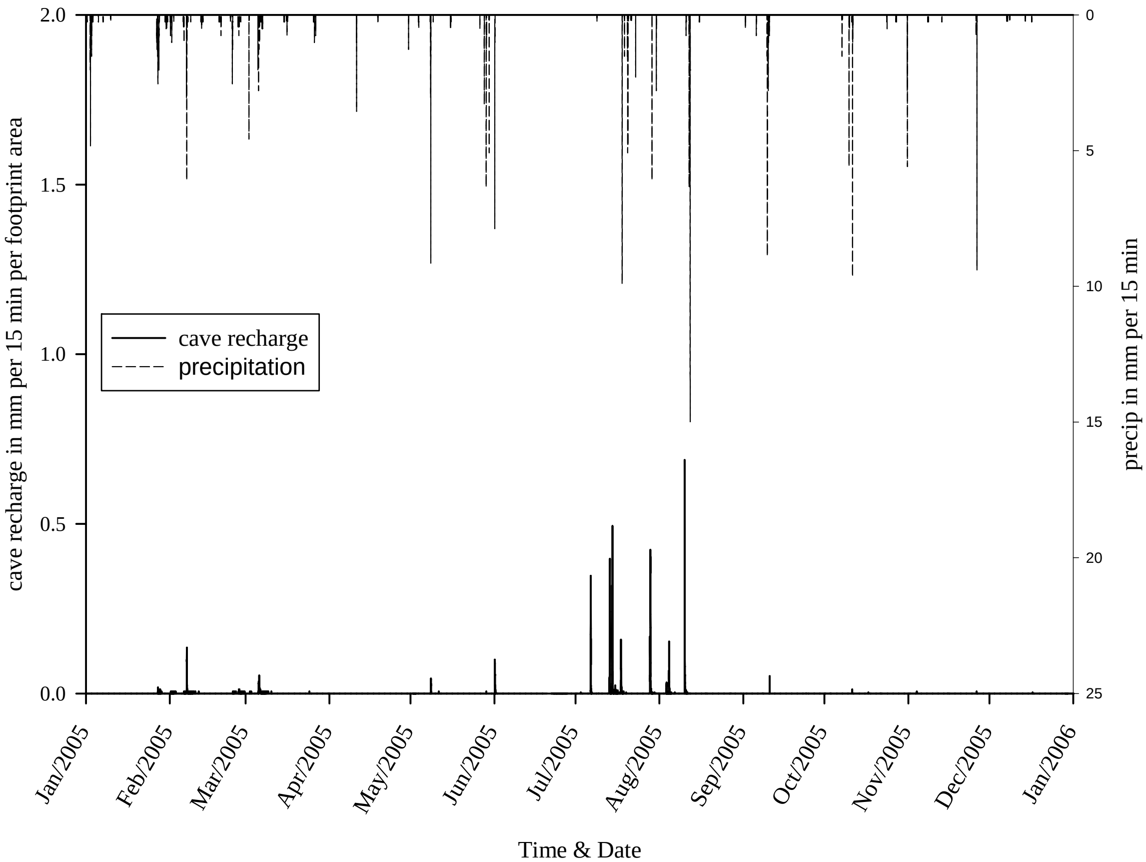


Figure 2E. Hydrograph of precipitation versus cave recharge in mm per cave footprint area at Bunny Hole for 2005

Table II E. Water budget at Bunny Hole for 2005

| **Yearly Totals** | Liters | mm | Percent |
|---|---|---|---|
| precipitation | 67983 | 399.9 | 100.00 |
| stemflow | 324.7 | 1.9 | 0.48 |
| throughfall | 40766 | 239.8 | 59.96 |
| water reaching surface | 41090.7 | 241.7 | 60.4 |
| cave recharge | 2910.8 | 17.1 | 4.28 |
| [a] interception | 26894 | 158.2 | 39.56 |
| storage/subsurface flow/ET | 38179.9 | 224.6 | 56.2 |

[a] Interception values are estimates derived by subtracting stemflow and throughfall from precipitation and its accuracy depends on the accuracy of the other measures

This budget only includes events for which data were collected

Cave recharge numbers are low due to equipment failure throughout the year

# VITA

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Publications: Gregory LF, Veni G, Shade BL, Wilcox BP, Munster CL, Owens MK. 2005. Quantifying recharge via fractures in an Ashe Juniper dominated karst landscape. Proc. Sinkholes and the Engineering Environmental Impacts of Karst, B.F. Beck, ed. September 24-28, 2005, San Antonio, Texas. Geotechnical Special Publication no. 144, ASCE. p. 216-223.

Posters presented:

Monitoring cave recharge in the Edwards Aquifer Recharge Zone for natural and simulated rainfall events. American Geophysical Union Conference, December 5-9, 2005. San Francisco, California.

Quantifying recharge via fractures in an Ashe Juniper dominated karst landscape. Sinkholes and the Engineering Environmental Impacts of Karst Conference, September 24-28, 2005. San Antonio, Texas.

Quantifying the water budget in an Ashe juniper dominated karst landscape. American Geophysical Union Joint Assembly, May 23-27, 2005. New Orleans, Louisiana.

Experience: Research Assistant for the Texas Agricultural Experiment Station from October 2003 to May 2006.