

NCKRI REPORT OF INVESTIGATION 8

**KARST HYDROGEOLOGY SCOPING INVESTIGATION OF
THE SAN SOLOMON SPRING AREA:
CULBERSON, JEFF DAVIS, AND REEVES COUNTIES, TEXAS**



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February 2018



Published and distributed by

National Cave and Karst Research Institute

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400-1 Cascades Avenue
Carlsbad, NM 88220 USA

www.nckri.org

The citation information:

Land L, Veni G. 2018. Karst Hydrogeology Scoping Investigation of the San Solomon Spring Area: Culberson, Jeff Davis, and Reeves Counties, Texas. National Cave and Karst Research Institute Report of Investigation 8, Carlsbad, New Mexico.

Cover photo: Dr. Lewis Land examines East Sandia Spring, the furthest downgradient spring of the San Solomon Spring Group.

ISBN: 978-0-9910009-9-9

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and
- 6) promote and develop environmentally sound and sustainable resource management practices.

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KARST HYDROGEOLOGY SCOPING INVESTIGATION OF THE SAN SOLOMON SPRING AREA: CULBERSON, JEFF DAVIS, AND REEVES COUNTIES, TEXAS

Lewis Land and George Veni
National Cave and Karst Research Institute

Introduction

In 2016, Apache Corporation announced the discovery of Alpine High, a large oil and gas complex in West Texas in the southwest corner of the Delaware Basin near the junction of Culberson, Jeff Davis, and Reeves counties. Excitement about this announcement has been tempered by concern about the potential impact of the development on water resources and water quality in the region (e.g., Myers, 2016). The southwest edge of the Delaware Basin contains the San Solomon Spring Group, a series of karst springs that discharge groundwater from Cretaceous limestones along the northeast flank of the Davis Mountains. The springs and related groundwater provide water resources for much

of the agricultural activity in the area, and municipal water supplies for the towns of Balmorhea and Toyahvale (Figure 1). The main San Solomon Spring is the centerpiece of Balmorhea State Park, another important component of the local economy (Figure 2; “San Solomon Spring” refers to this spring, while “San Solomon Springs” refers to the San Solomon Spring Group).

While regional flow patterns are broadly understood relative to the San Solomon Spring Group (e.g., LaFave and Sharp, 1987; Sharp, 2001; Sharp et al., 2003), specific details of the hydrogeology of the aquifer that feeds those springs are not well-constrained. Existing

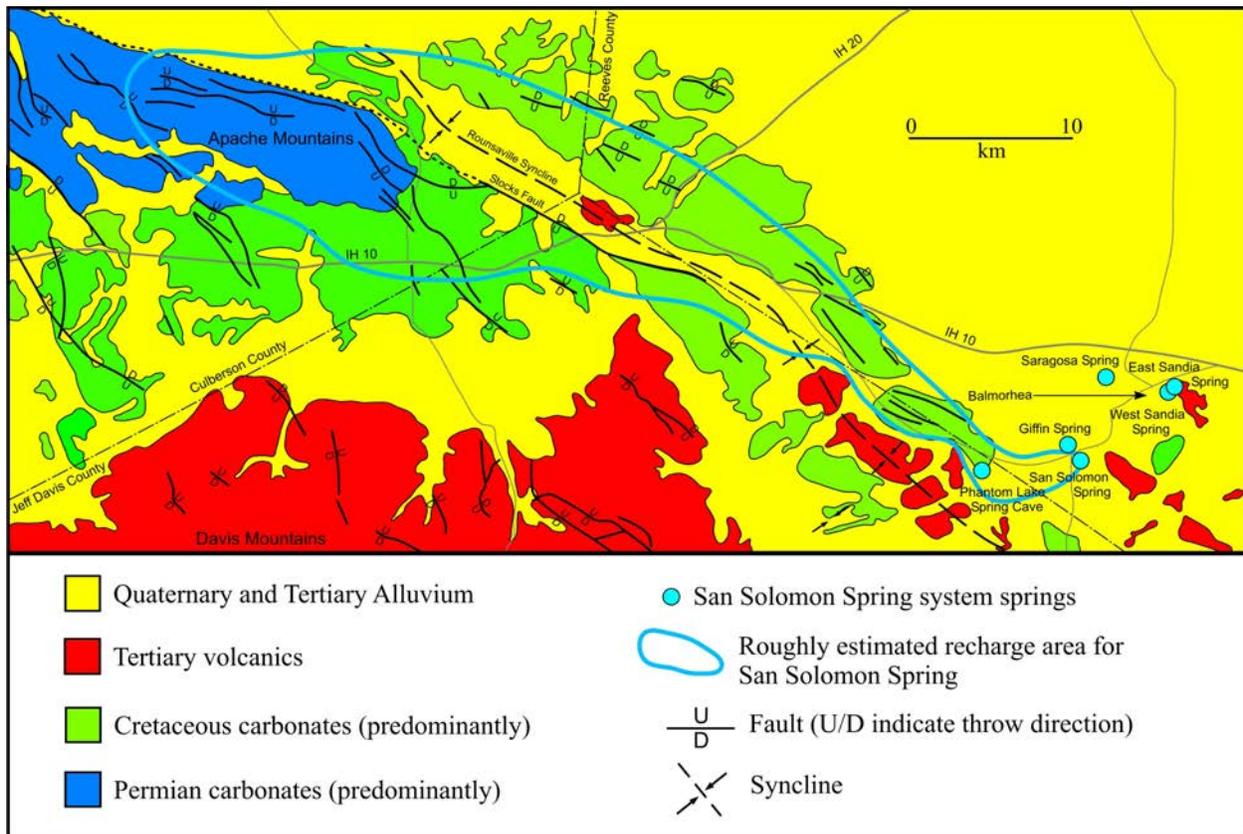


Figure 1. Hydrogeologic map of the San Solomon Spring system area (Veni, 2013; based on Barnes, 1975; 1976; 1979; 1982).



Figure 2. San Solomon Spring at Balmorhea State Park.

conceptual models of regional flow systems are based primarily on geochemical data (e.g., Chowdhury et al., 2004; Uliana et al., 2006), and there has been very little analysis of hydraulic and geologic data to support these models of regional flow. Apache Corporation contracted the National Cave and Karst Research Institute (NCKRI) to conduct this scoping study. This report is not intended to be an independent assessment of previous work conducted in the area. The purpose of the study is to evaluate all available relevant data and literature in order to recommend a series of investigations to better characterize the San Solomon Springs' aquifer system. These investigations will focus on the local and regional hydrologic framework of the aquifer, and the potential for impact by future development activity in the area, including oil and gas production, agricultural activity, municipal groundwater withdrawals, industrial activity, and groundwater export development projects (e.g., Finch, 2017).

This scoping study evaluates published and unpublished reports and data potentially valuable to understanding the hydrogeology of the aquifer and spring group, and considers their utility toward investigations of the following research topics:

- Accurate delineation of the San Solomon Spring

Group's groundwater drainage basin.

- Identification of major groundwater flow paths to the individual springs, in addition to the two municipal public water supply wells and other notable water wells in the area.
- Establishing groundwater flow velocities, dispersion, dilution, and related flow conditions along the flow paths to those springs and wells.
- Determining the proportion of spring flows derived from the matrix, fracture, and conduit flow segments of the aquifer.
- Ascertaining if the springs downgradient of San Solomon Spring (i.e., Saragosa Spring, East and West Sandia Springs) are influenced more by flow through karstic conduits, which would decrease travel times to the springs and decrease the potential for attenuation of contaminants, or if flow is occurring primarily through the alluvial aquifer, which would increase travel times and increase natural attenuation of contaminants.

Data types examined for this scoping study include but are not limited to geologic mapping, geophysical mapping, hydrologic mapping, groundwater levels, groundwater discharge, groundwater chemistry, groundwater models, spring, cave, and karst information, biological data that may reflect groundwater flow conditions,

groundwater tracing studies, well logs, and well pumping data. Sources examined for data include:

- **Federal agencies:** US Bureau of Reclamation, US Fish and Wildlife Service, US Geological Survey.
- **State agencies:** Texas Bureau of Economic Geology, Texas Commission on Environmental Quality, Texas Natural Resources Information System, Texas Parks and Wildlife Department, Texas Railroad Commission, Texas Water Development Board.
- **Regional agencies:** Jeff Davis County Underground Water Conservation District, Reeves County Groundwater Conservation District, High Point, Toyah-Limpia, and Upper Pecos Soil and Water Conservation Districts.
- **Private organizations:** Apache Corporation, Madera Valley Water Supply Corporation, Texas Speleological Survey, The Nature Conservancy.

This report does not cite the broad set of materials that duplicate the references cited herein. It also does not include a review of oil and gas data or other information that does not provide insight into the hydrogeology of the San Solomon Spring Group and its aquifer.

Historical spring and groundwater management

The San Solomon Springs were used by Native Americans since prehistoric times; their irrigation canals were visible as late as 1898 (Hutson, 1898). The springs became known to European explorers and settlers in 1583 when Spanish explorer Antonio de Espejo made the historic discovery of San Solomon Spring (Castañeda, 1936). Modern settlement of the area did not begin until the mid-1800s with the establishment of the nearby town of Balmorhea, named for three of the early developers of the area—Balcom, Morrow, and Rhea (LaFave and Sharp, 1987; Miller and Nored, 1993). An irrigation canal was excavated in 1853 that carried flow from Phantom Lake Spring Cave northeast to agricultural fields (Brune, 1975).

There has been long-term interest in the volume of flow from the San Solomon Springs. Ridgeway et al. (2005) suggested that a magnitude 6.0 earthquake that affected the region in 1931 may have affected spring discharge through altered historic groundwater flow paths by allowing cementation of regional fracture systems. However, historical data are insufficient to confirm a correlation between seismic events and diminished spring flow, so

this hypothesis remains untested. Ashworth et al. (1997) examined declines in San Solomon system spring flows and concluded that they resulted from decreased rainfall since 1992 to the date of their study. However, Brune (1981) showed that the drought of record in the 1950s had no measurable effect on flow from Phantom Lake Spring Cave. Brune (1981) did, however, document generally sustained declines in flow from East Sandia Spring, Phantom Lake Spring Cave, San Solomon Spring, and Saragosa Spring since 1945, when irrigation pumping began to increase greatly and major declines in water levels occurred in the adjacent Cenozoic Pecos Alluvium Aquifer in the Toyah Basin in northern Reeves County (Texas Water Development Board, 1986; Sharp, 2001). Although irrigation pumping in the Toyah Basin would not directly affect groundwater discharge from the San Solomon Springs Group, it could cause diversion of a component of the regional flow system originating in Wildhorse Flat that recharges both the Cenozoic Pecos Alluvium and the San Solomon Springs (Sharp et al., 2003).

The effect of diminished spring flow has been most obvious at Phantom Lake Spring Cave. Observing this decline, the cave was purchased by the US Bureau of Reclamation, in cooperation with the US Fish and Wildlife Service (USFWS), and a refugium canal and pool were built in 1993 to protect the populations of the Comanche Springs Pupfish (*Cyprinodon elegans*) (Figure 3) and Pecos Gambusia (*Gambusia nobilis*), which are federally listed as endangered species. In 1999, flow ceased from the cave's entrance and in May 2000 the US Bureau of Reclamation began pumping water from



Figure 3. Comanche Springs pupfish (circled).

inside the cave to the refugium pool, which flows over a small dam back into the cave, to sustain the species (Figure 4; Edwards, 2001). In addition to these fish, USFWS (2012) has proposed federal endangered species listing and establishing critical habitat for three aquatic invertebrates that are known only from East Sandia Spring, Giffin Spring, Phantom Lake Spring Cave, and San Solomon Spring: The Phantom Cave Snail (*Pyrgulopsis texana*), Phantom Springsnail (*Tryonia cheatumi*), and a diminutive amphipod (*Gammarus hyalleloides*). The principal environmental concern in the study area is thus preservation of water resources and water quality in the local aquifer system feeding the springs that provide habitat for these species. Veni (2013) examined the potential impacts of climate change on the spring system and its ecosystem.

Hydrogeology

Balmorhea area

The San Solomon Spring Group is located at the western edge of the Edwards Plateau in Jeff Davis and Reeves counties, Texas. The springs are located in and near the small communities of Balmorhea and Toyahvale, and Balmorhea State Park, which are surrounded by rural pasture and farmland. The spring system is comprised of the following six springs distributed over a 13-km long corridor extending southwest to northeast from Phantom Lake Spring Cave (Figure 1; precise coordinates are not provided in this public report to protect the endangered species habitat the springs provide, but they are available to Apache and other parties on a need-to-know basis).

- **San Solomon Spring** is the largest spring and the featured attraction of Balmorhea State Park. Discharge from San Solomon Spring averaged 848 L/s from 1965 to 2001, with a maximum recorded discharge of 2,356 L/s on October 31, 1975 (Ridgeway et al., 2005).
- **Phantom Lake Spring Cave**, located 6 km to the southwest, was historically the second largest spring, but spring flow began to diminish with the inception of irrigated farming in the 1940s (White et al., 1941). Between October 16, 1931 and August 28, 2001 the average discharge from the spring was 253 L/s. Since 1994, discharge rates have averaged less than 28 L/s (Ridgeway et al.,



Figure 4. Phantom Lake Spring Cave entrance and refugium pool.

2005). The only flows that have occurred since 1999 have been in response to heavy rainfall events (Myers, 2016).

- **Giffin Spring**, the third largest, is about 230 m northwest of San Solomon Spring. Discharge from Giffin Spring averaged 112 L/s from 1953 to 2001 (Ridgeway et al., 2005).
- **Saragosa Spring** is about 5.2 km northeast of San Solomon Spring. The spring had been erroneously illustrated in multiple reports in a dry upland area, probably the result of a generalized location estimate, and was accurately located during unpublished NCKRI research in 2013. Brune (1975) reported discharge measurements for 19 discontinuous years from 1919 to 1971, which average 79 L/s, with a maximum reported discharge of 850 L/s in November 1932, and a generally continuous

decrease in discharge after 1941. Although anecdotal reports describe Saragosa Spring as currently dry, NCKRI personnel observed minor flow (<5 L/s) from a channel originating in the spring pool when they visited the location during the winter of 2012-2013.

- West Sandia Spring and East Sandia Spring, historically roughly equal in flow to Saragosa, are respectively located 6.8 and 7.7 km northeast of San Solomon Spring. Brune (1975) described the Sandia springs as a three-spring system, although only East and West Sandia springs were identified in other reports and during the 2012-2013 NCKRI site visits. The third spring is unnamed and flowed in 1911 “about a mile upstream” of East and West Sandia springs. However, it seems likely that this spring is actually Saragosa Spring, which is approximately a mile (1.6 km) away, although in a different stream channel. Brune (1975) also reported discharge measurements for East and West Sandia springs for 24 discontinuous years from 1932 to 1971, which average 43 L/s for their combined flow, with a maximum reported discharge of 125 L/s in August 1945, and a generally continuous decrease in discharge after 1947.

The San Solomon study area consists predominantly of nearly horizontal alluvial plains that slope and drain to the east. Limestone hills skirt the western edge of the study area at Phantom Lake Spring Cave. Extensive outcrops of Tertiary-age volcanic rocks associated with the Davis Mountains occur south of the study area. Figure 1 is a simplified geologic map of the area. The drainage basin boundary for San Solomon Spring was estimated roughly based on likely geologic structural and stratigraphic controls, as well as published hydrologic and geochemical data discussed below. The drainage boundary is simplified and actually extends throughout the Apache Mountains, as suggested by several reports. The most detailed geologic mapping currently available is provided by Barnes (1975; 1976; 1979; 1982) at a scale of 1:250,000.

Phantom Lake Spring Cave discharges from the Upper Cretaceous Buda Limestone, which dips down to the northeast from the cave and is down-faulted beneath an alluvial plain. Well data from White et al. (1941) show that the Buda Limestone extends beneath the other San Solomon Group springs, which discharge from overlying gravels of the Cenozoic Pecos Alluvium but are almost certainly sourced from the Buda Limestone. The Cenozoic Pecos Alluvium Aquifer fills two structural troughs in West Texas formed by solution-collapse processes in underlying Permian strata (Maley and

Huffington, 1953), and thickens to greater than 450 m in the Toyah Basin in northern Reeves County (Ashworth, 1990; Jones, 2001). Balmorhea lies at the southern feather edge of the Cenozoic Pecos Alluvium (Barnes, 1976; 1982).

Regional hydrogeologic setting

On a regional scale, the San Solomon Spring Group is located at the far western edge of the greater Edwards-Trinity Aquifer system, which extends across the Edwards Plateau, one of the largest karst regions in the United States (Figure 5). From the area of the springs, the plateau extends roughly 500 km east to the Balcones Fault Zone in the Austin-San Antonio area, and maintains a north-south width of about 250 km. Kastning (1983) provides an extensive geologic analysis of the Edwards Plateau karst. Smith and Veni (1994) subdivided the plateau into seven karst subregions based on stratigraphy, hydrology, and their observed effects on cave development. The San Solomon springs occur within the Isolated Edwards Outliers subregion, named for its erosional limestone remnants although in the San Solomon area the limestone is contiguous beneath broad alluvial plains.

The Edwards-Trinity Aquifer is formed in the Cretaceous Edwards Limestone Group and its equivalent units, and underlying formations of the Trinity Group and its equivalents. Most of the water produced from the aquifer comes from the Edwards Limestone. Groundwater in the plateau flows vertically through the unconfined aquifer to the water table, which is often perched on less permeable Trinity Group units. Most of the groundwater flows south and southeast and discharges from hundreds of springs at the Edwards-Trinity Aquifer contact along the margin of the Edwards Plateau to provide the baseflow for rivers flowing off the plateau. Fewer and smaller springs are found along the plateau’s northern and western boundaries, making the San Solomon Group anomalously large for that area.

The San Solomon Spring area lies within the boundaries of several regional investigations of the Edwards-Trinity Aquifer system conducted over the past 24 years by the US Geological Survey (Barker et al., 1994; Kuniansky and Holligan, 1994; Barker and Ardis, 1996; Kuniansky and Ardis, 2004; Bumgarner et al., 2012; Thomas et al., 2013) and the Texas Water Development Board (e.g., Anaya, 2001; Mace et al., 2001; Anaya and Jones, 2009). Although the San Solomon Spring area was included at the margins of these regional studies, most of the groundwater flowing from these springs does not originate in the Edwards-Trinity Aquifer, as explained below.

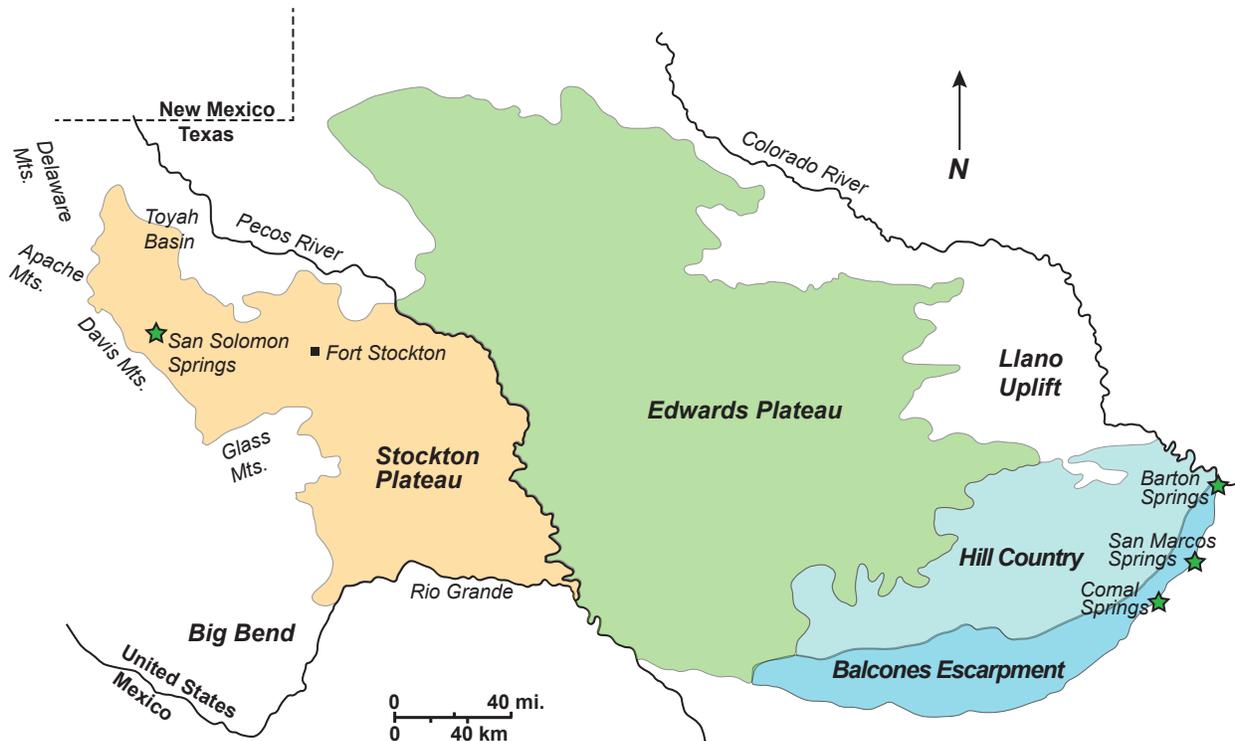


Figure 5. Physiographic map of west-central Texas. The various components of the greater Edwards-Trinity Aquifer System are indicated by color shading (modified from Barker and Ardis, 1996, Figure 3).

Much of the far western Edwards Plateau is a nearly featureless plain punctuated by caprock mesas and dissected by dry arroyos. Nearly horizontal carbonate strata of the Edwards-equivalent Fredericksburg and Washita Groups, and mixed carbonates and siliciclastics of the underlying Trinity Group form the Edwards-Trinity Aquifer in the region. In some areas, the Trinity-age basal Cretaceous sand aquifer, the principal source of groundwater beneath the northern Edwards Plateau, merges with permeable sands of the underlying Triassic Dockum Group (Barker et al., 1994; Barker and Ardis, 1996; Anaya, 2001). In northern Reeves County, sands of the Dockum Group are an important source of groundwater (Barker et al., 1994).

The Trans-Pecos region is an extension of the Edwards Plateau west of the Pecos River, where it is also known as the Stockton Plateau (Barker and Ardis, 1996). The Toyah Basin occupies much of the Trans-Pecos region northwest of Fort Stockton, where Cretaceous rocks are buried beneath sands and gravels of the Cenozoic Pecos Alluvium (Figure 5). The Edwards-Trinity Aquifer does not dominate the groundwater flow system in the Trans-Pecos region as it does farther east, and is, on average, less permeable than contiguous, hydraulically connected sediments of the Cenozoic Pecos Alluvium Aquifer in the Toyah Basin. However, southwest of

Fort Stockton the Fredericksburg-age Finlay Formation limestone contains a fault-controlled network of solution conduits that yields up to 9,500 L/min of groundwater to irrigation wells.

Barker and Ardis (1996) define the Edwards-Trinity Aquifer in the Trans-Pecos region to include all Fredericksburg and Trinity strata, plus all overlying Washita rocks below the Del Rio Clay, or below the Buda Limestone where the Del Rio Clay is absent (Figure 6). The San Solomon spring system is sometimes described as discharging from the Edwards-Trinity Aquifer. However, groundwater discharging from the San Solomon Spring Group originates from the Buda Limestone. Although the Buda Limestone is hydrologically continuous with underlying Washita-age rocks, it is technically not a part of the greater Edwards-Trinity Aquifer system that has been so extensively investigated by previous workers (Veni, 2013). In fact, the Balmorhea area appears to occupy a different hydrologic regime that has little to do with the Edwards-Trinity aquifer system, but is more closely related to regional groundwater flow systems originating in the Apache Mountains, and the salt basins and bolsons of far West Texas (Figure 7). The anomalously large spring flow from the San Solomon Spring Group relative to smaller springs in the Trans-Pecos region probably results from their unique hydrologic setting.

Focused hydrogeologic investigations

Trans-Pecos Texas experiences average annual precipitation of less than 300 mm; surface-water resources are scarce and brackish in this semi-arid region. Groundwater from wells and springs thus plays an important role in municipal, domestic and irrigation water supplies in the area (Sharp et al., 2003). For this reason, there have been a number of more focused studies of the groundwater system in the general vicinity of Balmorhea (e.g., White et al., 1941; Harden, 1972; Couch, 1978). Over the past three decades, a number of studies of groundwater and springs in the Trans-Pecos region have been conducted by Dr. John Sharp and students under his supervision from The University of Texas at Austin (e.g., LaFave, 1987; LaFave and Sharp, 1987; Sharp, 1989; Hart, 1992; O’Neil et al., 1995; Schuster, 1997; Boghici, 1997; Uliana, 2000; Uliana and Sharp, 2001; Sharp, 2001; Sharp et al., 2003; Uliana et al., 2007), and by researchers with the Texas Water Development Board (e.g., Ashworth, 1990; Ashworth et al., 1997; Boghici, 1999; Jones, 2001; Chowdhury et al., 2004; Anaya and Jones, 2009).

Early studies of the groundwater system in the Balmorhea area suggested that recharge to the springs originated via precipitation in the nearby Davis Mountains to the south and west (e.g., White et al., 1941; Ogilbee, 1962; Pearson, 1985). Water was thought to enter the Cretaceous-age Buda Limestone (which is stratigraphically above and not part of the Edwards-Trinity Aquifer) along the southwest limb of the Rounsaville Syncline (Figure 1) via seepage from the overlying volcanic aquifer, and from losing streams that flow across the syncline. Groundwater was then presumed to flow down dip, confined by lower permeability upper Cretaceous strata, and discharged from the San Solomon Spring Group where the upper Cretaceous units are displaced by faulting (LaFave and Sharp, 1987).

Harden (1972) and Couch (1978) suggested that groundwater originating in the Apache Mountains, which extend 40 to 80 km northwest of the Balmorhea area, might also contribute to San Solomon Group spring flow. LaFave (1987) tested this hypothesis and analyzed water chemistry and isotopic composition of the San Solomon area springs and groundwater sampled in the Davis Mountains. LaFave observed that the San Solomon Group spring waters are markedly dissimilar from Davis Mountains groundwater, and have a distinctively different isotopic signature. However, he found a striking similarity between the spring waters and water samples collected from wells screened in the Capitan Reef Aquifer in the Apache Mountains to the northwest

(Figure 1). Finch (2017) defines the “Capitan Reef Complex Aquifer” in the Apache Mountains to include correlative backreef units such as the Seven Rivers and Munn formations. Head data from wells in the Capitan Reef indicate that the springs are downgradient from the Apache Mountains. Based on this analysis, LaFave (1987) and LaFave and Sharp (1987) concluded that the San Solomon Spring Group is fed by two groundwater sources: a local source derived from precipitation on volcanic rocks of the Davis Mountains and recharged through nearby outcrops of the Buda Limestone; and a more distant source that originates in the thick, alluvial basin deposits in Wildhorse Flat and Lobo Flat in the southern Salt Basin to the west (Figure 7).

Water originating in the Salt Basin is hypothesized to flow through highly permeable carbonates of the Capitan Reef Complex Aquifer in the Apache Mountains and into Cretaceous rocks that are juxtaposed against the Capitan Reef carbonates in the subsurface by the Stocks Fault

Quaternary	Cenozoic Pecos Alluvium	
	Upper	Austin-Eagleford
Cretaceous	Upper	Austin Group
		Buda Limestone
	Lower	Washita Group
		Del Rio Clay
Lower	Fredericksburg Group	
	Trinity Group	
Triassic	Dockum Group	Basal Cretaceous Sand
Permian	Ochoa	Fort Lancaster Fm.
		Fort Terrett Fm.
		Glen Rose Limestone
		upper
	Guadalupe	Capitan Reef & backreef; older units
Leonard		
Wolfcamp		
Lower Paleozoic rocks of Ouachita structural belt		

Figure 6. Generalized stratigraphy of Trans-Pecos region. Modified from Barker and Ardis (1996).

near the mountains' east end. This more distant source of groundwater flows through a northwest-southeast oriented network of solution-enlarged fractures associated with the Stocks Fault (Figure 1), and contributes to the warm, steady, mineralized baseflow of the springs; whereas the storm flow component of groundwater originating locally from Davis Mountains runoff onto the Cretaceous limestones is cooler and less saline. LaFave's (1987) results have been confirmed by more extensive geochemical and stable isotope analyses by Uliana (2000), Uliana and Sharp (2001), Chowdhury et al. (2004), and Uliana et al. (2007). Sharp (2001) emphasized the importance of extensive regional fracture systems oriented sub-parallel to the Stocks Fault on the north flank of the Davis Mountains. This regional flow system also discharges directly into the Cenozoic Pecos Alluvium Aquifer in the Toyah Basin (Sharp et al., 2003). Chowdhury et al. (2004) used results from tritium and carbon-14 dating to conclude that groundwater originating in the southern Salt Basin and Apache Mountains was recharged during the late Pleistocene, about 10,000 to 16,000 years ago, whereas Davis Mountains runoff recharge is much younger.

Hydrogeologic summary

Although often described as discharging from the Edwards-Trinity Aquifer, the San Solomon Spring Group appears to be only indirectly associated with that system. Springs in the Balmorhea area are in fact part of a different hydrologic regime more closely associated with the Apache Mountains and the southern Salt Basin almost 100 km west of Balmorhea (Figure 7). Groundwater in the Apache Mountains is hypothesized to flow into Cretaceous limestones where they are juxtaposed with Permian units in the subsurface by the Stocks Fault. From there, groundwater flows southeast through solution-enlarged fractures associated with the fault, and continues southeast down the Rounsaville Syncline through Cretaceous-age limestones until it emerges at Phantom Lake Spring Cave, followed by the other San Solomon area springs. The Cretaceous limestones include the Buda, plus underlying rocks associated with the Edwards-Trinity Aquifer, but the geochemical data indicate that most of the groundwater does not originate in the Cretaceous or Edwards-Trinity during baseflow conditions; short-term increases in spring discharge do

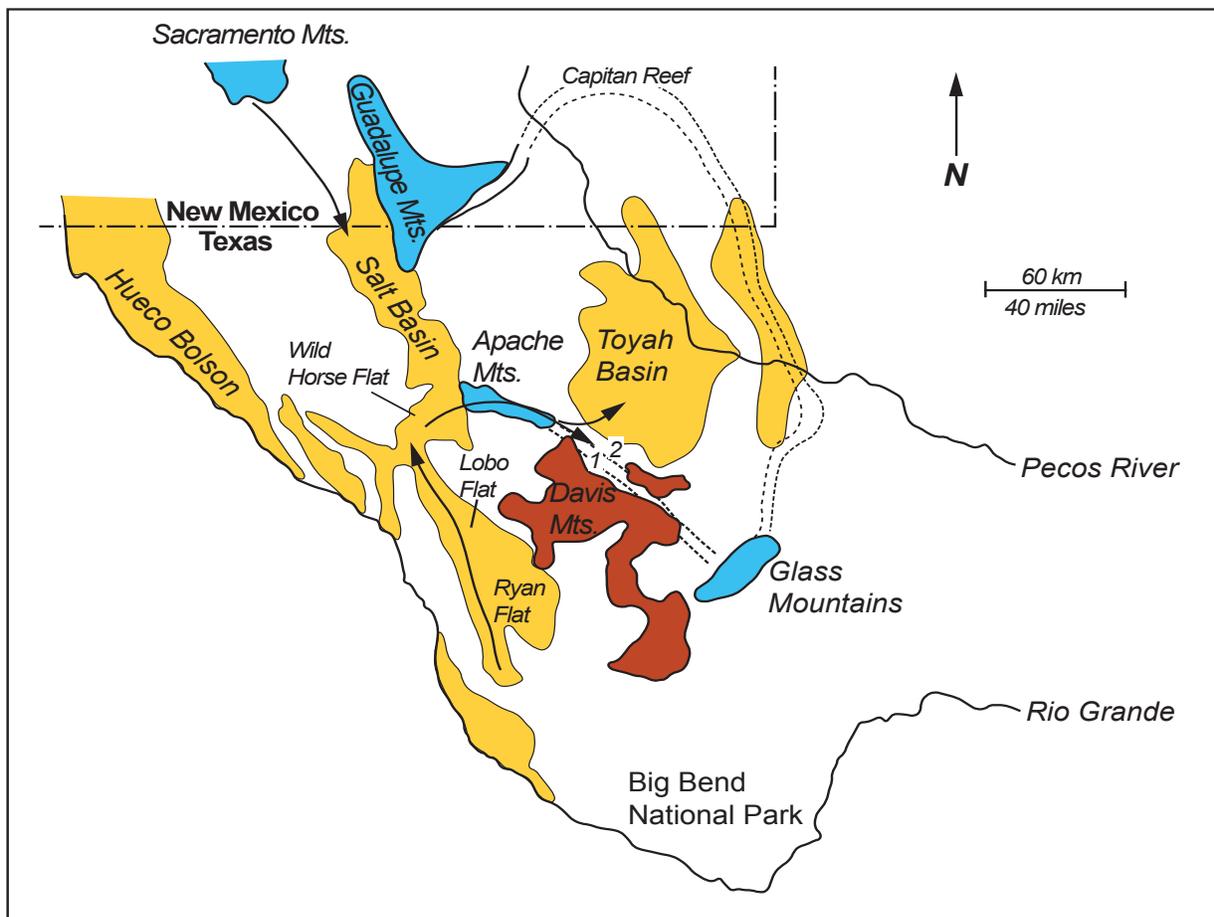


Figure 7. Regional groundwater flow systems in West Texas. Modified from Sharp (2001). 1 = Phantom Lake Cave; 2 = San Solomon and downgradient associated springs. Arrows indicate regional groundwater flow paths. Tan shading indicates Quaternary basin fill; brown shading indicates igneous and volcanic rock; blue shading represents carbonate outcrops.

occur by recharge through the Cretaceous limestone during local significant storm events (LaFave, 1987; LaFave and Sharp, 1987).

Upstream exploration of Phantom Lake Spring Cave by divers appears to support this conceptual model (Figure 8), having extended the survey of the cave 1.4 km north-west of the entrance along the east flank of the Roundsville syncline. Phantom Lake Spring Cave now has a total surveyed length of 3,075 m and a depth of 140.8 m at the current limit of exploration, making it the deepest underwater cave in the US; a map of the cave is not available for publication. The cave continues unexplored at its upstream and downstream ends (Pickel and Iliffe, 2012; ADM Exploration Foundation, 2013).

Future research needs

The primary purpose of this investigation is to compile all available relevant hydrogeologic and related information, and evaluate it to determine what information or data gaps exist in the understanding of the hydrogeology of the San Solomon Spring Group, and recommend studies to fill those gaps. For example, more geologic data is clearly needed to understand the extent of the karst system and the role that faults play in regional groundwater flow (conduits vs. barriers). The above literature review demonstrates that a substantial body of previous research is available on the hydrology of the Trans-Pecos region. That work includes both regional studies of the greater Edwards-Trinity Aquifer system, and investigations of the hydrology of the Balmorhea area. Water chemistry and stable isotope analyses have been employed to identify local and regional groundwater flow systems that contribute to the San Solomon Springs. The hydrology of the area has thus been fairly well-characterized on a regional scale. However, a detailed understanding of the local and sub-regional groundwater flow system is much more limited.

The known Alpine High area does not extend over the entire estimated San Solomon Spring Group drainage basin, but does overlap most of the basin's downgradient area including the springs. To better define the hydrology of the Balmorhea area and the possible impact of future industrial and commercial devel-

opments on the San Solomon Springs Group, the following research is recommended for the study area, as shown in Figure 9. The proposed boundaries of the study area are flexible and should be expanded if accessible wells, springs, or other potentially relevant data sources are nearby, or if tentative field interpretation of the data collected, or later analysis, suggests they are insufficient to encompass the entire area (excluding the alluvial basins) that is estimated to drain to the spring group. Additionally, these boundaries extend beyond that drainage area in order to establish its approximate potentiometric boundaries, which are currently not known and cannot be defined without collecting data from each side of the boundaries. These boundaries include areas suspected as being downgradient of the spring group to the east and southeast, where oil and gas production is planned, but which may flow to the springs.

Synoptic groundwater elevation study

Groundwater elevations have been collected from wells throughout the region during many different time periods. While they have been used to map the potentiometric surface in the Edwards-Trinity Aquifer, no published map has been found of the potentiometric surface for the area draining to the San Solomon Spring Group. Such a survey is needed to evaluate general groundwater flow patterns. Given the relatively few water wells in the region, it is especially important that this survey is conducted synoptically (i.e. collecting all of the data as close to the same time as possible) to minimize or eliminate variables due to changes in recharge, and discharge through spring flow and pumping in the study area over the period of measurement.



Figure 8. Diver at a depth of 140.8 m, at the upstream limit of exploration in Phantom Lake Spring Cave (photo courtesy of Andrew Pitkin).

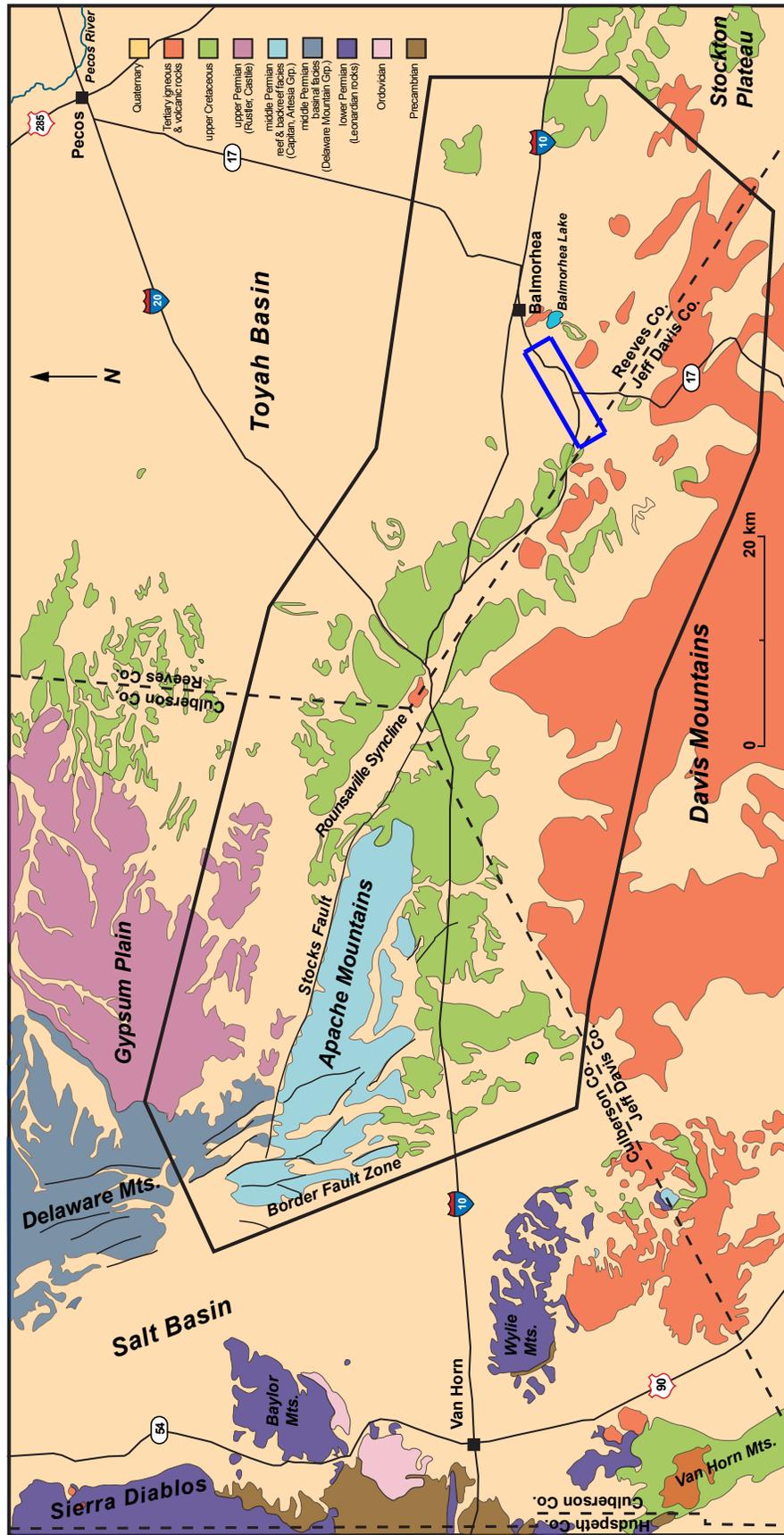


Figure 9. Generalized geologic map of the Pecos-Van Horn region of West Texas. Heavy black line shows the proposed study area. Blue rectangle shows the location of the San Solomon Spring Group (modified from Barnes, 1975; 1976; 1979; 1982).

The survey should begin with a thorough search of local and state records and interviews with knowledgeable local residents to document and include all springs and wells producing fresh water from Cretaceous and Permian rocks within the study area. For the most accurate synoptic analysis, surveying this broad area is vital in order to include as many wells as possible since well density will likely be relatively low and multiple flow paths to the springs may exist. Dye injected into Phantom Lake Spring Cave in 2013 was recovered only in San Solomon Spring and not in Giffin Spring, about 230 m to the northwest (Figure 10), nor any other spring of the San Solomon Spring Group (Veni, 2013).

The synoptic survey should be performed twice. One survey would occur during baseflow conditions. The second survey should occur during the July to September monsoon season, ideally following a brief period, one week or less, of rainfall that totals about 50% or more of annual average precipitation. Groundwater conditions, including flow directions, often change rapidly in karst aquifers during high potentiometric levels, and monitoring such a period will better characterize aquifer behavior.

Finally, before the synoptic survey, selected wells included in the survey should be logged via caliper, gamma ray, neutron porosity, and video methods, where any or all such methods can be applied. The results of this logging will be valuable to interpretation of the synoptic study, and to all of the studies recommended below.

Synoptic groundwater chemistry study

During the two synoptic groundwater elevation studies, water samples should be collected for analysis of the constituents. Based on well logging data, groundwater samples should be collected from the stratigraphic interval that produces the greatest volume of water in a well, if the well is not cased, or the most productive screened interval if the well is cased. Like the water elevation data, which can be plotted to create a map of the water table, concentrations of the chemical constituents in groundwater can be plotted to create isochemical contour maps, which also illustrate aquifer behavior. These maps will supplement the water table map to more effectively characterize the aquifer, which is important given the low distribution of wells in the region.

The geochemical analyses should include all major anions and cations typical of groundwater in that area, plus any trace elements that might identify areas of cross-formational flow, including upward leakage of water from deep brine units. pH and temperature should be measured in the field immediately upon collection,

with pH accurate to within 0.01 pH units to accurately calculate saturation indices and other parameters useful to interpreting groundwater conditions. The water samples should also test for polyaromatic hydrocarbons and other contaminants indicative of pollution from oil and gas production activities to establish baseline conditions for those potential constituents

Groundwater tracer studies

Dye tracing is generally the most effective method for delineating the area of the springs' groundwater drainage basin. The use of fluorescent dyes has been applied in many areas to characterize karst aquifer systems (e.g., US Environmental Protection Agency, 1996; Johnson et al., 2010). These tracers are distinctive, easy to use and identify, work well to identify specific point-to-point flow paths, and can be used to measure aquifer parameters such as time of travel, dilution, and dispersion. Only one dye tracer study is known to date in the study area, when NCKRI personnel demonstrated a hydrologic connection by injecting dye into Phantom Lake Spring Cave and detecting it in the discharge from San Solomon Spring at Balmorhea State Park. The results of that study are summarized by Veni (2013).



Figure 10. Staff gage in the outflow channel of Giffin Spring. No dye was recovered from Giffin Spring during a 2013 dye trace, in spite of its proximity to San Solomon Spring where there was a positive test for dye.

A systematic series of dye traces are recommended to delineate the boundaries of the groundwater drainage basin of the San Solomon Spring Group. These investigations should be designed to build on the existing tracer study (Veni, 2013). Cave and karst feature data from the Texas Speleological Survey and other unpublished and published sources (e.g. O'Neill et al., 1995) should be examined carefully to identify potential dye injection points. If LiDAR surveys of the landscape are available, they should be analyzed for additional karst features, not known to any current databases, which may serve as dye injection sites. If such surveys are not available, they are recommended, at least for areas where karst features are not known. Additionally, well logging results of the synoptic well survey will identify specific wells that would prove most effective for injecting and detecting dyes. As with the recommended dual synoptic survey, during baseflow and high groundwater elevations, certain sites that have been traced successfully should be traced again during elevated groundwater conditions to test for changes in flow routes, as well as velocity, dilution, and other pertinent aquifer characteristics.

Conducting a dye trace investigation in an arid environment such as Trans-Pecos Texas presents special challenges (Veni, 2014). The chief issue is that substantial volumes of water will be needed to flush the dye from the surface, through the vadose zone to the water table, and the locations of many injection sites will not allow easy delivery of large volumes of water. Thus, while dye tracing is a powerful and precise tool, it may not be feasible for all locations. Consequently, the other recommendations in the report are designed to enhance the interpretation of dye tracing studies, and to provide useful insights for areas where dye tracing is not possible or its results are limited.

Geologic mapping

As discussed above, the most detailed geologic mapping currently available for the area is provided by Barnes (1975; 1976; 1979; 1982). However, this 1:250,000-scale mapping is insufficiently detailed to offer a high level of confidence in predicting groundwater flow patterns in the San Solomon area to supplement dye tracing and other proposed studies. The estimated spring recharge area identified in Figure 1, and immediately adjacent lands, should be mapped at a scale of at least 1:50,000 to include defining mappable hydrostratigraphic units, as well as structural measurements such as folds and faults, and illustrating them on maps of the outcrops. Any caves or karst features discovered during the mapping should also be recorded. Additionally, well data should be used to map the location, structure, and

depth of those hydrostratigraphic units below the alluvium between the bedrock outcrops and the six springs of the San Solomon Group.

Groundwater monitoring study

We recommend continuous monitoring of discharge and electrical conductivity at each of the six San Solomon springs, and stage height and electrical conductivity in both municipal water wells located southeast of Phantom Lake Spring Cave. While the springs have long been presumed to discharge groundwater from the same source, the appearance of dye injected in Phantom Lake Spring Cave from only San Solomon Spring may reflect related but adjacent groundwater drainage areas for some or all of the springs and the two wells.

While many other parameters could be measured, water level, discharge and electrical conductivity provide the most useful information in characterizing the general hydrology of each spring's drainage basin, response to recharge, groundwater movement through the conduit, fracture, and diffuse flow components of those sections of the aquifer, and related parameters such as groundwater storage. These parameters offer important insights regarding when to collect water samples for analysis to geochemically characterize the aquifer during high and low flow conditions; and also for when to sample when contaminants from a known release, and to some degree from unknown releases, are most likely to appear and/or appear at the highest concentrations. The value of such sampling is that groundwater contaminants are less likely to go unnoticed if present, as compared to standard sampling at regular intervals with little or no regard to aquifer conditions, and it offers a higher level of assurance that contaminants are not present if they do not appear in the samples.

Following the synoptic surveys and some tracer tests, additional wells should be added to the monitoring network. Non-pumping wells are preferable in order to measure natural groundwater level fluctuations (with wells, water level changes would be used instead of discharge to characterize the flow paths and conditions leading to the wells). The number of wells that should be monitored should be determined following the synoptic studies and at least a few tracer tests. Pump tests on wells are frequently used in aquifer studies. Any pump test data available should be incorporated into this study but pump tests are not generally recommended. Pump tests in karst aquifers are reliably effective in characterizing the well tested, but are often poorly effective or ineffective in characterizing the aquifer or a drainage basin within the aquifer.

Groundwater ecology study

Following the synoptic and well-logging study, wells found to intersect water-filled conduits and caves should be sampled with the appropriate baits and traps for groundwater fauna. Additionally, any caves that extend to the water table should be biologically sampled. The collected species should be identified morphologically as to their general taxonomy and ecology, but also genetically. The genetic distance between individuals of the same aquatic species, but from different sites, can be used to determine if those sites are or are not hydrologically connected, and if not connected to evaluate the degree of disconnection relative to aquifer development. This technique was pioneered by Krejca (2005), and has the potential to powerfully supplement dye tracing and potentiometric data, especially where data points for those studies are sparse.

Precipitation studies

NEXRAD rainfall data over discrete portions of the potential drainage area for the San Solomon Spring Group should be quantified volumetrically. Afterward, discharge, water level, and geochemical data for monitored wells and springs should be examined for changes that reflect those recharge events. These analyses will also supplement the dye tracing data by identifying the general areas that contribute recharge to specific wells and springs, and roughly quantifying their hydrologic behavior.

Geophysical studies

Water from the five San Solomon Group springs northeast and downgradient of Phantom Lake Spring Cave rise to the surface through overlying alluvium. White et al. (1941) show that limestone underlies the alluvium, and while cave passages or smaller karst conduits are the presumed sources for the springs, this has not been proven. Potentially the water could instead flow only through the alluvium and rise in topographically low areas. Most likely, groundwater flows through caves, conduits, and the alluvium.

Electrical resistivity surveys (ER) are frequently employed to identify air and water-filled conduits in karst terrain (e.g. Land, 2012; Land and Veni, 2012). ER surveys should be conducted around the five alluviated San Solomon springs to determine the relative degree of groundwater contribution from caves and conduits and the alluvium. Any caves or conduits discovered should be followed by additional ER transects to establish their general directional trends. This information is useful in characterizing groundwater-flow conditions at each spring for more effective tracer and other studies and interpretation of their data. Additionally, in the

event of a contaminant release, it is vital to understand if groundwater will move rapidly to a given spring through conduits with essentially no filtration, or slowly through alluvium with some attenuation of the contaminants. Such knowledge allows for effective emergency planning for the area's agricultural water supply and protection of its endangered species.

Summary of recommendations

The above recommendations follow or improve on the ASTM (1995) standards for monitoring and studying karst aquifers (ASTM has officially withdrawn these standards because they have not been updated within ASTM's required revision period, but their technical merits have not been refuted and they remain widely accepted). While each individual study will provide useful information and insight, the data from each of the studies, within the operational limits of the investigation, can be maximized through integration to further enhance the conceptual model of groundwater flow in the area.

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ISBN 978-0-9910009-9-9

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