Journal of Hydrology 570 (2019) 850–862

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Aridland spring response to mesoscale precipitation: Implications for groundwater-dependent ecosystem sustainability

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ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Joshua Larsen, Associate Editor

Keywords:
Springs
Regional flow systems
Hydraulic fracturing
Unconventional oil and gas
Delaware Basin
Permian Basin

ABSTRACT

Aridland springs maintain groundwater-dependent habitats for aquatic and terrestrial species. San Solomon Spring (Texas, USA) is part of a regional karst spring complex in the Chihuahuan Desert that supports several species of federal and state conservation interest. However, drought, climatic variability, and groundwater abstraction threaten discharge and water quality. In the surrounding Delaware Basin, expansion in unconventional oil and gas development using hydraulic fracturing may increase demands on aquifers that also provide flows to the springs. A critical knowledge gap limiting habitat conservation and sustainable groundwater abstraction is that the flow system is not well understood. While the source of most spring discharge is from a Pleistocene-recharged regional flow system, evidence suggests that a modern local flow component provides fresh water influx. However, the exact sources, mechanisms, and timing of localized recharge are unknown. To address these questions, this study combined long-term in-situ spring water quality monitoring (specific conductance, turbidity, and temperature) data with weather station-corrected 4 km gridded precipitation data to quantify the lag response at San Solomon Springs to mesoscale storm events and to delineate potential local recharge zones. Between April 2011 and March 2012, 26 event-flow responses were documented, with an average lag of 43 days between storm event and spring response. Response time varied depending on storm magnitude, spatial extent, and antecedent soil moisture conditions. Cross-correlation analysis of spatially distributed precipitation indicated zones of potential local recharge in the mountain block/mountain front zones and alluvial channels issuing from the Davis Mountains. Some local flow paths appear to cross known watershed boundaries, suggesting that groundwater abstraction in sensitive capture zones should be managed carefully to maintain spring flows and conserve habitats.

1. Introduction

Springs in arid regions provide crucial water supply and habitat in areas with limited surface water resources (Patten et al., 2008; Davis et al., 2017). Increasingly, threats to sustainable water supplies in arid regions arise through a combination of increasing reliance on groundwater for industrial, agricultural, domestic purposes, and the influence of climate change (Millennium Ecosystem Assessment, 2005; Nevill et al., 2010; Kløve et al., 2011, 2014). The Balmorhea regional springs complex in far west Texas, USA, (Fig. 1) discharge from a karst system and serve as habitat for endemic aquatic and groundwater dependent species of federal and state conservation interest (Table S1; FWS, 1983, 2011, 2013a,b,c; TPWD, 2018a, 2018b; Rio Grande Fisheries, 1983) as well as providing water for irrigation and domestic use. While most spring discharge is hypothesized to source from paleo-recharged (Pleistocene-aged) regional flow systems further to the west, evidence supports that some spring water is sourced from local flow paths originating in the Davis Mountains, supplementing flows and decreasing the salinity of the system (Bumgarner et al., 2012; Chowdhury et al., 2004; LaFave and Sharp, 1987; Land and Veni, 2018; Sharp, 2001). Drought and growing demand for water resources in the area has raised questions about how spring discharge and salinity may change in response to these demands.

Between 2000 and 2017, the portion of the Chihuahuan Desert where the springs occur experienced drought conditions extending over at least 80% of the watershed during 9 of 17 years (Lower Pecos, HUC 130700: National Drought Mitigation Center et al., accessed February, 2018). During four of those nine years, severe to exceptional drought conditions persisted across > 80% of the watershed. Historically, the response to regional drought conditions has been to increase reliance on

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https://doi.org/10.1016/j.jhydrol.2018.12.074
Received 27 February 2018; Received in revised form 14 September 2018; Accepted 29 December 2018
Available online 14 January 2019

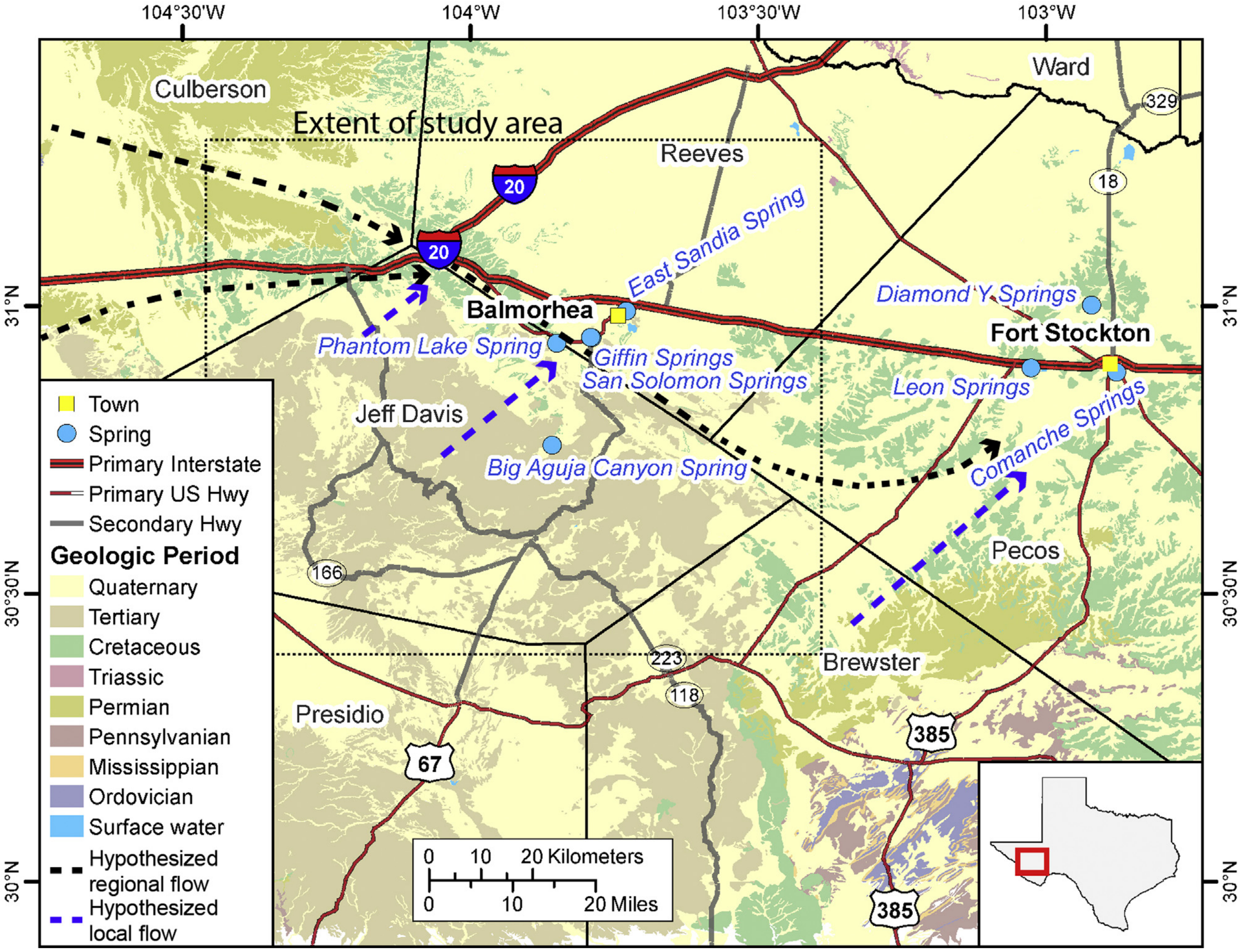

Fig. 1. Trans-Pecos study area with generalized surficial geology and locations of hypothesized regional and local flow systems (after Uliana and Sharp, 2001; Uliana et al., 2007).

groundwater for agricultural, domestic, and industrial needs (Ewing et al., 2008, 2012; Anaya and Jones, 2009); this has likely driven declines in spring flow and water quality (Ashworth et al., 1997; Sharp et al., 2003; Texas Parks and Wildlife Department Staff, 2005). Drought in the region is sensitive to teleconnections with remote sea-surface temperature patterns, particularly those accompanying the pattern of cool sea-surface temperatures across the equatorial Pacific known as La Niña, contributing to the severe drought seen during 2011 (Seager and Hoerling, 2014; Patten et al., 2008). Forecasts under future climate scenarios indicate a continued drying trend for the region (Seager et al., 2007; Seager et al., 2013; Cook et al., 2015). This suggests the potential to limit groundwater supplies through decreased recharge and increased reliance on groundwater resources. Compounding these challenges to sustainable groundwater development and conservation of groundwater-dependent ecosystems in the region is the expansion in drilling of unconventional oil and gas resources in the Delaware Basin (part of the larger Permian Basin), where hydrocarbon extraction utilizing hydraulic fracturing will require large volumes of water (Apache, 2016a, b; Olson and Ailworth, 2016; Scanlon et al., 2017; Bubenik, 2016).

The objective of this study is to delineate areas where local recharge may occur and quantify the response time between precipitation events and spring discharge. Complicating this delineation is that most precipitation in the region results from mesoscale convective precipitation with large spatial variability in intensity and duration over small distances. When combined with the karst nature of the spring flow system (Land and Veni, 2018; Uliana et al., 2007), the result is the potential for high spatial and temporal variability in recharge. Thus, there is a need to explore local and regional groundwater flow paths in this complex to better understand the springs and implications for the associated groundwater-dependent ecosystems.

2. Site description

The Trans-Pecos region is located in far west Texas, USA, extending east to west from the Pecos River to the city of El Paso and north to south from the Texas-New Mexico border to the Rio Grande and is part of the Basin and Range province. Between the Pecos and Rio Grande rivers, springs are the only perennial source of surface water. There are at least 150 known springs in the Trans-Pecos region with varying rates of discharge and water quality (Heitmuller and Reece, 2003). The Balmorhea and Fort Stockton spring systems extend east from the foothills of the Davis Mountains to Fort Stockton, TX (Fig. 1) and includes Phantom Lake, East and West Sandia, Giffin, and San Solomon springs (Balmorhea system) and Diamond Y, Euphrasia, Comanche, and Leon springs (Fort Stockton system; Hart, 1992; Heitmuller and Reece, 2003; Beach et al., 2004). The region is semi-arid to arid, with annual average precipitation of up to 495 mm in Davis Mountains and approximately 250 mm in the Toyah Basin (Western Regional Climate Center, 2017); regional precipitation generally correlates with elevation, which ranges from 740 to 2550 m above sea level (Gesch et al., 2002). Common vegetation types are typical Chihuahuan Desert species including mesquite, juniper (at high elevations), cottonwood, shin oak, short grasses, and desert cacti (Texas A&M Forest Service, 2018).

Annual rates of potential evaporation (~2000 mm) greatly exceed annual average precipitation (~250 mm) in the Toyah Basin (Anaya and Jones, 2009). High intensity convective precipitation events can drive infiltration and recharge in mountain front/mountain block zones and ephemeral channels, however, widespread infiltration of precipitation is limited (Beach et al., 2004; Anaya and Jones, 2009).

The springs discharge from a fracture and fault-controlled regional flow system (Fig. 1; S1) comprised primarily of Cenozoic, Cretaceous, and Permian aged sedimentary rocks. Several of the springs also contain a component of local flow sourced from precipitation over the Davis Mountains (Brune and Besse, 2002; Nielson and Sharp, 1985; Uliana et al., 2007). The Permian rocks are a combination of siliciclastic, carbonate, and evaporite rocks deposited in the Delaware Basin. Formations classified as aquifers in the state of Texas include the Capitan Reef and Rustler Aquifers (Ewing et al., 2012). Overlying the Permian is the Cretaceous carbonate Edwards-Trinity Plateau Aquifer, (Barker et al., 1994; Anaya and Jones, 2009) and the Triassic Dockum Aquifer, which is present in parts of the Trans-Pecos (eastern Reeves County and northwestern Pecos County) (Bradley and Kalaswad, 2003; Ewing et al., 2008). In Jeff Davis County and southeastern Reeves County, Tertiary extrusive igneous rocks overly the Cretaceous formations and form the Davis and Barilla Mountains; they are part of the Igneous Aquifer system, a collection of small, discontinuous aquifers located in porous extrusive flows and weathered volcanic sediments (Hart, 1992; Chastain-Howley, 2001; Beach et al., 2004). In most of the Toyah Basin, Cretaceous rocks are overlain by Cenozoic alluvial deposits (sands, gravels, clays, silt, and caliche) that can be up to 460 m thick and form the Pecos Valley Alluvial Aquifer (LaFave and Sharp, 1987; Anaya and Jones, 2009).

Recharge to the Permian and Cretaceous formations occurs along outcrops and through fractures and karst features at the surface and beneath unconsolidated sediments in arroyos and alluvial fans (Bradley and Kalaswad, 2003; Anaya and Jones, 2009). The Tertiary Igneous aquifers receive recharge from infiltration of precipitation at fractured and weathered zones (Chastain-Howley, 2001; Beach et al., 2004). The Pecos alluvial aquifer receives recharge through a mix of sources including infiltration of precipitation (predominantly along the mountain-front zone) and irrigation return flow (Anaya and Jones, 2009; Meyer et al., 2012). Hydraulic head and water chemistry data indicate hydraulic connectivity and cross-formational flow between the Igneous, Pecos alluvium, Edwards-Trinity Plateau, Dockum, Rustler, and Capitan Reef Aquifers (Dutton and Simpkins, 1986; Nativ and Gutierrez, 1988; Hart, 1992; Barker et al., 1994; Boghici, 1997; Anaya and Jones, 2009; Meyer et al., 2012).

The Permian aquifers contain fresh to brackish water (200–5000 mg/l TDS; 389–8715 μS/cm) with quality that (generally) declines with depth and distance from outcrop/recharge zones (Ewing et al., 2008, 2012). In the Trans-Pecos region, the Cretaceous Edwards-Trinity (Plateau) Aquifer is generally fresh (< 1000 mg/l TDS) except where cross-formational flow occurs from underlying aquifers (Barker et al., 1994; Anaya and Jones, 2009). The groundwater of the igneous units is generally fresh (200–700 mg/l TDS), reflecting a (largely) meteoric recharge source (Chastain-Howley, 2001; Beach et al., 2004). The Pecos alluvial groundwater is brackish (1000–3000 mg/l TDS; 1820–5300 μS/cm) and represents a mixture of recharge sources including meteoric water, irrigation return flow, and cross-formational flow (Igneous, Edwards-Trinity Plateau, Capitan Reef, Rustler, and Dockum aquifers; Anaya and Jones, 2009; Meyer et al., 2012).

In Trans-Pecos Texas, the spring-fed ecosystems provide aquatic and terrestrial habitats for many of species of state and federal conservation interest (Table S1; FWS, 1983, 2011, 2013a, b, c; TPWD, 2018a,b). Primary issues of concern for groundwater-dependent aquatic and terrestrial species are maintaining flows and water quality (i.e., salinity and temperatures). The current major water users in the study region are agricultural (irrigation and livestock), domestic, and industry, with some municipal use in towns (Bradley and Kalaswad, 2003; Ewing et al., 2008, 2012; Anaya and Jones, 2009). Recent developments of the Alpine High resource play in southwest Reeves County will require additional water resources to support hydraulic fracturing including brackish groundwater and aquifers that supply the springs (Apache, 2016a, b; Olson and Ailworth, 2016). Anthropogenic stresses on groundwater supplies in the region are well documented; water levels in portions of the Pecos Alluvial Aquifer declined noticeably between 1940 and 1990 due to intense groundwater extraction (LaFave and Sharp, 1987; Anaya and Jones, 2009). Pumping of the Edwards-Trinity Plateau Aquifer in Pecos County for irrigation starting in mid-1900s is correlated with the drying of Leon and Comanche Springs near Fort Stockton, TX (Sharp et al., 2003). Additionally, flow from San Solomon Spring and Phantom Lake Spring (Balmorhea system) declined from the 1940's to the 1990's, likely due to a combination of groundwater abstraction for irrigation and regional climatic shifts (Ashworth et al., 1997; Texas Parks and Wildlife Department Staff, 2005). Flow at Phantom Lake Spring ceased in 2001, leading to U.S. Bureau of Reclamation Staff installing a pump in order to maintain aquatic habitats for federally protected species. San Solomon Spring continues to flow; it is at a lower elevation than Phantom Lake Spring and was excavated to ~25 ft (6.7 m) below the ground surface in the 1930's as a part of a works project by the Civilian Conservation Corps (Texas Parks and Wildlife Department, 2018a,b).

Depending on where and how much groundwater abstraction occurs for agricultural, energy, livestock, and domestic uses, there is a possibility that spring discharge may decline. Additionally, groundwater-dependent species in the region have adapted to relatively consistent temperature and salinity ranges. If the inputs of fresh water from local recharge as well as flows from the regional aquifer system decline, groundwater flows to springs could be reduced, potentially leading to loss of habitats (and possibly federally-protected species), in addition to declines in agricultural productivity, loss of recreational and tourist revenue, and potentially reduced water supplies for the energy industry.

3. Previous research

3.1. Differentiation of local and regional spring flow

Topography, permeability, and aquifer thickness control the formation of local, intermediate, and regional groundwater flow paths (Tóth, 1970). Local and regional components of spring flow can be differentiated by examining physical and geochemical characteristics such as specific conductance, temperature, turbidity, isotopes, major ion chemistry, and discharge (Jones et al., 2017; LaFave and Sharp, 1987; Land and Veni, 2018; Maxey and Mifflin, 1966; Springer et al., 2017). Generally, groundwater discharging from local flow paths is fresher, more turbid, and has a temperature reflective of the air temperature at recharge while groundwater discharging from regional flow paths often has higher total dissolved solids, less turbidity, and a temperature reflective of long-term climatic averages or slightly elevated due to geothermal influence. These differences can be pronounced in dual (or triple) porosity systems such as karst, which tend to display rapid responses to storm events (Hess and White, 1988; Ryan and Meiman, 1996; Halihan and Wicks, 1998; Desmarais and Rojstaczer, 2002; Winston and Criss, 2004). This pattern has occurred at San Solomon Springs with observations of turbid, fresh discharge at the springs following storm events (Brune and Besse, 2002; Uliana et al., 2007). Research on the Trans-Pecos springs has focused on identifying the source and likely locations of regional flow (Sharp et al., 2003; Uliana and Sharp, 2001; Uliana et al., 2007). While the local component is recognized to exist, we are aware of no previously published research that has delineated local recharge zones or identified the timing of spring response.

3.2. NEXRAD/Advanced hydrological precipitation system (AHPS)

The NEXRAD dataset has multiple applications in the field of hydrology and meteorology; including precipitation estimation, identification of convective storms, flood prediction, streamflow forecasting, and groundwater recharge (Fulton et al., 1998; Young et al., 2000; Glenn et al., 2001; Latif and Hantush, 2006; Williamson et al., 2009; Healy, 2010; Seo et al., 2010; Kitzmiller et al., 2013; Zhang et al., 2015, 2017). Common meteorological applications operationally include forecasts or post analysis of flash flooding (Smith et al., 2005) and incorporation into hydrological prediction (Mcenery et al., 2005). However, there are limitations to approaches using NEXRAD, especially for derived precipitation estimates including beam range related issues. For example, when the radar beam does not sample sufficient depth of clouds to make accurate estimations at close proximity, or when precipitation is distant from the radar and clouds occur below the minimal scan height (Smith et al., 1996). There are also limitations in the empirical calibration used to derive precipitation amounts, such that correction using gauge data into synthesized products for quantitative precipitation estimation can produce a superior estimation compared to either the radar or rainfall-gauges used independently (e.g. the Advanced Hydrological Precipitation System (AHPS); Mcenery et al., 2005, or the Multi-Radar Multi-Sensor archive; Zhang et al., 2015). Computational improvements have meant that considerable historical records of these precipitation products at high spatial and temporal fidelity have become available, providing long term hydroclimate monitoring.

NEXRAD applications for groundwater recharge estimation became more commonplace as distributed hydrologic models came to prominence; the dataset has a spatial resolution (4 km × 4 km) that cannot be matched by precipitation gauge density in most catchments (Young et al., 2000; Moreno and Vieux, 2013). Studies examining karst systems frequently use NEXRAD data for high-resolution precipitation inputs over discrete and discontinuous recharge zones (Glenn et al., 2001; Moreno and Vieux, 2013 and others), and these data have been successfully used in analyzing cross-correlation and spatial correlation between precipitation and spring flow response in karst systems (Budge and Sharp, 2009).

4. Methods

This study focused on San Solomon Spring (Balmorhea system) because it has the largest discharge (0.7–0.85 m^3/s) of the regional springs, hosts multiple species of state and federal conservation interest (Table S1), and historical and anecdotal observations indicate that the springs are fed by a combination of regional and local flow systems (Uliana and Sharp, 2001). In order to characterize the local components of groundwater flow, the investigation combined in-situ monitoring of water quality parameters (pH, specific conductance, turbidity, and temperature) with AHPS-corrected aggregate NEXRAD reflectivity and regional daily precipitation for the period between April 2011 and March 2012.

4.1. Field deployment

An In-Situ™ Troll 9000 with pressure, pH, specific conductance, temperature, and turbidity probes was deployed at the base of San Solomon Springs pool (Balmorhea State Park, Texas, USA) where groundwater discharges through the sand/gravel bed. The sensor recorded measurements at 15-minute intervals from April 2011 to February 2012 and at 5-minute intervals from February through mid-March (2012). The equipment was retrieved and recalibrated on a monthly/bi-monthly basis throughout its deployment. The pH sensor was calibrated using a 2-point calibration curve (pH 7 and pH 10), the conductivity sensor was calibrated for fresh to brackish water (1412 μS/cm), and the turbidity sensor was calibrated with 1-point calibration (10 NTU); all standards were National Institute of Standards and Technology (NIST)-traceable and purchased from the sensor manufacturer.

4.2. Other datasets

National Weather Service (NWS) Cooperative Observer Program (COOP) records from four stations logging daily precipitation (Ft. Davis, Kent, Mt. Locke, and Balmorhea) were obtained from the National Centers for Environmental Information (NCEI) for the period April 2011 and March 2012 (NOAA National Centers for Environmental Information, 2017). These data were used as a first order identification of precipitation events over the region.

To mitigate potential spatial variations in precipitation estimates that can arise in regions with topographical variations and sparse observation networks, AHPS-derived multi-sensor quantitative precipitation estimates (Seo and Breidenbach, 2002, Mcenery et al., 2005) were obtained for the period of interest, each day from February 1, 2011 to March 31, 2012. These data combine multiple sensors to yield more accurate precipitation estimates than estimates produced using a single sensor (i.e. radar-only, gauge-only). The resulting output blends both the quality-controlled gauge observation network and NEXRAD radar-derived precipitation estimates using the relationship between scattered reflectivity and rainfall to produce a 24-hour analyzed rainfall period between 12UTC to 12UTC on each day (6 am to 6 am) 4x4 km daily analysis over the continental United States (NOAA, 2017).

4.3. Analysis of meteorological data

To ensure all precipitation events were identified, GOES-13 infrared and visible band satellite data and raw NEXRAD radar data were assessed for all days between February 2011 and March 2012. Daily single-polarity NEXRAD data from Midland with potential precipitation from the NWS big data project (NOAA, 1991) was scrutinized to identify the period of precipitation. The positioning of the region relative to the nearest radar in Midland, Texas, produces an elevated base level scan of the radar beam, which at 130 miles from the radar site scans the volume 2575–6250 m above ground level over Mt. Locke (2070 masl), and higher over surrounding lower terrain. This can lead to underestimation of precipitation amounts, as averaging across a wide radar beam width can lead to low beam averaged returns, in addition to non-detection of shallow water bearing clouds below this altitude. To offset this limitation, satellite data and AHPS data were reviewed to identify significant precipitation events that were potentially not detected by radar. Precipitation was included when it occurred over any one or more of Pecos, Reeves, Jeff Davis, Culberson, Presidio and Brewster counties. In all cases, AHPS or radar identify an event when significant precipitation occurred. The only non-agreement between AHPS and the gauge data was consistent with trace measurements at the daily precipitation sites. This analysis also revealed errors within the Mt. Locke record, which had ~50 days of precipitation during the period, with many trace events. Several minor events were also recorded that did not match with nearby Fort Davis. The frequency contrasted the three other stations containing between 15 and 35 days of precipitation. Examining the radar data for each Mt. Locke-indicated event identified that the region in question has limited rainfall on many of these dates, and the matching satellite data identified that a number of the measurements occurred on days when no cloud was present. In light of this of this potentially errant data, events detected using Mt. Locke were discarded. The cross-validation procedure identified that precipitation records from the other three stations were accurate. Events with trace precipitation but no significant cloud cover over the region were discarded from the set prior to analysis. Snowfall is also not a relevant factor for the region with little accumulation leading to minimal melt runoff.

Due to uncertainties in the spring discharge dataset for daily aggregations of rainfall, mesoscale precipitation events were consolidated into single events if they occurred on consecutive days. Trace events (< 0.254 mm or 0.01 in.) were discarded as these amounts of precipitation most often evaporate from the surface environment outside of the gauge. Cross-correlation analysis was performed between the specific conductance data and dates with AHPS accumulated daily precipitation for varying lag-leads of up to −100 days prior to streamflow for each 4 km grid over the period July-March reflecting the continuous available record. Analysis for lags of this duration is consistent with theoretically hypothesized recharge periods of 0.5–114 days based on permeability estimates of the Edwards-Trinity Plateau Aquifer (Bumgarner et al., 2012). Correlations and lags were only retained when associated with p-values of < 0.01.

4.4. Analysis of spring data

The logging equipment experienced power supply interruptions and memory malfunctions which resulted in partial losses of water quality data during the period of record; once between 5/28/2011 and 6/8/2011 (11 days), and again between 6/25/2011 and 8/27/2011 (62 days). Five storm events occurred leading up to or during the data gaps; however, three of these had minimal accumulation which would not have resulted in spring response. Only two major events were missed (June 1–7, 2011 and July 11–15, 2011; Fig. 2a and e), and, the record does capture spring response to another 15 events during the period of record; base/event differentiations and lag response analysis are based on these data. The missing data are displayed as gaps and represent a loss of ~18% of the total record (April 2011–March 2012). The pH sensor displayed noticeable drift throughout the period of record despite frequent re-calibration and the variability of pH readings between calibrations (0.1–0.2 pH units) were on the order of sensor accuracy (0.1 pH units); therefore the pH data were not used in the analysis.

To differentiate base conditions from event conditions (e.g., hypothesized response to storms), histograms (Fig. S2) of temperature, specific conductance, and turbidity were created using the long-term in-situ monitoring data. Each variable was plotted versus the expected normal probability distribution function (Fig. S2). Large deviations from the normal distribution at the tails were interpreted as spring response to inputs by local or intermediate groundwater flowpaths; local groundwater flow is often fresher and more turbid, with a temperature reflective of the precipitation event that generated the recharge than regional groundwater flow (Brune and Besse, 2002; Uliana et al., 2007). Identification of an inflection point (p-value) and change in slope at the tails were used differentiate event conditions from the expected random distribution of measurements. Observations at or beyond the p-value (p ≥ inflection for variables where event flow results in higher measurements (e.g., turbidity) p ≤ inflection for variables where event flow results in lower measurements (e.g. specific conductance)) were identified as event conditions.

5. Results

5.1. Precipitation

In the lead up to the period of analysis, conditions over the region, and more broadly west Texas were accompanied by a declared extreme to exceptional drought that began during March 2011 (National Drought Mitigation Center et al., accessed February, 2018). These levels of drought are characterized by extremely low percentiles of streamflow (below the 5th percentile), modeled soil moisture (below the 5th percentile), and extremely low standardized precipitation anomalies. This pattern persisted throughout the summer months, reflecting the most severe period of drought over the region in the monitoring record since maps were first issued in 2000, until large precipitation events in late August and September (Fig. 2). In close vicinity of the Davis Mountains this precipitation reduced drought conditions to severe to mostly extreme levels for the remainder of the analysis period, while the region more broadly was characterized by exceptional drought.

Almost all events generating significant rainfall accumulations identified were associated with non-organized or organized and long-lived convective storms that initiated over the Davis Mountains (Fig. 2). Assessment of AHPS precipitation revealed that precipitation at the observational sites was not the only precipitation to fall over the basin, suggesting caution is necessary when considering solely gauge data for assessing connections to regional flow systems. Maximum frequency of non-trace rainfall days over the region was 35 days over the mountains. These data consolidated into 21 mesoscale rainfall periods of one or more days of consecutive rainfall during the full period, with 20 of these events occurring between June 1, 2011 and March 31, 2012 (Fig. 2) suggesting a summer dominated rainfall pattern during the drought year, with many of these events reflecting protracted periods of as many as ten days. The isolated, cellular nature of many convective rainfall events is reflected by the limited number of high-precipitation grid points, and the individual paths of storms, where locally intense precipitation extends over a straight line following prevailing winds. This leads to a dataset of precipitation events, that when aggregated, can appear to be somewhat spatially disparate. In several cases, weak prevailing winds led to slow motion of convective storms, resulting in extremely localized high precipitation totals. The largest single day rainfall total was 100–125 mm over the mountains and occurred on June 1, 2011 although other accumulated multi-day events produced equivalent volumes of precipitation over the same region (e.g. Fig. 2h). Peak rainfall accumulations over the region are unsurprisingly well correlated with the highest topography and igneous geological features (Fig. 4), with accumulated precipitation over the record of 200–250 mm over the Davis Mountains to the southwest of the springs.

5.2. San Solomon spring discharge

Water levels in San Solomon springs pool (as determined by barometric-corrected pressure from the Troll 9000) were maintained at relatively constant levels (within 3 ft of capacity) throughout the monitoring period, with the exception of 5/11–5/17; during this period, the pool was partially drained for annual maintenance and cleaning. No storm event response was anticipated during this time period, so the draining of the pool had no effect on our analysis. The 3 foot variation in water level observed during the remainder of the monitoring period occurred on the time scales of weeks and represents a fluctuation of approximately 1.2 million gallons of water. San Solomon springs discharges approximately 15 million gallons of water per day; therefore the slight variations in water level of the pool are assumed to have minimal effect on mixing conditions and water quality monitoring.

The spring temperature record deviated significantly from a normal probability distribution throughout the range of collected data (Fig. S2); we infer the cause was the low resolution (± 0.1 °C) of the thermistor. Because deviation could not be clearly derived by examining the probability distribution, we did not assign temperature an inflection point (p-value) to differentiate base from event conditions. There is a clear inflection point in the turbidity data (pval ≥0.9995); however, upon closer analysis of the data it appears that all of these measurements were collected on a single day in February 2012. This may be due to maintenance work in the pool, algal blooms, sensor interference, or an event response producing extremely turbid discharge. Another inflection point is visible at pval > 0.9 that may represent event conditions; however, we elected not to analyze this in favor of selecting the most conservative approach for differentiating base and event conditions as the turbidity record may be affected by external factors (e.g., swimmers, SCUBA divers, and pool maintenance). A clear inflection point was also identified in the specific conductance record (pval ≤0.0015); differentiating the record using this value yielded 43 measurements recorded during 26 days (multiple measurements captured the falling and rising limbs of inferred event responses for several

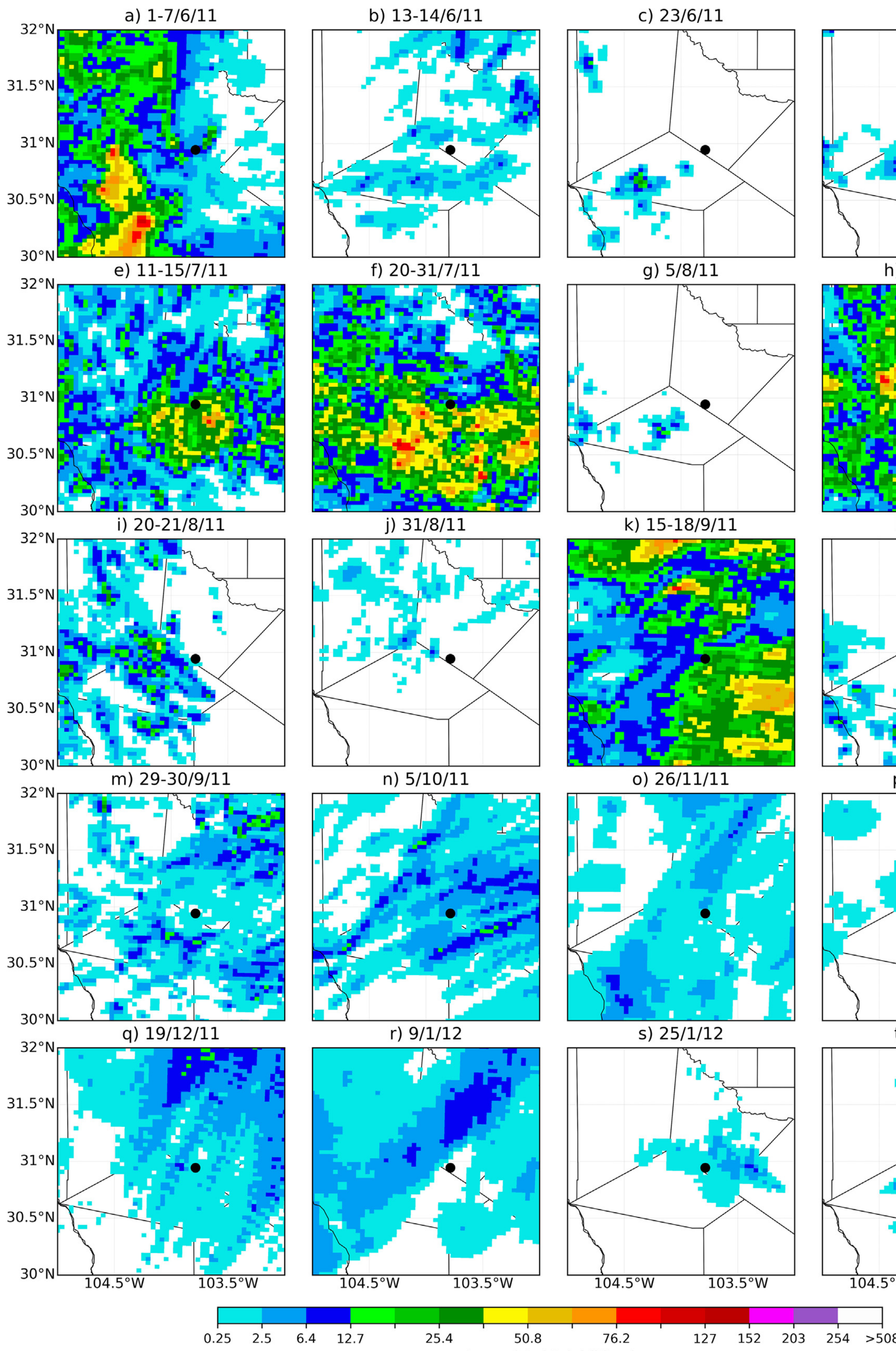

Fig. 2. National Weather Service (NWS) (NOAA, 2019) Advanced Hydrologic Prediction Service (AHPS) 4 km accumulated gridded precipitation events from January 2011-March 2012. From 55 non-trace precipitation days, these collated into twenty events over the region. The black dot indicates the location of San Solomon Springs.

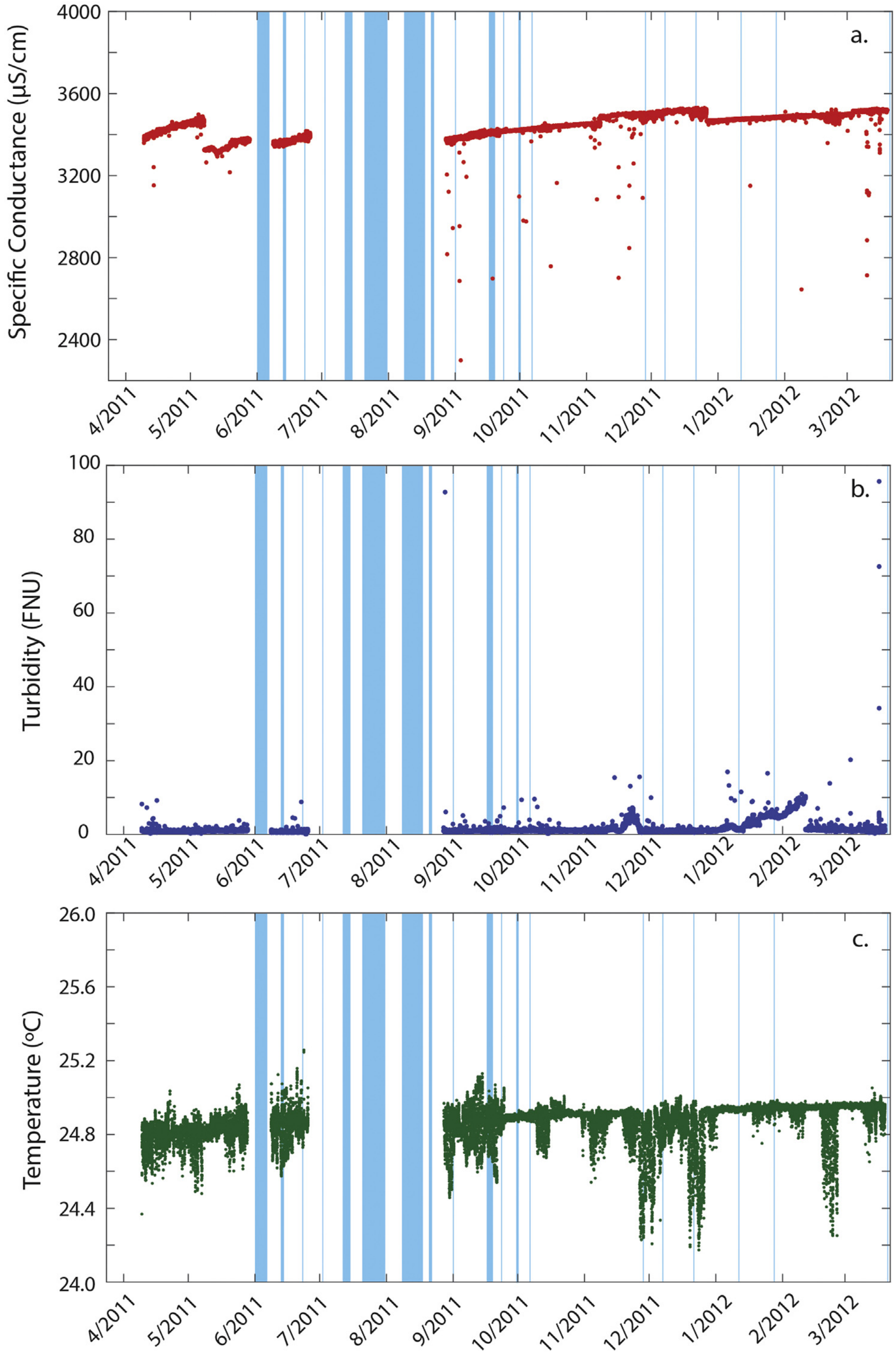

Fig. 3. Time-series monitoring data from San Solomon Springs (TX) of a. specific conductance (µS/cm; temperature corrected, calibrated), b. turbidity (FNU; calibrated); and c. temperature (°C) April 2011-March 2012. Blue bars show dates of non-trace precipitation in the study area.

(n = 8) of the observed events).

During base flow conditions in 2011–2012 (i.e., spring discharge is not influenced by precipitation), the mean specific conductance of water discharging from San Solomon Springs was 3450 µS/cm ± SE 0.3 (~2210 ppm TDS). This is higher than the values measured in grab samples and synoptic surveys from previous research (~3200 µS/cm; Uliana et al., 2007) and specific conductance had an apparent increasing trend over the monitoring period. We infer that the extended drought conditions occurring between 2010 and 2012 drove the elevated mean value and increasing trend. With significantly lower than average precipitation, local flow paths provided less recharge to dilute the more saline regional component of groundwater leading to the observed increase in specific conductance over the monitoring period. There was a degree of observed sensor drift between re-calibration periods, however, this magnitude of drift was generally small (< 50 µS/cm; Fig. S2).

Mean turbidity during base conditions was 1.5 FNU ± SE 0.01. The mean temperature of discharging water during base conditions was 24.8 C ± SE 0.01. Deviations from mean temperature tended to occur more frequently and last for longer periods than deviations from mean

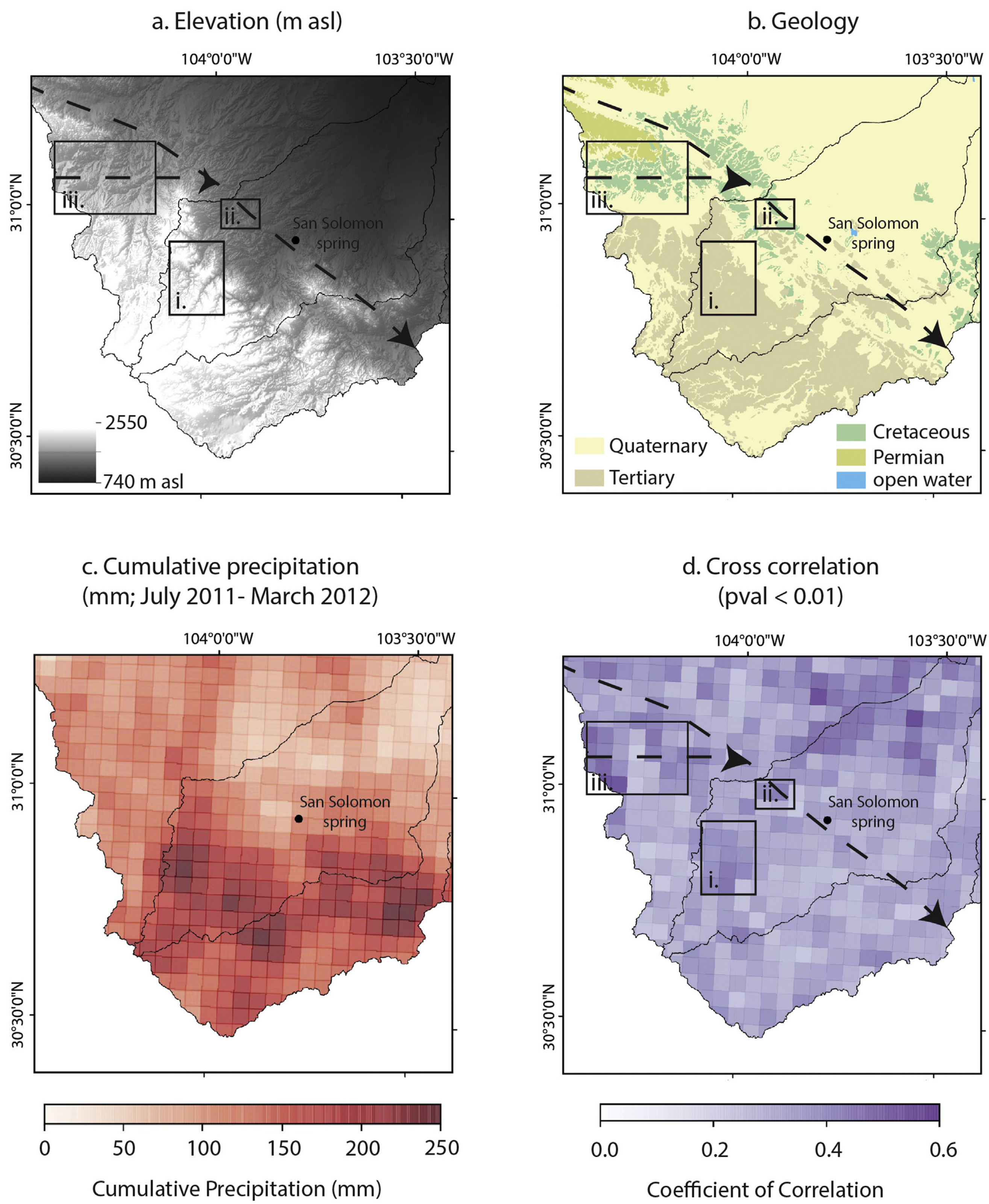

Fig. 4. Study region a. elevation (meters asl), b. surficial geology, c. cumulative precipitation (mm; July 2011–March 2012); and, d. Coefficient of cross-correlation between precipitation and spring response at San Solomon Springs. Watersheds unlikely to contribute to local flow are masked in white. Boxes i-iii show locations of inferred local recharge zones based on cross correlation of precipitation and spring response. Dashed arrows show hypothesized regional flow (modified from Uliana and Sharp, 2001; Uliana et al., 2007).

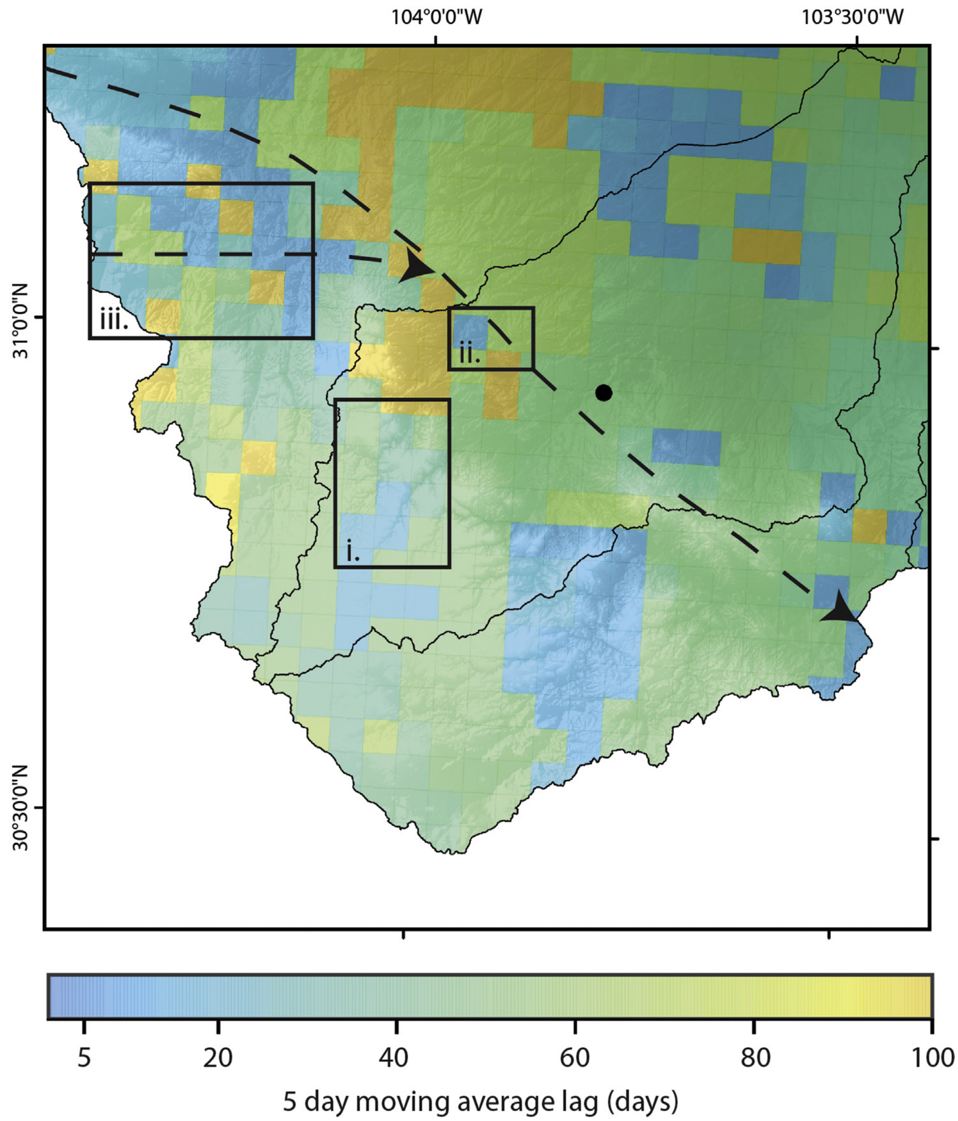

Fig. 5. Five-day moving average of lag times between Advanced Hydrologic Prediction Service (AHPS)-corrected NEXRAD precipitation and spring response overlain on study area topography. Boxes i-iii show locations of inferred local recharge zones based on cross correlation of precipitation and spring response. Watersheds unlikely to contribute to local flow are masked in white. Dashed arrows show hypothesized regional flow (modified from Uliana and Sharp, 2001; Uliana et al., 2007).

specific conductance or turbidity. The cause of this deviation may be a result of sensor resolution or other compounding factors (e.g., thermal conduction in the pool).

From the analysis of the deviations from normal probability distribution, 26 days of event flow were identified in the specific conductance record (Fig. 3; Fig. S2). Other dips in specific conductance are observable in the record, however they were not included in the analysis because the aim for the first 'cut' identification was to be conservative with the differentiation between base and event flow. Dips in specific conductance tend to have associated spikes in turbidity and fluctuations in temperature (Fig. 2); this is consistent with the anticipated system behavior where event flow should provide an influx of fresher, more turbid, and cooler water (Uliana and Sharp, 2001). The largest dip in specific conductance observed in the record was to 2299 μS/cm, on September 3, 2011; 18 of the 26 event days recorded minimum specific conductance values of < 3100 μS/cm. Event flow response from San Solomon springs was rapid during the study period; none of the identified responses altered specific conductance values for longer than 2.5 h, based on the inflection-point probability distribution function identification method. With the available data, it is unclear whether this is characteristic of event flow at this spring or if an unusual response occurred in 2011–2012 due to drought conditions. Based on synoptic measurements of discharge the average flow at San Solomon spring is approximately 13,000 Gal/min (0.86 m^3/s; Heitmuller and Reece, 2003), so the volume of recharge from a local precipitation event would need to be sizable in order to alter the specific conductance of the discharging water for an extended period of time.

Visual analysis of the time series where dates of non-trace precipitation events at the three COOP stations (Ft. Davis, Kent, Balmorhea) were compared to dates of event flow response (dips in specific conductance) at the spring yielded a median lag of 43 days (Fig. 3a), with a maximum lag of 50 and a minimum lag of 30 days. This range does not represent an absolute value for travel time; a limited dataset collected in a drought year complicates the calculation of a lead-lag correlation based solely on precipitation at weather stations and spring response. Additionally the specific conductance record indicates a multi-modal response, which we infer is dependent on scale and timing of precipitation events and antecedent moisture conditions; this could significantly alter estimates of travel time for local flow.

5.3. Correlation of spatial precipitation and spring response

Cross-correlations over the region of interest (Fig. 4d) illustrate a significant ($p < 0.01$) positive relationship between the daily signal for rainfall magnitude and the aggregated daily spring event flow with values of specific conductance below 3300 μS/cm. While significant positive correlation occurs across the domain, this is likely a result of the widespread convective storms producing heavy rainfall on the same days as those in the hypothesized contributing and recharge zones (Fig. 2). The gridded precipitation data are relatively granular (4 km resolution) compared to the local variability in topography and geology, however despite this limitation, the analysis capture patterns consistent with recharge features. A substantial portion of the Davis Mountains within the same HUC-8 watershed as San Solomon spring was strongly correlated (0.4–0.6) with event flow (Fig. 4, box i.); this area overlaps several of the major drainage channels that empty to alluvial fans at the mountain front and onto outcrops of Edwards-Trinity (Cretaceous) bedrock. Direct precipitation and/or runoff onto bedrock outcrops on the basin floor may also create recharge (Fig. 4, box ii.), though based on this dataset, diffuse infiltration through the alluvium does not appear to be a major source of recharge. This could be a result of antecedent moisture conditions (drought) or natural system behavior; a longer dataset that captures the range of precipitation and antecedent moisture conditions is necessary to determine whether diffuse recharge plays a major role in local flow. Also of note is the area with strong correlation (0.3–0.6) between the Davis and Apache Mountains (Fig. 4, box iii.) where another large outcrop of Cretaceous bedrock is present. It is located in an adjacent watershed that, according to topography, should flow north-northeast and bypass the springs. Instead, these analyses indicate that flow over this outcrop is a potential source of local recharge to San Solomon spring. This is consistent with the hypothesized areas through which regional flow moves within the system (Uliana and Sharp, 2001; Uliana et al., 2007); where outcrops to these formations occur, it is possible that they can act as conduits of both local and regional flow.

Spatial distribution of moving average lag-lead periodicity between mesoscale precipitation events and response flow provided a less noisy record centered on the principle lag relationship, and is consistent with the visual analysis-derived lag estimates (Fig. 5). Period of flow from the strongly correlated regions in boxes (i) and (iii) reveals spatially varying values of approximately 30–45 days over both the alluvial fans and Edwards-Trinity bedrock, and over the catchment region associated with Cretaceous bedrock between the Apache and Davis mountains (Fig. 4b, box iii). While positive correlations are identified to the south and southeast of San Solomon springs, these two systems reflect flow that likely is directed down gradient towards Ft. Stockton, and reflect a spatial region where precipitation days were often coincident with precipitation over the catchments described above. This type of signal is not unsurprising given the relatively small number of samples contained in the dataset. A preliminary analysis of the time series of individual grid-box cross correlations to the spring discharge series was indicative of multi-modal behavior in both lag and correlation (i.e., one storm event may drive a staggered set of spring responses because of differing travels times for each local flow path). This suggests that flowpaths of varying length may contribute to the overall discharge, and lead to a range of lags within a given catchment, or between different catchments. While such features certainly merit future investigation, the statistical limitations of the current dataset precludes any such analysis within this study. Furthermore, the nature of the responses seen here may reflect characteristics unique to periods with low antecedent moisture conditions.

6. Discussion

The analysis presented here illustrates that San Solomon spring discharge is modulated by local flow derived from mesoscale precipitation events over recharge (or contributing) zones. The local flow system appears to have a regular periodicity of arrival, with a lag period of 30–45 days and strong, statistically significant ($p < 0.01$), correlations to monitored specific conductance; rainfall intensity, location, and antecedent moisture conditions appear to alter lag times. Back-of-the-envelope estimates of travel time in this system yield an anticipated travel time of 0.5–114 days from the hypothesized recharge zones to San Solomon springs (using estimates of Edwards-Trinity permeability from Bumgarner et al., 2012), not including time for infiltration through the unsaturated zone or overlying alluvium; this is consistent with the observed correlations and with estimates of travel time and permeability in other, similar, regional karst systems (Halihan et al., 1999). While the lag analysis does allow us to identify the dominant signal of the relationship between rainfall and subsequent spring discharge; there are likely variations that exist due to varying magnitudes of precipitation and the underlying system base state. For example, the significant drought period that coincided with measurements over the region led to potentially abnormal antecedent moisture conditions, which may have an effect on the characteristic lag period of the spring response. Other relevant factors include seasonality, and whether events are intense, isolated or protracted. However the length and sampling period of the existing dataset make these features difficult to analyze, suggesting the need for further observations. There has been one event response documented at San Solomon spring prior to this research; on November 1, 1990, a synoptic survey of water quality at the spring captured a sample with a specific conductance value of 1,298 μS/cm (Texas Water Development Board, accessed July 2017); this was attributed to storm event influence on spring discharge (Uliana and Sharp, 2001), and is substantially larger than any that were observed over the course of this study (maximum deviation was to ~2300 μS/cm; Fig. 4). Non-trace rainfall was recorded at the Ft. Davis, Kent, and Balmorhea weather stations on 9/15/1990–9/22/1990 and again on 10/1/1990–10/3/1990; these were the only non-trace events in the 75 days preceding the observed spring response. Comparing precipitation event timing to spring response provides a lag of 30–47 days, which is consistent with the results described in herein.

A significant advantage in this analysis is the use of AHPS precipitation and the meteorological conditions to identify the occurrence of precipitation events, rather than gauges in order to identify spatial granularity in rainfall distribution and intensity, and co-locate these characteristics with geological formations that have the potential to serve as recharge zones for local flow (Uliana et al., 2007). However, challenges exist in the relative proximity of NEXRAD radar sites to systems of interest in capturing rainfall, particularly for shallower non-convective systems. It is also unclear as to whether the 15-minute spring monitoring interval used over most of the course of this study was of sufficient temporal resolution to capture maximum excursions from the mean, or associated rising or falling limbs. A sampling interval of 5 min captured more of the rising/falling response (February/March 2012 data; Fig. 4), however, the drain on the battery life of the equipment was rapid enough (2 weeks) that a 5-minute interval is not practical for remote monitoring. Modifications of the sampling protocol, evolving technologies or an external power supply could provide solutions to these challenges and enable collection over a longer period of record and a wider range of hydrologic and meteorological conditions.

The predominance of precipitation cases driven by summer convective rainfall suggests that a comparatively short period of observations during and following the summer months would allow a better understanding of the influence of these systems on discharge from San Solomon springs. Ideally, such sampling would involve both a similar drought or dry period, and a more normal or wetter year to investigate the potential implications of antecedent moisture. Focused sampling for additional parameters such as stable isotopes during storm event response and baseflow conditions (Springer et al., 2017), combined with continuous monitoring of spring discharge and a detailed survey for karst features within the hypothesized recharge zones would help to refine this approach (Jones et al., 2018). Obtaining this type of dataset would provide a context to potentially allow for predictability for changes in subsequent streamflow discharge following mesoscale precipitation events. More broadly, this approach illustrates that careful analysis of rainfall context is needed for monitoring intrusion of other flows into aquifers.

7. Conclusions

San Solomon Springs is characteristic of aridland springs and groundwater-dependent ecosystems in the Trans-Pecos region; while most of the spring discharge results from a documented regional flow system, they also contain a significant component of local flow system water. In this study, analysis indicates that the lag time between precipitation event and spring response is 30–45 days, with an average of 43 days. Likely recharge zones for the local flow system includes alluvial fans and outcrops of Cretaceous bedrock (Edwards-Trinity Plateau Aquifer). Furthermore, recharge to the local flow system appears to cross watershed (surface water) divides, indicating that strategies applied to protect sensitive habitat will have to span outside of traditionally acknowledged management boundaries. Currently, the limitations of the dataset generated by this study preclude a more generalized prediction of spring response, particularly as it relates to non-drought periods and changes to precipitation extent and intensity. However, it does serve as a proof-of-concept for the application of this method to an extended dataset. This suggests the need for additional monitoring of the spring system to better understand recharge zones and flow paths and to inform strategies for habitat and groundwater management.

Environmental implications of these results are also notable, as issues of concern for groundwater-dependent aquatic and terrestrial species include maintaining spring flows and water quality (i.e., salinity and temperatures), which over the period of this study showed the influence of continual drought in terms of increasing salinity. Threats to the system from groundwater abstraction, drought, and climate change are ongoing. Unless properly managed, expanding drilling for unconventional oil and gas resources in the Delaware Basin, along with associated groundwater development for hydraulic fracturing water needs, has the potential to increase vulnerability of groundwater dependent ecosystems as a result of reduce spring flow and/or water quality, adversely affect habitats for species of conservation interest, and potentially reduce regional groundwater water supplies. Aridland springs in Texas and around the world are facing threats to water supply and water quality from drought, increased abstraction, and climate change; characterization of flow paths, recharge, and response timing – such as applying the approach in this study – is critical to developing informed management strategies for these resources.

Acknowledgements

Field work for this research was funded by The University of Texas at Austin Jackson School of Geosciences through Graduate Travel Funds and Sharp's Endowed Professorship (Carlton Professor of Geology). Wolaver was partially funded by the Jackson School of Geosciences. Thanks to C. Norris (TPWD) for helpful discussions. Brent Hewett (CMU) contributed to the meteorological analysis of the period of interest. Thanks to Jason Barnes for field assistance. The authors would like to thank the anonymous reviewers for their time and comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2018.12.074.

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