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Implications of Climate Change for the Water Supply of the Chisos Mountains Developed Area

Big Bend National Park Technical Assistance Request 4945

Natural Resource Report NPS/NRSS/CCRP/NRR—2019/2045

ON THE COVER

Chisos Basin including Ward Mountain and the flow path towards Oak Spring.
Photograph courtesy of NPS/Max Woolley

Implications of Climate Change for the Water Supply of the Chisos Mountains Developed Area

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Abstract

Big Bend National Park (BIBE) needs to replace or repair a 1950s drinking water system in the Chisos Mountain Basin (estimated cost, $8-10M). In addition to the issue of aging infrastructure, the current water source for the system (Oak Spring) has experienced intermittent reductions in flow, prompting the park to also consider developing an alternative water source, rather than investing in Oak Spring improvements. Prior studies indicate discharge from Oak Spring reflects contemporary climate conditions. To help evaluate the long-term reliability of Oak Spring as a water source, we examined this potential climate connection and also assessed projected future climate conditions at BIBE to provide supporting information for this water development decision.

Our analysis of ten years of data suggests flows from Oak Spring are sensitive to contemporary changes in precipitation. Oak Spring flows correlate with monthly precipitation falling in the local area, with a two month lag time, where precipitation explained 58% of the variation in spring flow. Although there is significant unaccounted for variation in this relationship, and thus error, we used the correlation between Oak Spring flow records and local precipitation to develop a statistical model relating precipitation to flow. This model was then paired with precipitation projections from two climate change scenarios – a "Warm Wet" and "Hot Dry" scenario derived from 20 global climate models – to explore how discharge of Oak Spring may change through a time period centered on 2065 (2050-2080). We recognize the limitations of discharge projections, given unaccounted for variation in the statistical model, but considered projections (with appropriate caveats) useful to the management question at hand.

The premise of this approach is that, given contemporary climate change, historical conditions may not be a reliable indicator of future Oak Spring discharge. Global climate models are quantitative representations of our understanding of how the earth responds to increasing greenhouse gas concentrations in the atmosphere and provide a tool to evaluate how key parameters such as temperature and precipitation may change in the future. The scenarios we developed are intended to bracket the range of potential futures for BIBE, and in turn Oak Spring as a water source. The Warm Wet scenario represents the largest projected increase in annual precipitation and the smallest increase in temperature of any of our global climate models; a "best case scenario". The Warm Wet scenario also assumes humans use a range of strategies and technologies to reduce carbon emissions and ultimately stabilize emissions through time. The Hot Dry scenario represents the largest projected decrease in annual precipitation and the largest increase in temperature from our model set; a "worst case" scenario. This scenario assumes business as usual, with emissions of greenhouse gases increasing through time.

Under the (best case) Warm Wet scenario, precipitation increases and so does interannual precipitation variability. This increased variability results in flows at Oak Spring that fall below 20 gallons per minute (gpm) in the 2060s at about the same number of months per decade as that observed during the 1950-2000 historical period. This threshold is directly relevant to the park's decision, as flows below 20 gpm are generally inadequate to support BIBE operations in the Chisos developed area, and may invoke a drought conservation plan. Warm Wet projections through time

(2020-2100) indicate there will be decades where flows fall below this threshold more often than the past, and others less often. Under the Hot Dry scenario, the number of months per decade in which Oak Spring flows fall below 20 gpm in the 2060s is more than double the historical average. If this worst case scenario is realized it may substantially challenge the reliability of Oak Spring as a water supply.

Our findings are consistent with prior climate change studies of the Big Bend region that found some global climate models project increases in total precipitation and some project decreases; however models consistently project increases in precipitation extremes (i.e., high and low precipitation events). By evaluating different scenarios of change managers can stress-test the decision about whether to re-develop Oak Spring or seek an alternative water source, considering how different climatic changes may influence the long-term reliability of this water source.

Acknowledgments

We would like to thank Jeff Bennett, Paula Cutillo, John Gross, Cat Hawkins Hoffman, Marie Landis, David Larson, Stephanie Latimer, Steve Rice, Forrest "Ed" Harvey, Mark Schuler, Gregor Schuurman, Pat Shanks, David Thoma, and Rebecca Weissinger for their support and input during this study.

Background

In 2018 the NPS Climate Change Response Program (CCRP) received a technical assistance request to evaluate changing climate conditions at Big Bend National Park (BIBE) to provide supporting information for water development decisions in the Chisos Basin (hereafter referred to as the Basin). Over the past 10 years, Oak Spring, the current water source for the Basin, experienced intermittent reductions in flow, which in turn led to a need for water conservation measures by concession operators and visitors in the Basin area. Data are insufficient to determine if Oak Spring has exhibited long term trends of increasing or decreasing flow. Several lines of evidence suggest the spring depends on annual precipitation, such that changing climate conditions could compromise the reliability of this water source. This report evaluates the range of climate conditions BIBE may experience in the future and interprets implications of those changes for Oak Spring. We recognize there are numerous factors involved in major capital investment decisions such as this, and provide this analysis as one source of information to inform the decision process.

Infrastructure supporting the acquisition and delivery of water from Oak Spring to the Basin is aging and BIBE plans to replace/repair this 1950s-era drinking water system in FY22 at a cost of $8-10 million. BIBE is also considering changing this water source to groundwater acquired north of the Basin near Lone Mountain. Groundwater from this site is supported by a larger aquifer that may be less dependent on annual precipitation for recharge and therefore may have a slower and more muted response to contemporary climate change. Small aquifers are expected to more immediately respond to climate change relative to large aquifers, which can buffer the effect of climate change through larger groundwater storage (Kløve et al. 2014). This evaluation focuses on Oak Spring, as data required to assess the influence of climate change on Lone Mountain groundwater are not available at this time. Additional information on the aquifer near Lone Mountain can be found in Wilson and Schroeder (1984).

Existing knowledge on Oak Spring

Groundwater that supplies water to Oak Spring is recharged from localized rainfall and consists of a mixture of old and young components, with approximately 60% of the water >50 years old (Appendix 1, Shanks et al. 2008). The age of the modern component is uncertain (Shanks et al. 2008). Noble gas concentrations indicate that Oak Spring water is recharged at significantly higher elevations (>1,900 m) than where the spring discharges, probably on Ward Mountain (Shanks et al. 2008). Based on their interpretation of helium-tritium and noble gas solubility data, Shanks et al. (2008) report the older water found in Oak Spring is likely recharged in fractured bedrock drainages of the Chisos Mountains, while the younger component is recharged in alluvium or sedimentary deposits closer to Oak Spring.

Relationship between precipitation and Oak Spring flow and hypothesized recharge mechanism

Key information to assess the degree of climatic influence on Oak Spring recharge and discharge is paired climate data (i.e., precipitation, temperature) and flow data from Oak Spring.

Baker and Buszka (1993) assessed the influence of precipitation on Oak Spring flow based on an incomplete Oak Spring flow dataset and continuous precipitation records over a three year period from 1986 to 1989. They found that Oak Spring flow increased in response to precipitation events, where flow peaks were associated with large precipitation events, and flow steadily declined over a below-normal precipitation period. Their data suggested a short (one month) lag between precipitation and spring flow response, which they interpret to indicate a shallow aquifer with effective recharge areas able to absorb precipitation rapidly and an extremely permeable aquifer material (further supported by their assessment of the geology of the recharge area). Flow rates varied between 22-167 gallons per minute (gpm) during their observational period.

Staff from BIBE provided intermittent Oak Spring flow data recorded from a roll chart from 1986 to 1989, 1995 to 2003, and 2007 to 2012 (Stephanie Latimer, BIBE Science and Resource Management, *personal communication*). More recent flow data over the period from 2012 to 2018 were also provided (Mark Schuler, BIBE Utility Operations and Repair, *personal communication*). We combined records from 2007 to 2012 and 2012 to 2018 to form a fairly complete decade of flow records measured weekly (on average). Flows during this time ranged from 9 to 212 gpm.

We compared these flow data with a series of climate variables to determine if we could identify primary climatic correlates that correspond with Oak Spring flow. Daily climate information (i.e., air temperature and precipitation) recorded during 2007 to 2018 at a weather station at the Chisos Basin Visitor Center, approximately 4 miles away from the spring, supported this analysis (Station ID GHCND:USC00411715; Figure 1). The available Oak Spring flow record was discontinuous, most notably missing data for a large portion of 2009 and 2014. From the time the record began (7/01/2007) until it ended (6/01/2018), 15 of the 132 months were missing data (11%). We used linear approximation to interpolate flow for periods of missing data to provide the complete time series necessary for this analysis. Drawbacks of this method are that gaps where several months of flow data are missing could be misinterpreted. For example, Figure 2, which plots observed flow at Oak Spring and the rolling 3 month average of total monthly precipitation, shows a period in late 2014 where flow data is missing that corresponds with the period when flow typically peaks annually. Interpolating the missing period results in flow estimates that do not have a peak in that period, although a peak may have occurred, which could ultimately lead to an underestimate of the strength of the relationship between flow and climatic variables.

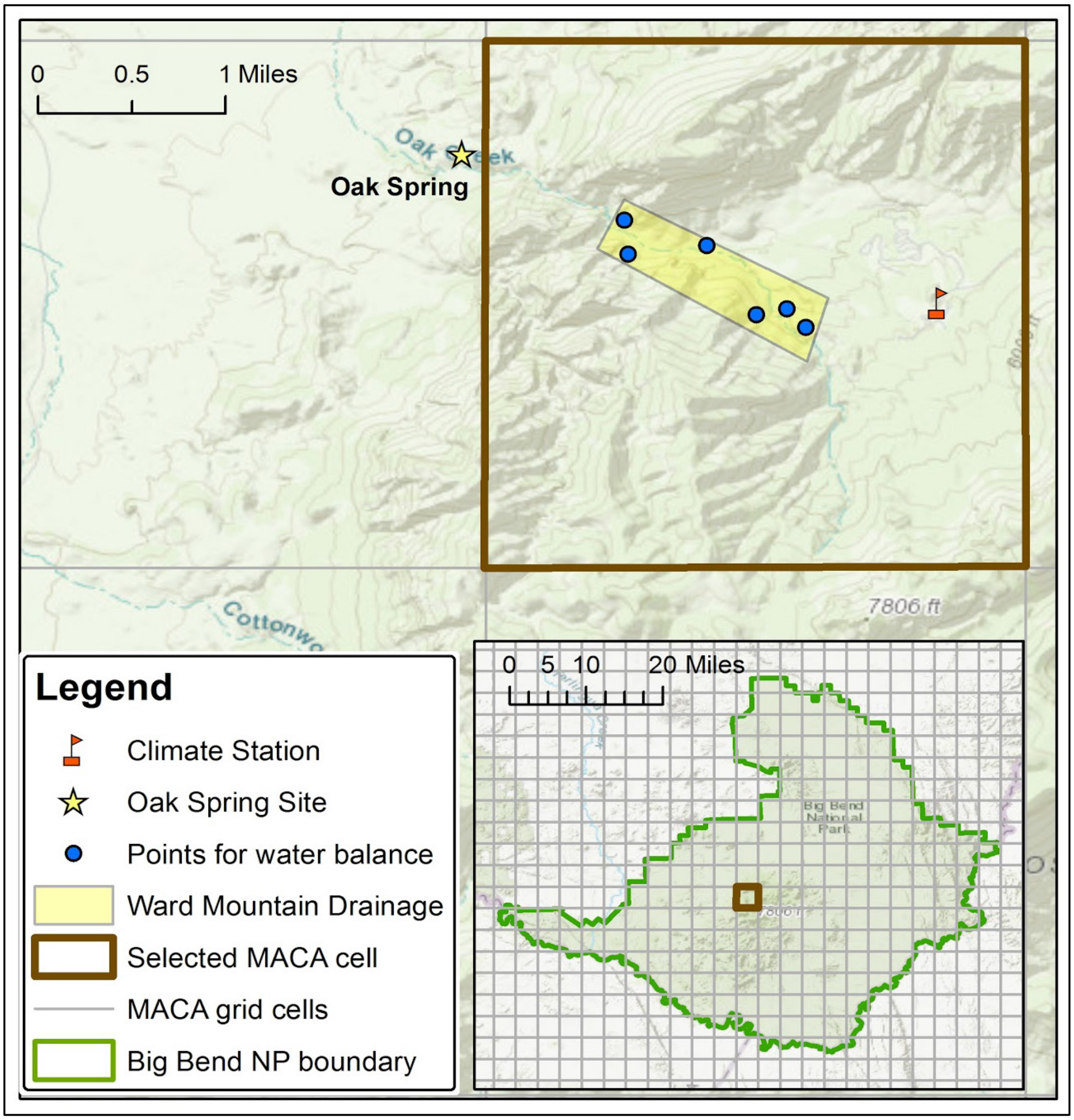

Figure 1. Oak Spring (yellow star) relative to various points of interest described in this study. The climate station used to obtain local precipitation to correlate with Oak Spring flow is represented by the orange flag (located at the Chisos Basin Visitor Center). The location of the selected MACA grid cell used to develop future climate projections is outlined in brown. Oak Spring is located in the MACA cell adjacent to its recharge area (signified as the yellow Ward Mountain Drainage area); thus the brown cell was selected for the development of future climate projections. Blue points represent sites used for water balance modeling. The inset shows the modeled area, outlined in brown, relative to the park boundary.

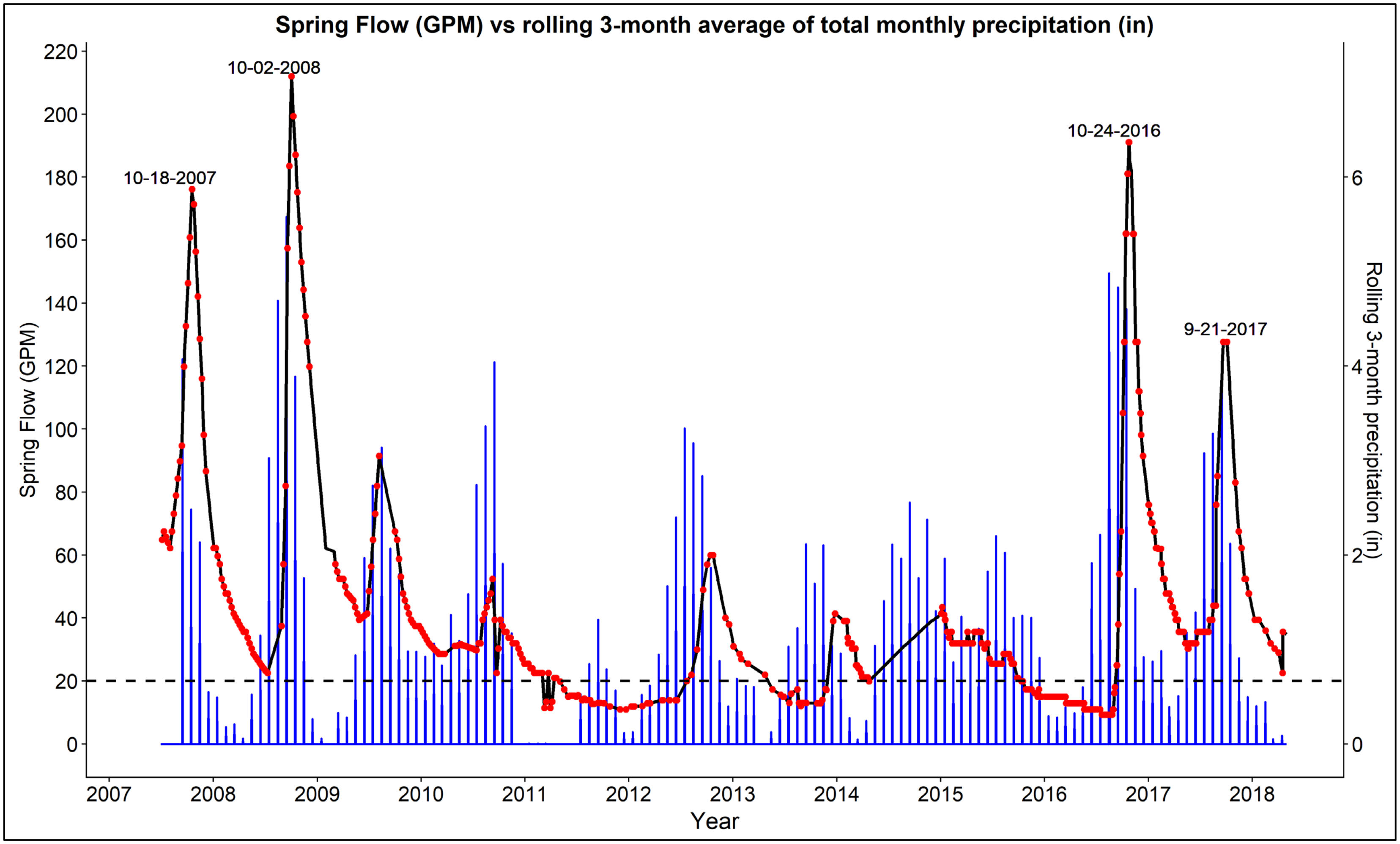

Figure 2: Observed Oak Spring flow (red circles) and interpolated data (black line) relative to a rolling three-month average of total monthly precipitation (blue lines) from Chisos Basin Visitor Center (~4 miles apart). Note: 2016 low flow values are between 9 and 11 gpm. Station data are daily summaries of the Chisos Basin Visitor Center, obtained from the NOAA National Climate Data Center https://www.ncdc.noaa.gov/cdo-web/datatools/findstation. The 20 gpm line indicates a threshold of flow that makes park operations using Oak Spring difficult.

We anticipated there would be a time lag between climatic conditions (e.g., precipitation) that influence recharge and the expression of that recharge via discharge at Oak Spring. Therefore, we used a cross-correlation function (Brockwell and Davis 1991) to statistically identify lags in climatic variables that might be predictors of Oak Spring discharge. We used two precipitation metrics when evaluating lagged relationships between climate and Oak Spring discharge: (1) the total monthly precipitation and (2) the rolling 3 month average of (total monthly) precipitation. We used the rolling 3 month average of precipitation to capture antecedent conditions that may influence how precipitation moves through the aquifer and how rain events interact with the ground surface and thus alter the resulting recharge (e.g., precipitation falling on dry versus previously wetted soils). Figure 3 illustrates the cross-correlation for each metric. Both plots validate observations from park staff indicating that Oak Spring flow increases in response to local rains, with a lag time of 6 to 8 weeks (Mark Schuler, *personal communication*, 7/30/2018). The rolling 3 month average of precipitation with a two month lag explained 58% of the variation in flow from Oak Spring, whereas the monthly average of precipitation with a two month lag explained 37% of the variation (Table 1). Thus, the strongest correlation exists between precipitation and flow when we included a representation of antecedent conditions (Figure 4). That being said, there is still significant unexplained variation in the relationship between precipitation and flow (42%) that could be related to gaps in the data record, differences in precipitation falling at the weather station compared to the local recharge area, as well as unaccounted for complexities in the relationship between climate and Oak Spring discharge (e.g., the mixture of old and young water components, multiple recharge areas whose relative contributions could change seasonally, etc.; see Shanks et al. 2008). When evaluating Figure 4 it is also important to note that flow does not drop below ~9 gpm, which along with the (10.5 gpm) y-intercept of the linear model correlating precipitation and Oak Spring flow, suggests flow rates on the order of 9-10 gpm may be the base flow for this spring.

In addition to purely precipitation-based metrics, we assessed several other climatic variables to determine the strongest climatic correlate with Oak Spring flow (Table 1). We included temperature within the lagged precipitation model (i.e., added a temperature interaction term), reasoning that precipitation that falls during cool versus warm temperatures may have a greater or lesser likelihood of becoming recharge due to temperature influences on soil evaporation rate and plant transpiration, but it did not improve performance (Table 1). We also tested the lagged ratio of precipitation to potential evapotranspiration (P:PET), reasoning that higher PET during the rainy season may reduce infiltration, and therefore recharge. Including this representation of PET did not provide a better correlation than purely precipitation-based metrics. Finally, we evaluated if large precipitation events were better correlated with spring flow, but found no improvement in the statistical correlation with large (0.62 in) and extremely large events (>1.05 in), which correspond to the 95th and 99th percentile of rain events from the station record. Overall, these analyses suggest precipitation is the dominant climate driver of Oak Spring discharge (rather than the combination of precipitation and temperature-driven evaporation and transpiration processes), and a large precipitation event is not required to achieve recharge.

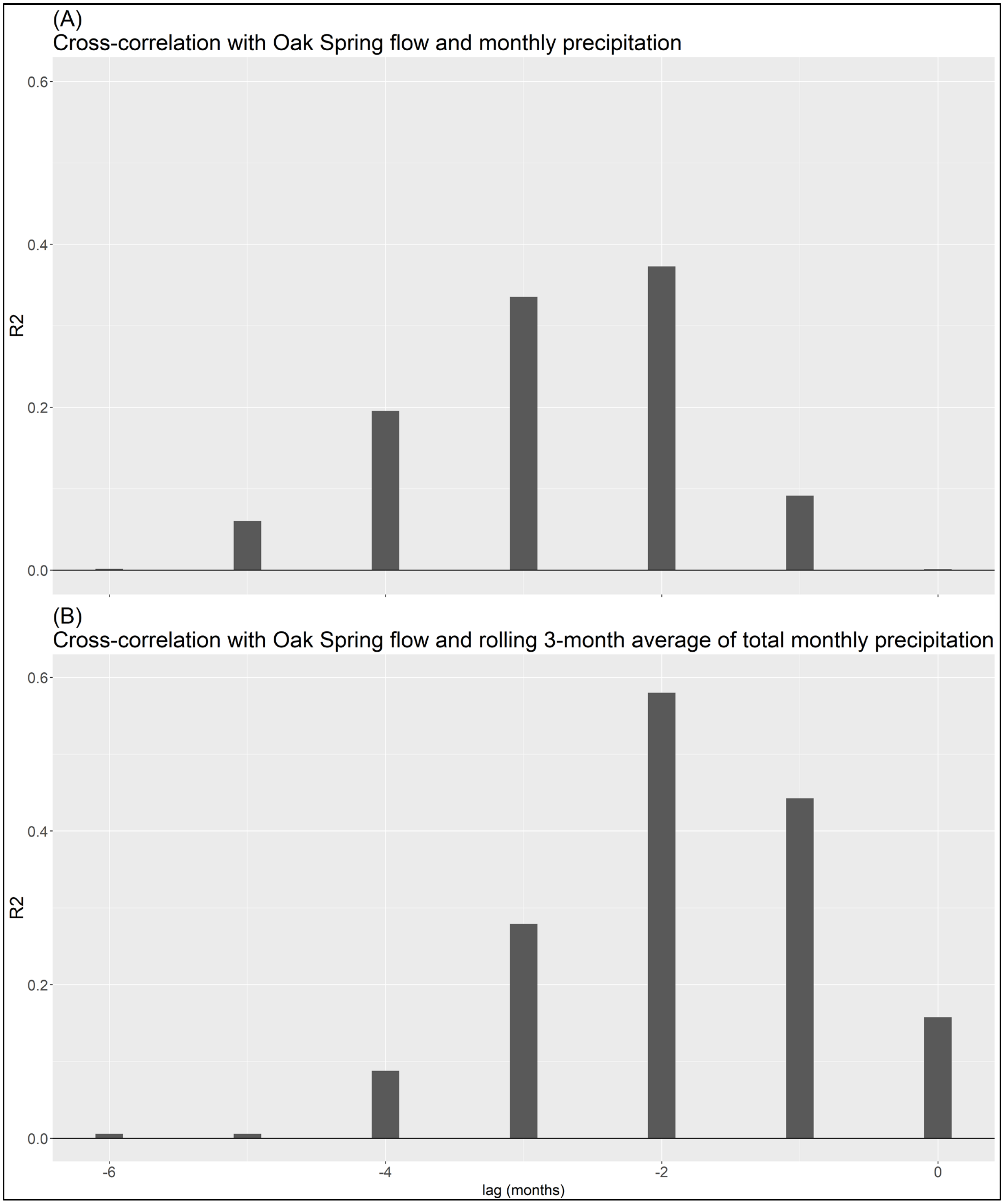

Figure 3. Cross-correlation between mean daily flow from Oak Spring and: (A) monthly total precipitation at the Chisos Basin Visitor Center station; and (B) the rolling three month average of total monthly precipitation, measured at different time lags, from no lag (0) to 6 months.

Table 1. Correlations between climatic variables and mean daily Oak Spring flow. Lag refers to time lag in months.

Climatic variable	Lag	Process	R^2
Rolling three-month average of total monthly precipitation	-2	Precipitation, accounting for antecedent conditions	0.58
Total monthly precipitation	-2	Precipitation	0.37
Total monthly precipitation * air temperature	-2	Precipitation interacting with air temperature	0.31
P:PET	-2	Evapotranspiration before infiltration	0.33
Large precip events (>0.62")$^+$	-2	Heavy precipitation, 95th percentile event	0.03
Extremely large precip events (>1.05")$^+$	-2	Heavy precipitation, 99th percentile event	0.02

$^+$ Indicates data evaluated on a daily time step, rather than monthly. The -2 lag is converted from -60 days.

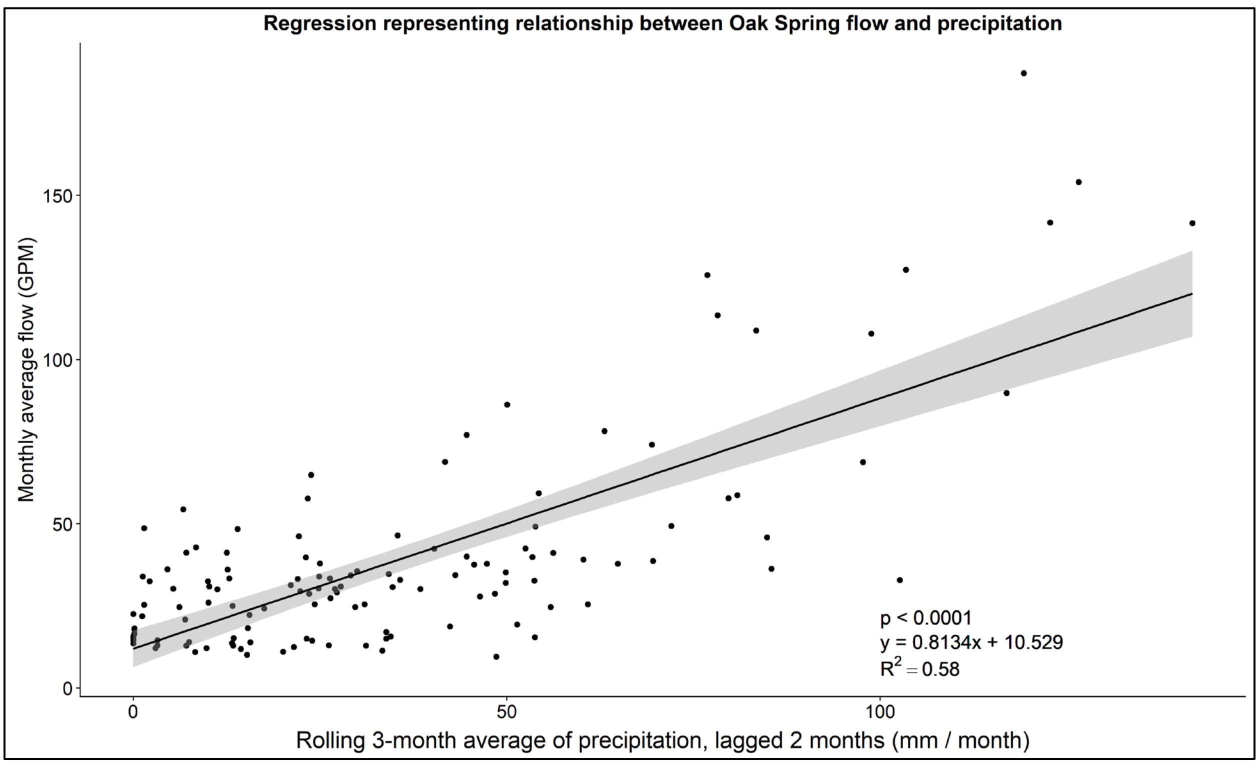

Figure 4. Scatter plot of the mean daily flow of Oak Spring for each month versus rolling 3 month average of precipitation with a two month lag. The line, fitted using a linear regression model, represents the relationship between the two variables, also expressed in Table 1. Grey shading is the standard error for the linear regression.

To further investigate the recharge process, we also examined the correlation between precipitation and actual evapotranspiration (AET), as determined using a water balance model (Appendix 2). We found precipitation and AET were highly correlated (R^2=0.83), suggesting these processes happen simultaneously and are proportional. Because the majority of rain seasonally falls during the hot summer months at a time when evapotranspiration is highest, almost all of the precipitation that falls returns to the atmosphere (97% according to the water balance model). The fact that Oak Spring flow responds to precipitation and contains a modern water component suggests recharge is driven by a direct and rapid infiltration process, i.e., a fraction of the precipitation that falls moves quickly to the groundwater aquifer and therefore is not subject to evapotranspiration, otherwise there would be no water available to recharge the spring – it would essentially all be returned to the atmosphere. By implementing a direct runoff routine in the water balance model and calibrating the water balance modeled runoff to Oak Spring flow (i.e., developing the best relationship between precipitation and runoff, and runoff to Oak Spring flow; Hay and McCabe 2002) we found approximately 20% of the precipitation that falls directly infiltrates into the recharge area. This direct and rapid infiltration could occur if the recharge was occurring through a combination of fractured bedrock and loosely consolidated alluvium, as Shanks et al. (2008) propose.

Several lines of evidence support our proposed hypothesis of direct and rapid infiltration of the Oak Spring aquifer, including statistical and water balance modeling, as well as a separate investigation by Shanks et al. (2008). First, the statistical model relating precipitation to flow was not improved through incorporation of any temperature interaction terms (precipitation x temperature, P:PET). Additionally, although some literature suggests large rain events may result in greater recharge than small events – because enough rain falls to saturate the soil, overcome its water holding capacity, and then becomes runoff – we found no relationship between intense rain events and Oak Spring flow. Both findings suggest interactions with soil are not likely to play a dominant role in the recharge process. Modeling using the water balance, where the best calibrated model includes a direct infiltration term, further supports the direct infiltration hypothesis. Finally, Shanks et al. (2008) report the underlying geology of the Oak Spring recharge area is composed of fractured bedrock and unconsolidated alluvium; substrates that promote a combination of rapid runoff and infiltration to recharge. Baker and Buszka’s (1993) hydrogeology report for the Oak Spring area also supports the hypothesis of rapid infiltration based on high permeability of the geology underlying the recharge area.

The primary conclusion from this analysis of climate and Oak Spring flow data is that discharge measured at Oak Spring is related to precipitation falling in the recharge area, where most recharge occurs through direct infiltration to the contributing aquifer.

Historical climate conditions in Big Bend National Park

Historical climate conditions for BIBE were assessed using the PRISM dataset[1], which represents climate conditions for the US as an 800m gridded surface. We selected the 800m grid cell that overlaid the recharge area for Oak Spring within BIBE to investigate patterns of historical temperature and precipitation change. Those patterns are described below.

Temperature

Mean annual air temperatures in BIBE have increased since 1890, with the rate of change increasing more rapidly from 1970 to 2017 (4.27° F/century) compared to the whole period of record (1895-2017; 1.31° F/century; data not shown). Both maximum and minimum temperature have also increased significantly since 1970, with minimum temperatures increasing at a faster rate than maximum temperatures (6.60° F/century and 1.94° F/century, respectively; data not shown). The temperature trends from the PRISM dataset corroborate another historical climate analysis of BIBE conducted by Monahan and Fisichelli (2014). By comparing the average temperature for recent 10, 20, and 30 year intervals (2003-2012; 1993-2012; 1983-2012) to temperatures observed over the entire record (1901-2012), Monahan and Fisichelli found that 5 temperature metrics describing annual and seasonal temperatures at BIBE were "extremely" warm, meaning that the most recent observations are greater than the 95^{th} percentile of the long-term record.

Precipitation

BIBE has a semi-arid climate, where annual precipitation in the grid cell that overlays the Oak Spring recharge area averaged 14.9 inches from 1970 to 2017 (PRISM Climate Group 2004). Most precipitation comes during monsoon thunderstorms during the months of July, August, and September. Precipitation data from the PRISM dataset demonstrates high variability in annual rainfall with no statistically significant temporal trend from 1895 to 2017 (Figure 5). In a separate, but complimentary analysis, Monahan and Fisichelli (2014) found no recent precipitation metrics they evaluated over the periods 2003-2012, 1993-2012, or 1983-2012 were extreme (i.e., > 95th percentile or < 5th percentile) compared to the long term record (1901-2012).

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[1] PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu

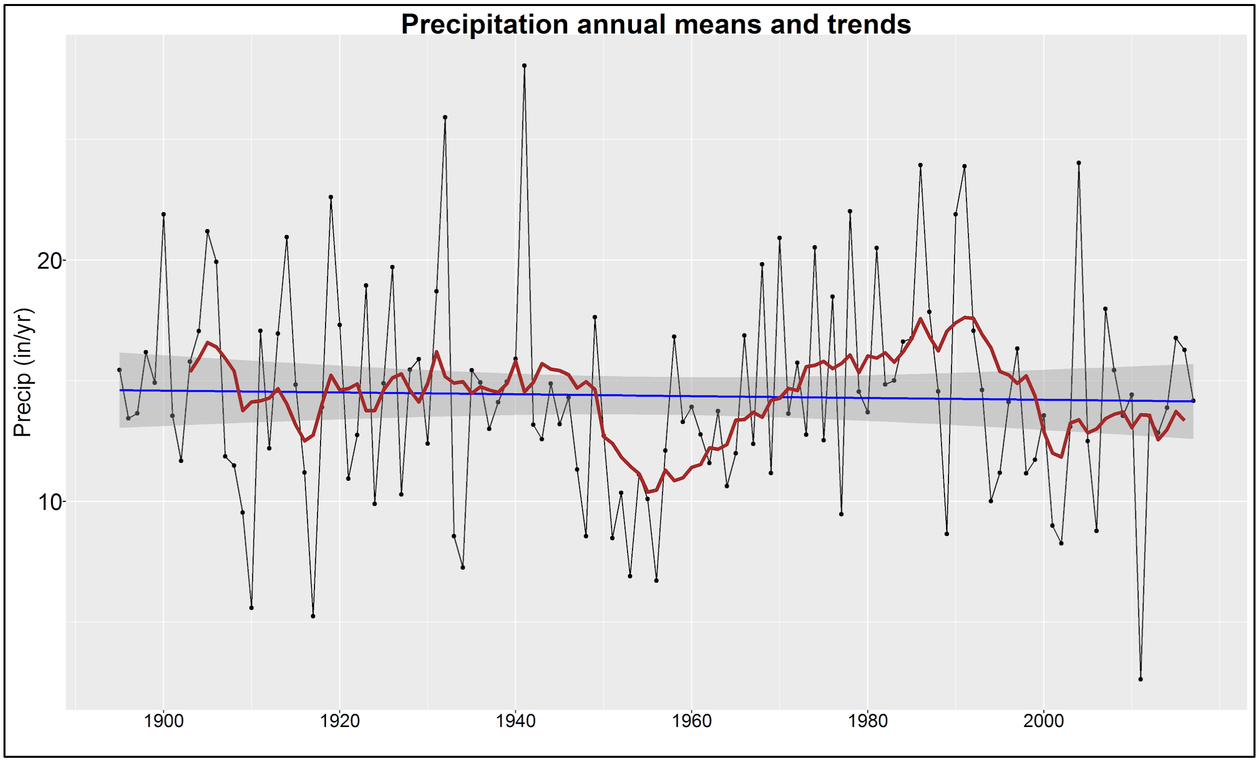

Figure 5. Historical precipitation (black), ten-year running average (red), and regression line for 1895-2017 (blue) for the Chisos Basin. Data from PRISM (Parameter-elevation Relationships on Independent Slopes Model; from PRISM Climate Group. 2004, prism.oregonstate.edu).

Climate projections for the Big Bend region

A variety of studies project increasing temperatures for Texas, while identifying no significant trends in annual precipitation (Nielsen-Gammon 2008, Banner et al. 2010, Jiang and Yang 2012, Liu et al. 2012, Hernandez and Uddameri 2014, Venkataraman et al. 2016). Agricultural droughts are projected to increase in the state, driven in part due to the interaction between precipitation changes and increased evaporation associated with increasing air temperatures (Liu et al. 2012, Hernandez and Uddameri 2014, Venkataraman et al. 2016). Intense rainfall events are also projected to increase (USGCRP 2017). Increases in atmospheric water vapor resulting from high temperatures are expected to increase the frequency of extreme precipitation events (i.e., exceeding a 5 year return period) ~45% to ~90% for the Southern Great Plains, depending on future carbon emissions (Janssen et al. 2014). Even in regions where annual precipitation is projected to decline, heavy precipitation events are projected to increase (USGCRP 2017).

Diffenbaugh et al. (2008) identifies west Texas as one of three hotspots of climate change for North America, characterized primarily by changes in year-to-year variability, particularly for precipitation. When projected precipitation and temperature changes are accounted for simultaneously, several studies of Texas and its various subregions project a drier regime, particularly for the latter half of the 21st century, where multi-year agricultural droughts may become the norm (Seager et al. 2007, Liu et al. 2012, Hernandez and Uddameri 2014, Venkataraman et al. 2016).

Future climate projections for Big Bend National Park

Future climate projections for BIBE were developed from a series of 20 global climate models (GCMs) derived from the Coupled Model Intercomparison Project Phase 5 archive (CMIP5; Taylor et al. 2012) and statistically downscaled to a 4 km grid using the Multivariate Adaptive Constructed Analog method (MACA, Abatzoglou 2013); see Appendix 3 for details. The 20 GCMs employed here represent the full complement of models available from the MACA dataset. We evaluated multiple model projections of climate change for the region, both to represent the range of possible climate change outcomes as well as characterizing the uncertainty associated with different GCM representations of the climate system. Two future representative concentration pathways (RCPs) were retained for each of the 20 GCMs (RCP 4.5 and RCP 8.5), for a total of 40 projections of the future climate at BIBE. RCP 4.5 represents a middle of the road emissions scenario and assumes atmospheric CO_2 stabilizes through time by using a range of strategies and technologies to reduce future emissions. RCP 8.5 represents a business-as-usual greenhouse gas emissions scenario, with human emissions of CO_2 increasing through time (IPCC 2014).

Downscaled future climate projections were analyzed for the 4 km grid cell encompassing the suspected recharge area of Oak Spring (Figure 1, Appendix 3, Shanks et al. 2008) over the time period centered on 2065 (2050-2080). We choose to focus on this period given the project life of a 2020 water development for the Chisos Basin is estimated to be 50 to 70 years (David Larson, BIBE Chief of Resources, *personal communication*), so the project is expected to persist until the 2070s-2090s climate. This period was compared to a baseline reference period of 1950-2000 (Abatzoglou 2013). Note throughout the remainder of the report, when we refer to this 1950-2000 historical period, we are referring to the modeled historical period derived from the MACA dataset. Comparing future projections from the MACA downscaled product to the modeled historical period is the only way to ensure we are using internally consistent GCM representations of BIBE climate.

GCMs differed in (1) the extent of warming anticipated for BIBE (i.e., all models project increased temperatures, but differ in the magnitude of warming) and (2) the direction of change for precipitation (i.e., some models project more annual average precipitation, others project reduced precipitation). For the 2060s, all 40 GCM and RCP combinations project increasing annual average temperature for BIBE (ranging from 2.1 to 9.4° F), compared to the baseline period (1950-2000; Figure 6). Changes in precipitation varied across the GCMs, with some models projecting reduced annual average precipitation (up to -4.1 inches) while others projected increased annual average precipitation compared to the baseline period (up to +3.3 inches, Figure 6). Because the “correct” modelled future is unknown, we constructed plausible and divergent scenarios of change to allow managers to understand the range of potential changes Oak Spring could experience as a result of climate change (Star et al. 2016). More details on the scenarios are below.

Developing climate scenarios for Big Bend National Park

Two scenarios of change centered on 2065 (i.e., 2050-2080) were investigated to evaluate how climate change may influence recharge and discharge from Oak Spring in the future (Figure 6). Climate scenarios were developed to meet four criteria: *plausibility*, *relevance*, and *divergence* sufficient to be *challenging* and useful for guiding forward-looking resource management (National Park Service 2013). These climate projections were chosen because they represent a range of plausible climate outcomes and are intended to allow managers to evaluate their decision-making against different realizations of future climate for the region.

We developed divergent climate scenarios by plotting projections of average annual temperature (x-axis) versus projections of average annual precipitation (y-axis) and then breaking the plot into four quadrants (upper left, upper right, lower right, lower left; Figure 6). Each quadrant represents a plausible scenario of change. For this study we focused on two scenarios (of the four potential scenarios) that were divergent; a "Warm Wet" scenario (upper left quadrant, Figure 6), where temperatures increase moderately (2.1 to 5.1° F relative to the historical period) and precipitation increases (1.4 to 3.3 inches; average +14.9%), and a "Hot Dry" scenario (lower right quadrant, Figure 6), where temperatures increase more than the Warm Wet scenario (6.2 to 9.4° F) and precipitation decreases (-4.1 to -0.5 inches; average -16%).

Within a given quadrant, a scenario can be quantitatively derived by (1) averaging all the models within that quadrant (represented as stars in Figure 6) or (2) by using the most extreme models from the quadrant, circled in Figure 6. There are trade-offs associated with each methodology. The "average" of each scenario is a more moderate projection of potential change, noting that averaging GCMs washes out some of the variability of the models (and that variability may be important to the question at hand). The extreme models in the Warm Wet (inmcm4, RCP 4.5) and Hot Dry (IPSL-CM5A-MR, RCP 8.5) scenarios represent the greatest possible change BIBE could experience in the climate dimensions of precipitation and temperature, and therefore capture the greatest possible divergence between scenarios. Overall, we choose to focus on the extreme models because they meet our overall selection criteria (i.e., plausible, relevant, divergent), but they are also the most challenging to the park water resources, especially the Hot Dry extreme scenario. Another way to think of this is as a "stress test", allowing managers to ask themselves, can I live with the climatic consequences of these extreme scenarios of change in relation to my particular decision? Although we focus our presentation of results on the extreme scenarios of change (i.e., the extreme models), we also present the results for the quadrant averages in Appendix 4.

Table 2 presents a quantitative summary of climate variables for each scenario, focused on the extreme models to ensure consideration of "best and worst" plausible future conditions. Under both scenarios annual temperatures increase (Table 2) and notably, the variability of precipitation increases under the Warm Wet scenario (Figure 7).

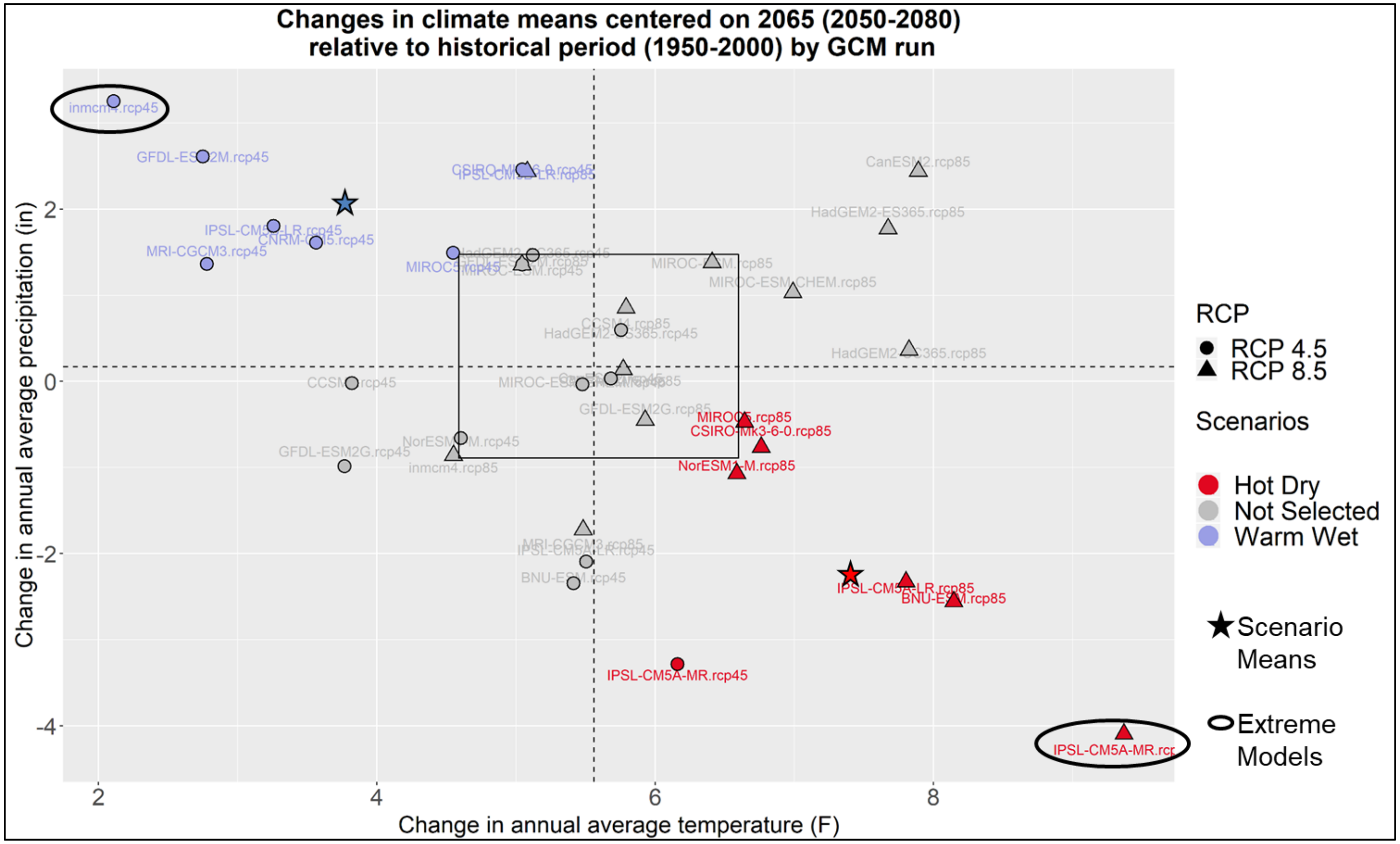

Figure 6. The two climate scenarios for Oak Spring, chosen to capture potential future divergence in terms of change in annual average precipitation and annual average temperature for the 30-year period centered on 2065, relative to the historical period (1950-2000). Dashed lines indicate the median value for each axis and the box indicates a central-tendency, which are those models inside of the 25th and 75th percentiles for each axis. Blue GCM/RCP combinations represent models in the Warm Wet scenario and red GCM/RCP combinations represent models in the Hot Dry scenario. For each scenario, the average of all models in those quadrants is represented by a star, while the most extreme model (i.e., that with the greatest relative change in precipitation or temperature) is indicated by a black circle. Grey GCM/RCP combinations were not considered for scenario selection.

Table 2. Quantitative scenario summary. Values are changes in the averages for the 3-decade period 2050-2080 compared with averages of the 1950-2000 historical period. W: winter (Dec-Feb); Sp: spring (Mar-May); Su: summer (Jun-Aug); Fa: fall (Sep-Nov).

Climate variable	Season	Extreme Model Warm Wet	Extreme Model Hot Dry	Historical Averages
Annual average temp increase (°F)	–	2.12	9.43	64.6
Seasonal daily average temp increase (°F)	W	1.71	8.33	49.17
	Sp	2.48	8.85	66.46
	Su	2.08	10.74	78.38
	Fa	2.22	9.78	64.5
Annual precipitation change (inches)	–	3.5 (24.5%)	-4.46 (-31.21%)	14.29
Seasonal precipitation change (inches)	W	0.2 (14.0%)	-0.54 (-38.03%)	1.42
	Sp	-0.19 (-8.6%)	-1.01 (-45.91%)	2.2
	Su	3.18 (45.23%)	-2.24 (-31.86%)	7.03
	Fa	0.31 (8.5%)	-0.67 (-18.41%)	3.64
Change in days/year > 92 °F (days/year) (Historical 95th percentile)	–	-2.64 (-14.5%)	17.09 (93.59%)	18.26
Change in days/year <32°F (days/year)	–	-0.84 (-49.33%)	-1.41 (-82.94%)	1.7
Change in days > 0.62 in precip / year (days/year) (Historical 95th percentile)	–	2.02 (46.40%)	-1.28 (-29.4%)	4.35

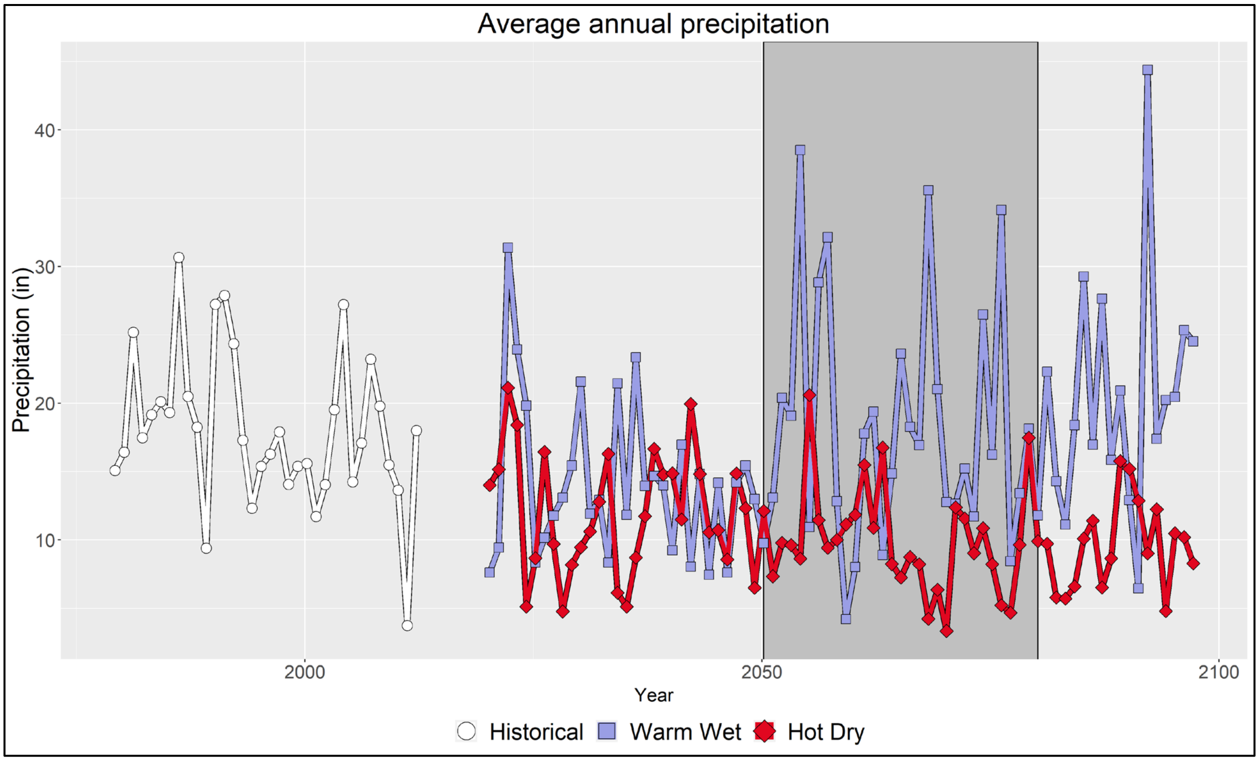

Figure 7. Average annual precipitation projected through 2100 for the extreme models under the Warm Wet and Hot Dry scenarios. The period of interest for this study (2050-2080) is highlighted in grey. Historical data in this plot are the gridded, observed data (gridMET[2]) that are used to train the projected data.

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[2] http://www.climatologylab.org/gridmet.html

Climate influences on projected future Oak Spring discharge

Given that Oak Spring recharge appears to be related to precipitation with a relatively short time lag (2 months), changes to the total amount of annual precipitation and its variability should influence the discharge observed at Oak Spring. The two climate change scenarios presented here differ in the annual precipitation projected for the recharge area of Oak Spring (Table 2). In the Warm Wet scenario, annual precipitation increases by 3.5 inches (+24%) in the 2060s compared to the historical reference period. In the Hot Dry scenario precipitation decreases by 4.5 inches (-31%) relative to the historical period. In terms of seasonal precipitation, the Warm Wet scenario projects a small decrease in precipitation in the spring (-9%) and an increase in the summer (+45%), fall (+9%), and winter (+14%). For the Hot Dry scenario precipitation is projected to decrease in all seasons, with the largest decreases relative to the historical period in the spring (-46%). Under the Warm Wet scenario the variability of annual precipitation increases (Figure 7). Thus, even though the Warm Wet scenario projects more rain over the 2050-2080 period on average, there are years where the annual precipitation falls below the historical average. This highlights the projected increase in extremes of precipitation (both high and low) under this scenario.

In an effort to project Oak Spring flow under each climate change scenario, we ran the projections of precipitation from each scenario through the statistical model derived by correlating ten years of paired precipitation and Oak Spring flow (Figure 4, see Appendix 5 for more details). Managers at BIBE expressed particular interest in how often Oak Spring flow fell below 20 gallons per minute (gpm), given this level of flow begins to challenge operations in the Chisos Mountains Developed Area of the park. Note we intentionally did not include a temperature interaction term in our model because several lines of evidence (highlighted above) suggest temperature and evapotranspiration are not strong drivers of the amount of precipitation that ultimately becomes Oak Spring discharge. Therefore, we would not expect future change in temperatures to play a large role in determining future variability in spring flow. Instead, our results suggest future changes in the amount of precipitation and variability in that precipitation, driven by climate change, will likely play a larger role in determining the reliability of Oak Spring as a water source.

For the period centered on 2065 (2050-2080), Oak Spring is projected to fall below the 20 gpm threshold 18 months per decade under the Warm Wet scenario and 33 months per decade under the Hot Dry scenario, compared to 14 months per decade during the historical 1950-2000 period (Figure 8A). This difference was not statistically significant from the historical baseline for the Warm Wet scenario (ANOVA, $p = 0.55$), while the Hot Dry scenario was significantly different from the historical period ($p < 0.001$). For reference, Oak Spring fell below the 20 gpm threshold during 35 months over the observed period from 2007-2017, in part reflecting the hydrological drought of 2012 (Figure 2).

It may seem counterintuitive that the number of months per decade that fall below the 20 gpm threshold would either stay the same (or slightly) increase in the Warm Wet scenario, compared to the historical period, given this scenario projects a 24% increase in precipitation relative to the 1950 - 2000 baseline. However, this reflects the high variability in precipitation projected under the Warm

Wet scenario (Figure 7), noting as stated earlier, the extremes increase under this scenario. To evaluate if this is an artifact of the particular model we choose for the Warm Wet scenario (inmcm4 RCP4.5), we modeled the same metric (i.e., the average number of months per decade below 20 gpm over 2050-2080) using all of the models that fell in the Warm Wet scenario quadrant (blue models in upper left quadrant of Figure 6, n=8). Across these Warm Wet models the average number of months per decade with flow below 20 gpm for the 2060s was 14.04 (SD = 2.78), compared to 14 months per decade for the historical period. This finding supports the premise that although the Warm Wet models project more annual precipitation than the historical period, the number of months per decade Oak Spring falls below the threshold of management interest is similar to the historical baseline. We ran a similar analysis to confirm all Hot Dry scenario models projected increases in the average months per decade falling below the 20 gpm threshold during the 2060s, and found all Hot Dry scenario models were consistent in this result (see red models in the lower right quadrant of Figure 6, n=7). On average the Hot Dry scenario models project that Oak Spring will fall below the threshold 22.86 months per decade (SD = 5.95), less than the extreme model we selected for the analysis (33 months per decade, IPSL-CM5A-MR RCP 8.5). This result is expected, as we purposefully choose extreme models that bracket the full range of projected future conditions to enable the park to stress-test water development decisions related to Oak Spring (see section "Developing climate scenarios for Big Bend National Park" for more details).

In addition to evaluating the average number of months per decade when flow hit the threshold of interest during the 2060s, we also examined the variability in the number of months per decade where Oak Spring is projected to fall below 20 gpm for each scenario through time (2020-2100; Figure 8B and 8C). Under the Warm Wet scenario the number of months per decade where flow dropped below 20 gpm varied through time, both above and below the historical baseline period depending on the time frame examined. Under the Hot Dry scenario the number of months per decade where flow falls below 20 gpm increases through time, reflecting increasing dryness towards the end of the century.

Overall, the anticipated impact of climate change on Oak Spring discharge depends strongly on the scenario. Under the Warm Wet scenario precipitation increases, extreme highs and lows of precipitation increase, and the average number of months per decade where Oak Spring falls below 20 gpm remains similar to the historical average. Under the Hot Dry scenario annual precipitation decreases, and there is a statistically significant increase in the average number of months per decade where Oak Spring falls below the flow threshold of interest (compared to the historical period). These results suggest changes in the annual average precipitation and year-to-year variation in precipitation will play an important role in the future reliability of Oak Spring as a water source.

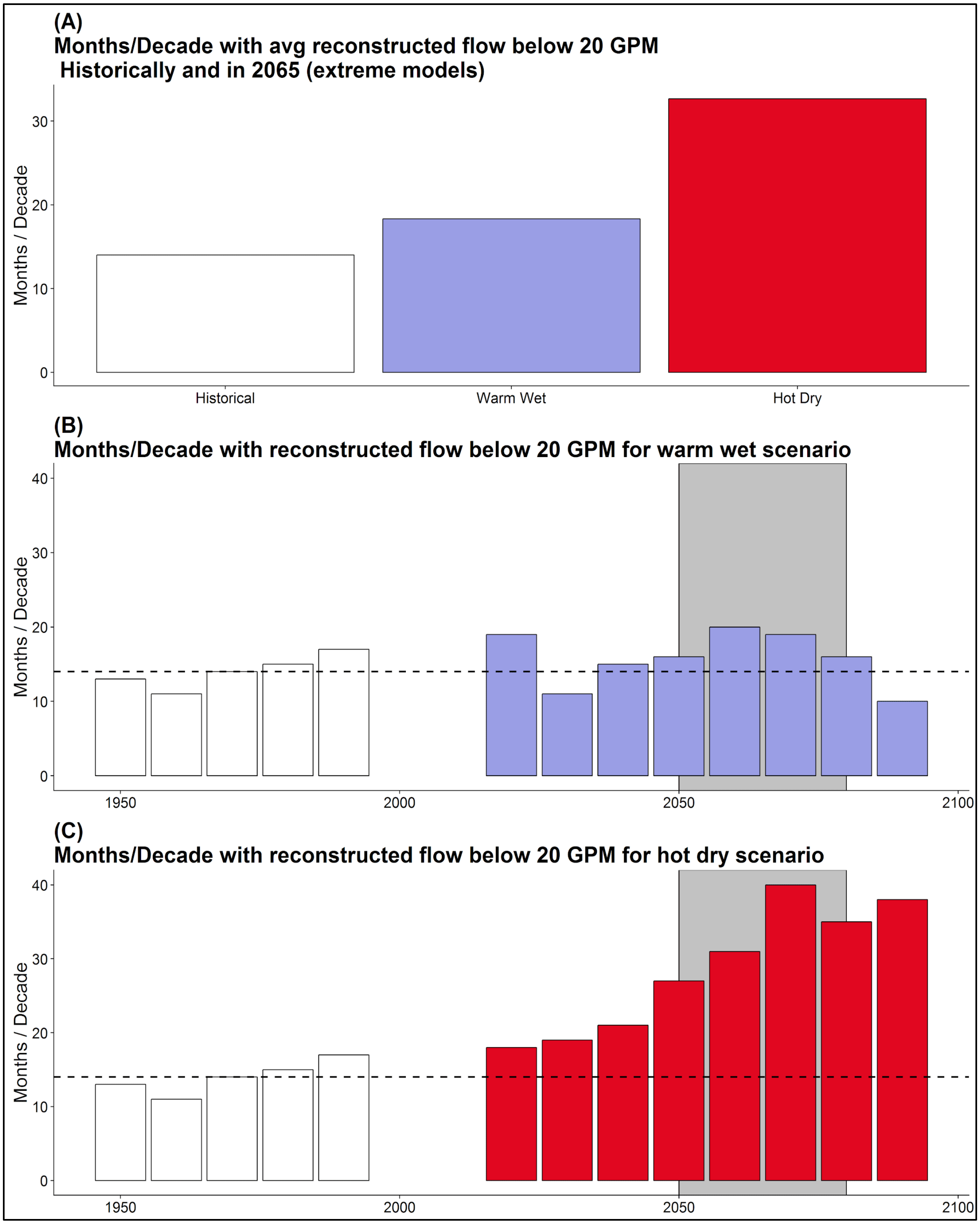

Figure 8. (A) Months per decade when the average flow is modeled to fall below the 20 gpm threshold under the Warm Wet (18 months) and Hot Dry (33 months) scenarios, relative to the 1950-2000 historical baseline period (14 months). (B-C) The number of months per decade when the modeled flow falls below the 20 gpm threshold through 2100 for the extreme models under the Warm Wet and Hot Dry scenarios. The dashed line is the historical average (14 months / decade). The period of interest for this study (2050-2080) is highlighted in grey.

Caveats and sources of uncertainty

Predicting climate-induced changes in the magnitude, timing, and mechanism of groundwater recharge is complex (Kløve et al. 2014). Overall, developing projections of groundwater and recharge requires a detailed understanding of the location, mechanism and season of recharge, the amount of groundwater in storage, and groundwater age. We lacked many of these details and therefore our understanding of the relationship between climate change and spring discharge in BIBE is limited. A more complete understanding of this relationship could be derived by developing a more sophisticated mechanistic groundwater model for Oak Spring (further calibrated with field data) and then adjusting the input parameters of that model to reflect anticipated changes associated with climate change. This is beyond the scope of this technical assistance request. Our process, instead, was based on first order principles and limited data showing how precipitation influences discharge from Oak Spring.

One important caveat to highlight is the statistical relationship we developed between precipitation and Oak Spring flow based on historical data was imperfect. While this relationship accounted for 58% of the variation between precipitation and flow, the remaining unaccounted for variation is significant (42%) and could have a variety of sources (e.g., gaps in the data record, differences in precipitation falling at the weather station compared to the local recharge area, as well as unaccounted for complexities in the relationship between climate and Oak Spring discharge). Because we used this statistical relationship (in conjunction with projections of precipitation) to model future spring flow, those estimates will necessarily contain errors due to errors in the statistical model.

Additionally, our projections of Oak Spring flow are based on changes in precipitation only, rather than projections that include the interactive influence of temperature on precipitation availability (e.g., changes in evaporation or plant transpiration, which may reduce precipitation available for recharge). This was a deliberate choice consistent with our understanding of the mechanism of recharge of Oak Spring (and supported by several independent lines of evidence), where infiltration occurs quickly enough that temperature-driven evapotranspiration does not have a strong influence on recharge during a rain event. If, however, infiltration was influenced by temperature our results would instead suggest decreasing recharge and ultimately Oak Spring discharge under even the Warm Wet scenario, due to the reduction in precipitation availability after accounting for temperature-dependent evapotranspiration processes.

We did not attempt to project changes in water demand that may emerge in the future due to growth in visitation. If visitation increases significantly the 20 GPM flow threshold that was the focus of our modeling efforts may underestimate the demand for water in future years. Accounting for this future demand would help to increase the robustness of water source evaluations in this decision process.

Note as well that the conclusions drawn here for Oak Spring do not necessarily apply to the discharge dynamics of other springs within BIBE in response to a changing climate. The underlying recharge characteristics and mechanism for those springs may be sufficiently different and result in different recharge/discharge dynamics (e.g., recharge location, soils, elevation and exposure, underlying geology, groundwater age).

Finally, all global climate models (GCMs) have their own associated uncertainties, which will necessarily result in uncertainties in interpreting how climate is likely to change in the region and ultimately influence Oak Spring. In some climate analyses those uncertainties can be constrained by only using GCMs known to perform well within a given region (e.g., they replicate historical conditions of temperature and precipitation). We did not have an *a priori* reason to exclude certain GCMs from this analysis, nor did we find one based on a review of the recent scientific literature so we retained all models. It is important to note that our approach is scenario-based – evaluating changes given divergent, plausible, relevant and challenging ends of the continuum of potential climate change – which contrasts trying to find the most "probable" climate change outcomes for BIBE (usually conducted by using an ensemble of GCMs). The benefit of the scenario approach is that it is intended to allow managers to evaluate and stress-test their decisions against a variety of plausible climate change outcomes.

Conclusions

In this analysis we evaluated how different scenarios of climate change are likely to influence the recharge and discharge of Oak Spring in BIBE. Using ten years of on-the-ground data, we found discharge from Oak Spring correlates with the amount of precipitation falling in the local area, where recent precipitation events explain about 58% of the variation in spring flow. Based on several lines of evidence, including a statistical and water balance model, as well as two independent investigations (Baker and Buszka 1993, Shanks et al. 2008), we hypothesize Oak Spring is recharged through direct and rapid infiltration into fractured bedrock and unconsolidated alluvium. Our data and the hypothesized mechanism of recharge suggest temperature and temperature-dependent evapotranspiration processes do not play an important role in the recharge process. Therefore, although we anticipate significant temperature increases to BIBE we do not expect this will have a strong influence on recharge and discharge dynamics of Oak Spring. Instead, we anticipate changes in the total amount of precipitation delivered to the recharge area, combined with changes in the variation of that precipitation, will play a more important role in determining the future reliability of Oak Spring as the climate changes.

Using a statistical model derived from on-the-ground data, we developed quantitative projections of Oak Spring flow intended to bracket a plausible "best case" and "worst case" scenario of climate change and related these projections of flow to a metric of management concern: the number of months per decade when discharge falls below 20 gpm. This is a threshold of direct relevance, as flows below this threshold challenge BIBE operations in the Chisos developed area, and may invoke a drought conservation plan. We focused our climate projections on the 2060s (2050-2080) because managers would like this spring to operate for 50-70 years, given the cost of updating the infrastructure supporting the Oak Spring water development is a large investment ($8-10M).

Under the (best case) Warm Wet scenario, climate projections for the 2060s indicate that both annual precipitation and the extremes of precipitation increase (i.e., the highs will be higher, and the lows, generally lower). Although the total amount of precipitation increases under this scenario, the average number of months per decade where Oak Spring falls below 20 gpm remains similar to the historical average. This is due to the increasing precipitation variability projected under this scenario, oscillating between years with high annual precipitation relative to the historical period followed by relatively low precipitation years. The Warm Wet scenario assumes humans use a range of strategies and technologies to reduce greenhouse gas emissions and ultimately stabilize emissions through time.

Under the (worst case) Hot Dry scenario, 2060s projections indicate the number of months per decade in which Oak Spring flows fall below 20 gpm is more than double the historical average (a statistically significant increase from 14 months per decade historically to 33 months per decade). For reference, Oak Spring fell below the 20 gpm threshold during 35 months over the observed period from 2007-2017, in large part reflecting the hydrological drought of 2012. This scenario assumes business as usual, with emissions of greenhouse gases increasing through time. Under this scenario, the reliability of Oak Spring as a water source may be especially compromised.

We recognize the limitations of our discharge projections, given unaccounted for variation in the statistical model that relates precipitation to Oak Spring flow. Error in this relationship will result in error in future flow projections. Recognizing this important caveat we believe the projections may still be useful to the management question at hand. See the section below for recommendations of information that would further resolve the relationship between precipitation and Oak Spring discharge and aid in understanding the complexities of this groundwater system.

Overall, these findings are consistent with prior climate change studies of the Big Bend region that found some global climate models project increases in total precipitation and some project decreases (Liu et al. 2012), but models generally project increasing variability in rain events (Hernandez and Uddameri 2014). In evaluating projected precipitation and temperature changes simultaneously, a variety of studies on Texas and its various subregions project a drier regime, particularly for the latter half of the 21st century, where multi-year agricultural droughts may become the norm (Seager et al. 2007, Venkataraman et al. 2016). However, Oak Spring appears to be specifically vulnerable to hydrologic drought (i.e., diminished precipitation), given we found recharge of the spring to be largely independent of changes in temperature (an important component of agricultural drought metrics). If this is correct, the interplay of the total magnitude of precipitation change and the year-to-year variability of this precipitation will play an important role in determining the reliability of Oak Spring in a changing climate.

The intent of this evaluation is to explore plausible scenarios of climate change and assess how these scenarios influence the future projected discharge of a critical water supply to BIBE. The scenario approach assists decision making when accurately forecasting the most probable outcome is impossible. By evaluating different scenarios of change managers can stress-test water development decisions related to Oak Spring, while considering how different climatic changes influence the long-term reliability of this water source.

Additional information recommendations

Below are a short list of recommendations that would enable enhanced decision making regarding management of Oak Spring.

- Isotope analysis of local precipitation and Oak Spring discharge would help to further evaluate *where* (i.e., relative contributions of near versus far recharge) and *when* (i.e., winter versus summer) recharge occurs for this water source. A tracer test on flow through the Ward Mountain fracture system, while monitoring groundwater flow in the alluvial/colluvial deposits near Oak Spring, would help substantiate the rapid recharge hypothesis posited within this report.

- A more complex, mechanistic, hydrological model calibrated with field data would be useful to more fully understand and evaluate the relationships between climate change and Oak Spring.

- Continuous monitoring of Oak Spring using a data logging pressure transducer would enhance future studies of how flows of Oak Spring change through time, as well as enhance our understanding of how climate and upland management influence Oak Spring. This information would be useful even if the site is not redeveloped.

- A weather station deployed at Oak Spring or in the suspected recharge area would more accurately represent precipitation events occurring within the area of interest. Precipitation in BIBE and the surrounding area is likely hyper-local, i.e., variable across small geographic extents. Characterizing the actual precipitation falling in the Oak Spring recharge area and relating it to continuous flow measurements (as measured by a pressure transducer, suggested above) would like help further resolve the relationship between local precipitation and spring flow. Note the weather station used to derive precipitation information in this study was approximately 4 miles away.

- Develop a list of alternate sources of water supply for the Chisos basin, and for all sources determine their long term potential reliability in a changing climate.

- Investigate potential water conservation measures that could reduce future water needs from Oak Spring.

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Appendix 1. Recharge flow paths

The suspected flow paths of water recharging Oak Spring from Shanks et al. (2008) who indicate Oak Spring is a combination of younger and older water (>50 years), recharged near the spring and from high in the Chisos Mountains (>1,900 feet), likely near Ward Mountain and La Paloma spring (Figure A1.1; *Figure used with permission)*.

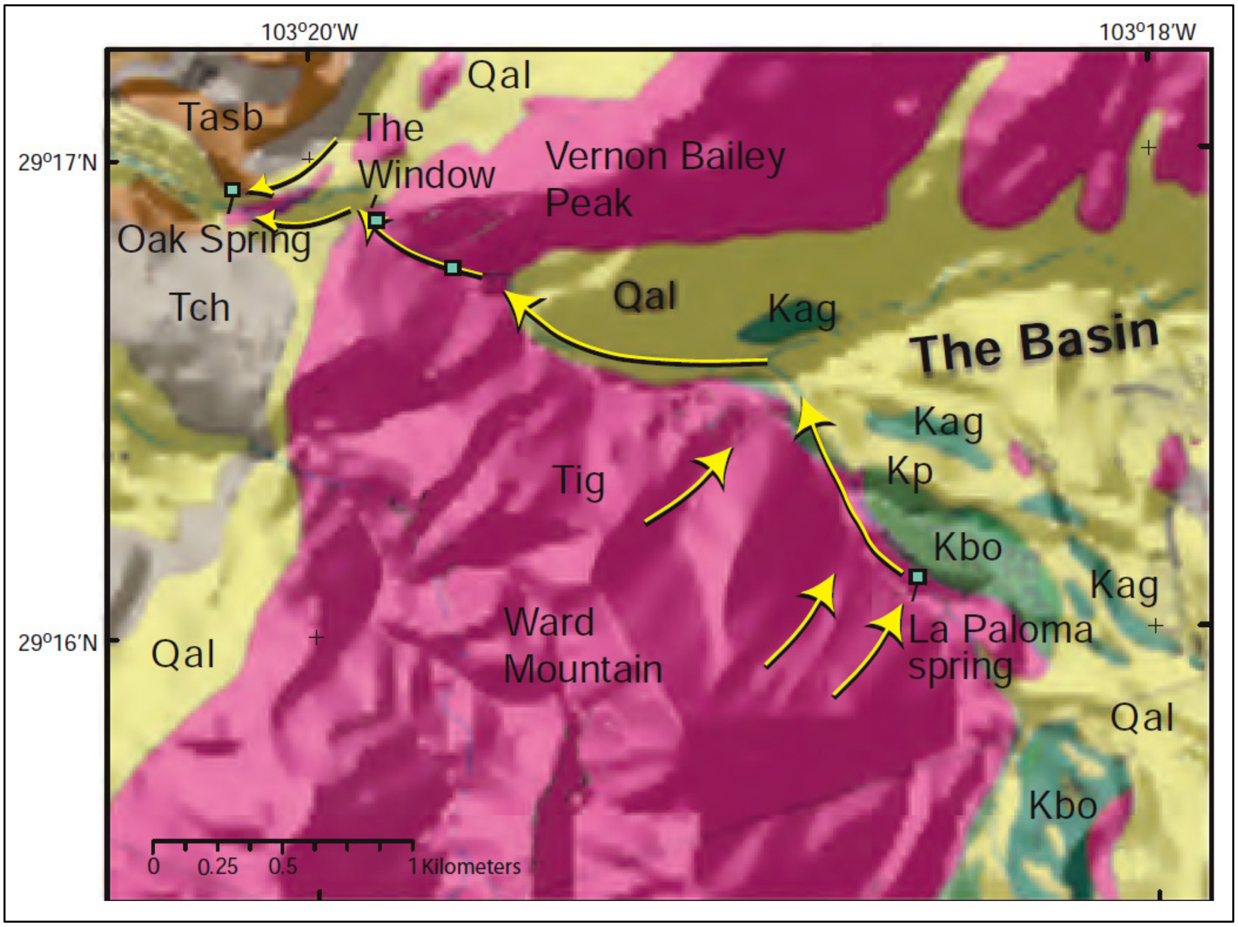

Figure A1.1. Suspected flow paths of water recharging Oak Spring (Shanks et al. 2008, figure used with permission).

Appendix 2. Water balance modeling

Water balance modeling was conducted using a model developed by David Thoma (NPS) to analyze how temperature and precipitation interact with site characteristics in BIBE to influence water availability. The model uses characteristics from point locations (e.g., coordinates, slope, aspect, soil water holding capacity). According to Shanks et al., (2008), much of the Oak Spring recharge comes from Ward Mountain, traveling northwest towards the spring (see Appendix A); therefore parameters derived and averaged from six random sites located throughout the Ward Mountain drainage area were used as model inputs (see Figure 1; parameter values, below).

Potential evapotranspiration (PET) was calculated using the Penman-Monteith method (Penman, 1948; Monteith, 1965; Zotarelli et al., 2018), which estimates the rate at which readily available soil water is vaporized from specified vegetated surfaces (Jensen et al., 1990). This methodology for calculating PET requires additional parameters (downward surface shortwave radiation, wind-velocity, humidity, and specific humidity), which were obtained from Daymet[3] climate data. From PET, the climatic water balance (Stephenson 1998) is calculated by estimating the actual amount that is extracted from the soil (AET), taking into account soil moisture derived from soil type, slope, aspect, and precipitation. Runoff is also calculated as excess water that is not either evaporated or retained in the top one meter of soil.

This model plots the relationship between output variables and Oak Spring flow. Due to the impervious characteristics of bedrock, combined with high temperatures and low precipitation, the model output resulted in almost all precipitation (97%) returning to the atmosphere through AET. If this was the case, very little recharge would occur and there would likely be no relationship between precipitation and Oak Spring flow, which is not the case. Therefore, we adjusted a model parameter that directs a given percentage of precipitation to runoff, a mechanism that simulates water quickly infiltrating fractures in bedrock or other highly pervious surfaces (without exposure to evapotranspiration processes). This parameter was adjusted to optimize the statistical relationship between flow and runoff, which more closely approximates mechanisms affecting recharge of Oak Spring (Table A2.1). Setting direct runoff to 20% in the water balance model (as determined through iterative optimization) resulted in the best relationship between precipitation and runoff (R^2=0.86). As shown below, this parameterization improves the relationship between Oak Spring flow and hypothesized recharge mechanisms.

[3] https://daymet.ornl.gov/

Table A2.1. R-squared values of the relationship between Oak Spring flow, runoff, and precipitation without any precipitation directed to runoff prior to running the model and with 20% of precipitation directed to runoff.

Relationship	R^2 with 20% runoff	R^2 with no runoff
Flow : Runoff	0.63	0.56
Runoff : Precip	0.86	0.61

Final model parameters as follows:

- P to direct runoff (%): 20
- Lat: 29.27
- Lon: -103.32
- Slope: 23
- Aspect: 180
- PET shade coeff: 1
- Wind (m/s): 0.75
- WHC (mm): 20

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Appendix 3. Scenario creation methods

We developed plausible and divergent scenarios using climate output from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model dataset (Taylor et al. 2012), which was used for the IPCC Fifth Assessment (IPCC 2014). Translating coarse global climate model (GCM) signals down to scales useable for applied climate work and resource decision making requires downscaling. The most frequently used downscaling method is Bias-Corrected Spatial Downscaling (BCSD), which assesses the GCM bias relative to an observed dataset and corrects the whole GCM (historical and future) accordingly (Wood 2004; Abatzoglou 2013). In contrast, the MACA method used to develop Oak Spring climate scenarios is a statistical downscaling method based on the assumption that when daily weather is processed over a period of time, long-term climate trends emerge, and if climate is processed long enough, climate changes will occur. This technique enables modelers to process the core determinants of climate change, rather than imposing a statistical correction on monthly data (as is done with BCSD). This method has been shown to be preferable to direct daily interpolated bias correction in regions of complex terrain due to its use of a historical library of observations and its multivariate approach (Abatzoglou and Brown 2012).

Three MACA datasets are available; we downloaded MACAv2-METDATA, in which climate forcings were drawn from a statistical downscaling of GCM data from the CMIP5 dataset (Taylor et al. 2012) using a modification of the MACA method (Abatzoglou and Brown 2012) with the METDATA (Abatzoglou 2013) observational dataset as training data. The product is available at a daily time step and downscaled to 1/24 degree (~4 km). Variables that are downscaled include 2-m maximum/minimum temperature, 2-m maximum/minimum relative humidity, 10-m zonal and meridional wind, downward shortwave radiation at the surface, 2-m specific humidity, and precipitation accumulation, all at the daily time step. We downloaded MACA maximum and minimum temperature, precipitation, and maximum and minimum relative humidity data for a grid cell that encompasses the Oak Spring recharge area (Figure 1), for two greenhouse gas emissions pathways (the moderate Representative Concentration Pathway [RCP] 4.5 and the high RCP 8.5).

The MACA archive contains output from 20 GCMs for the contiguous United States, available for RCP 4.5 and RCP 8.5, totaling 40 model-RCP combinations. We calculated average annual temperature and average annual precipitation for the 40 downscaled projections (20 climate models, 2 emissions pathways each) for use in selecting scenarios. We then calculated the difference in these metrics between the 1950-2000 historical period (Maurer et al. 2002) and a 2050-2080 planning period.

We visually inspected a graphical representation of these key climate metrics to choose two divergent climate scenarios (see Figure 6 in the main text): Warm Wet and Hot Dry. Using a specific projection for a scenario ensures that scenarios are internally consistent (physically coherent) and provides specific climate input for quantitative modeling.

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Appendix 4. Big Bend climate scenarios - Quadrant model averages

The quantitative scenario summary below (Table A4.1) shows averages for each scenario quadrant, rather than the extreme models presented in Table 2. Values are changes in the averages for the 3-decade period 2050-2080 compared with the averages of the 1950-2000 historical period. W: winter (Dec-Feb); Sp: spring (Mar-May); Su: summer (Jun-Aug); Fa: fall (Sep-Nov).

Table A4.1. Quantitative scenario summary showing averages for each scenario quadrant, rather than the extreme models in Table 2.

Climate variable	**Season**	**Quadrant Average Warm Wet**	**Quadrant Average Hot Dry**	**Historical Averages**
Annual average temp increase (°F)	–	3.64	7.35	64.6
Seasonal daily average temp increase (°F)	W	3.38	6.41	49.17
	Sp	3.74	7.47	66.46
	Su	3.8	8.03	78.38
	Fa	3.67	7.48	64.5
Annual precipitation change (inches)	–	2.13 (14.9%)	-2.14 (-15%)	14.29
Seasonal precipitation change (inches)	W	-0.06 (-4.23%)	-0.26 (-18.31%)	1.42
	Sp	0.12 (5.45%)	-0.51 (-23.18%)	2.2
	Su	1.41 (20.06%)	-0.73 (-10.38%)	7.03
	Fa	0.66 (18.13%)	-0.65 (-17.86%)	3.64
Change in days/year > 92 °F (days/year) (Historical 95th percentile)	–	3.56 (19.5%)	14.58 (79.85%)	18.26
Change in days/year <32°F (days/year)	–	-1.13 (-66.47%)	-1.39 (-81.76%)	1.7
Change in days > 0.62 in precip / year (days/year) (Historical 95th percentile)	–	1.13 (25.4%)	-0.79 (-17.8%)	4.45

Appendix 5. Flow modeling methodology

Development of equation to model Oak Spring flow

From the 10-year flow record it was determined that monthly precipitation, averaged for 3 months and lagged by 2 months, had strongest relationship to Oak Spring flow (Table 1). From this relationship, flow was modeled using a linear regression between monthly flow and precipitation:

$$y = 0.813x + 10.529 \quad R^2 = 0.58$$

(see Figure 4 in report). There were two sources of precipitation data used in this analysis, station data (from the Chisos Basin Visitor Center) and gridded, downscaled climate data (MACA, Abatzoglou 2013). Gridded data, based on global climate models have been shown to exhibit systematic biases, creating errors in simulations, relative to historical observations (Ramirez-Villegas et al., 2013), necessitating raw climate model outputs be bias-corrected in order to produce climate projections that correspond with station data. The bias-correction approach corrects the projected raw GCM output using the differences in the mean and variability between the GCM and observed station data in the reference period (Hawkins et al., 2013). Performing this bias correction over the time period corresponding with the flow record (7/1/2007 - 6/1/2018), ensured that the model equation would be applied consistently between the station and gridded data.

The difference between the mean monthly sum of precipitation from the station data and the gridded data was 5.38 mm / month. This number was subtracted from the gridded monthly observations before the linear equation was applied. Figure A5.1 shows the modeled flow from the two data sources, compared to the observed flow from Oak Spring.

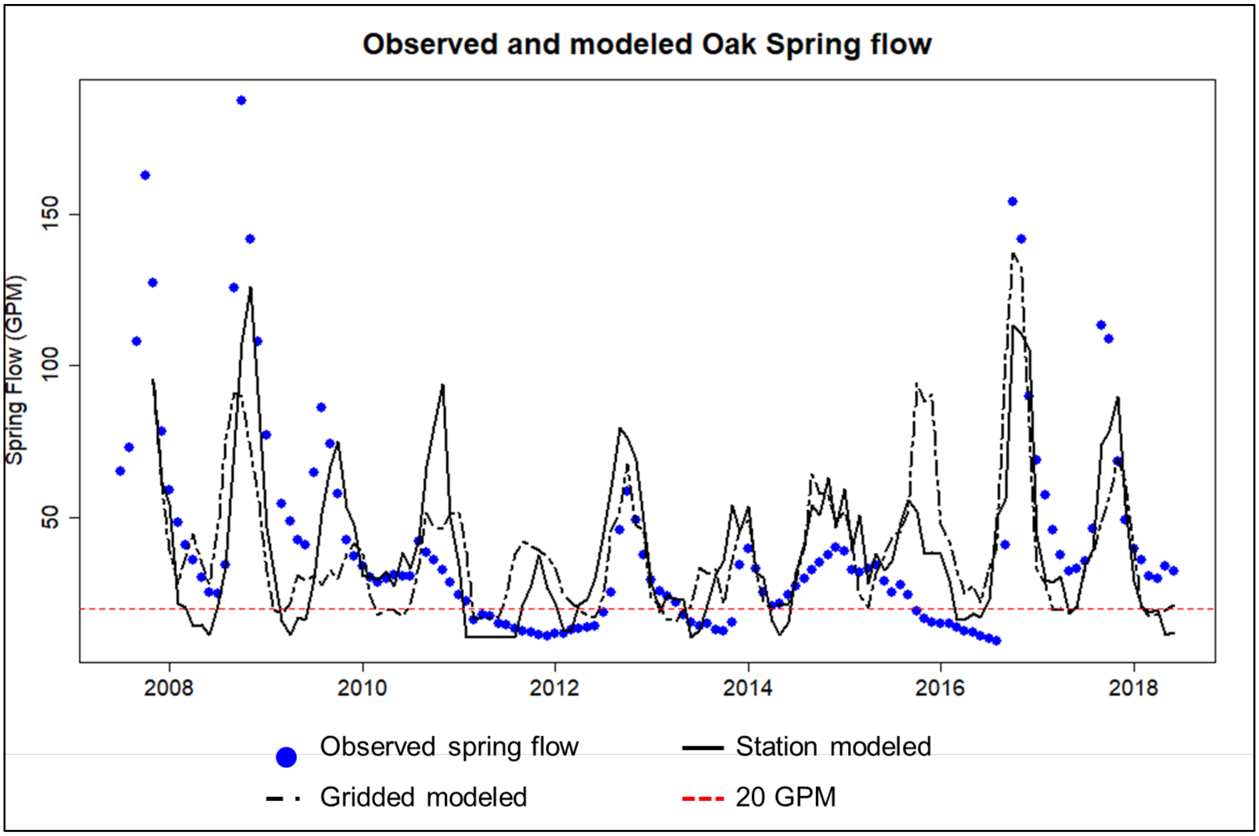

Figure A5.1. Observed mean daily flow from Oak Spring (blue dots), compared to modeled flow using station data (solid line) and gridded data (dot-dash line). The horizontal red dashed line delineates the 20 gpm threshold.

While both data sources reconstruct the overall trend in flow, the modeled flow is more variable, because it is solely driven by precipitation change and it does not capture the full extent of high and low flows. The implications of this, when estimating the number of months that fall below the 20 gpm threshold, are that the modeled flow – particularly from the gridded dataset – is a more conservative estimate.

Modeling Oak Spring flow for climate scenarios

The next step in analysis was to estimate and compare the number of times Oak Spring flow fell below the 20 gpm threshold historically and in both future climate change scenarios. Each GCM within the MACA dataset has its own historical dataset (1950-2005), trained on observed data. Each GCM is also projected from 2006-2100 for two RCPs – 4.5 and 8.5 – (see Appendix 3). To retain variability in precipitation across the historical datasets that drive flow to drop below the threshold, spring flow was modeled and the number of times it fell below the threshold was calculated on each GCM independently (inmcm4 and IPSL-CM5A-MR), then they were averaged for each decade (Figure 8). Alternatively we could have averaged the historical precipitation from each GCM (to develop one historical dataset), but doing so reduces the precipitation variability that generates low flow events.

Literature cited in Appendix 5

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