

WATER FOR PEOPLE

WATER SUPPLY VULNERABILITY ASSESSMENT FOR PROPOSED WATER SUPPLIES

AT VALLES CALDERA NATIONAL PRESERVE
January 2026



ECOSYSTEM SCIENCE
AND SUSTAINABILITY
COLORADO STATE UNIVERSITY



RADICAL
OPEN SCIENCE SYNDICATE

Prepared by:

Kristen Cognac¹, Kathryn Willi¹, Caitlin Mothes²,
Tyler Gilkerson³, David Lawrence⁴

1. Radical Open Science Syndicate, Colorado State University
2. Geospatial Centroid, Colorado State University
3. National Park Service Water Resources Division
4. National Park Service Climate Change Response Program



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Key Messages

This report is part of the “Water for People” project, a national initiative designed to bolster the security and sustainability of National Park Service (NPS) water supplies in the face of a changing climate. This assessment specifically addresses climate-driven vulnerabilities at Valles Caldera National Preserve, a New Mexico park unit currently transitioning from an aging surface water system to a more sustainable groundwater supply. This shift is critical to supporting planned infrastructure expansions, including new visitor facilities and utility upgrades, that are expected to coincide with increases in visitation and water demand. By employing a scenario-based vulnerability assessment, the study evaluates how future climate-driven shifts in water budgets, drought frequency, and wildfire regimes will intersect with these growing water demands.

To quantify these risks, the assessment evaluated the proposed groundwater supply under two contrasting climate futures: a “Hot Dry” and “Warm Wet” scenario. Vulnerability was defined as a function of exposure (the magnitude of climate-related stress) and sensitivity (the degree to which the system is affected by that stress). The system was assessed across six indicator categories: water budget, drought, water demand, wildfire, water quality, and water rights. Each indicator was assigned a vulnerability rating from “Low” to “High” or “More information needed” based on water balance models, wildfire assessments, demand projections, conceptual models, and literature review. This approach provides park managers with a set of divergent, plausible future conditions, offering a robust framework for long-term risk assessment and strategic adaptation.

Findings indicate that while groundwater is the most resilient source available, future hydroclimatic changes may significantly decrease freshwater availability while at the same time, rising visitation will drive up demand on remaining freshwater supplies. Under the Hot Dry scenario, the system faces moderate-to-high vulnerability due to severe groundwater recharge reductions (up to 50%), a 4.5-fold increase in the frequency of severe droughts, and reduced inflows during springtime from declining snowpack and temperature-driven increases in evapotranspiration. Conversely, the Warm Wet scenario presents lower overall vulnerability due to generally wetter conditions, though it remains moderately exposed to extreme precipitation, reductions in springtime inflows, and significant snowmelt declines. Both scenarios highlight shared vulnerabilities, including increased wildfire risk, substantial projected increases in demand from visitors, and uncertainty regarding water rights.

A critical limitation for the assessment is the lack of site-specific groundwater and aquifer data, which hinders a comprehensive understanding of the system’s sensitivity to these climate impacts. Recommendations are provided both to address these limitations through expanded data collection and to proactively address vulnerabilities identified in the report. In particular, increased groundwater data collection in Valle Grande is critical to ensuring the proposed supply can meet future demands.



Below is a summary of key findings and recommendations, further detailed in the [Conclusions](#) and [Recommendations](#) sections.

Key Findings

Recharge: Recharge projections for the Valle Grande aquifer range from -50% (decrease) to 9% (increase) relative to historical conditions, indicating potential for substantial reductions. Spring runoff and snowmelt are projected to decline, with potential to disproportionately impact recharge.

Sufficient Supply, Limited Information: Despite potential for recharge reductions, the annual recharge volume is still greater than the projected water demands, indicating a sufficient supply. However, significant uncertainty exists regarding hydrogeologic conditions at the proposed well site and future water demands.

Increased Wildfire Risk: The region faces a high probability of future wildfires, which can negatively impact water quality and reduce recharge rates. However, the proposed groundwater supply will be less impacted by wildfire than the current surface water supply.

Water Quality Concerns: Water quality concerns are minimal, though more wildfires and decreased recharge could lead to elevated levels of some contaminants. Continued monitoring and treatment will adequately address this.

Need for Monitoring: The analysis emphasizes the critical need for increased monitoring of water use and groundwater conditions to ensure a reliable water supply, particularly with increasing climate variability, drought, potential for well outages, and plans for development.

Recommendations

Hydrogeologic Testing: Limited information is available to determine plausible extraction rates from the proposed supply well. Hydrogeologic testing to determine basic aquifer information is essential for determining whether groundwater can be extracted at adequate rates to meet projected demands.

Enhance Monitoring: Implement continuous, real-time monitoring of groundwater levels and water use to improve efficiency, track changes, and improve supply and demand estimates.

Regular Well Maintenance: Establish a routine inspection and maintenance program for all wells to ensure optimal performance and longevity.

Data-Driven Management: Once data are available, develop models using collected data to proactively adjust water management strategies based on seasonal changes and climate variability.

Expand Wells & Storage: In the longer term, consider installing an additional supply well to ensure consistent water availability during outages and increasing water storage capacity to buffer against seasonal fluctuations and potential supply disruptions.

Water Rights: Inadequate water rights may limit the ability to meet future water demands. Assuring rights are available and in good standing is a critical next step to legally develop water resources.



Project Background

Rising temperatures, altered precipitation patterns, stronger storms, and other climate changes are evident across the United States' national parks (Hansen et al., 2014; Monahan et al., 2016; Gonzalez et al., 2018). These changes may impact the availability and quality of park water resources, including critical drinking water sources. This directly challenges the National Park Service (NPS)'s ability to provide safe drinking water, potentially impacting visitor experiences, recreational opportunities, and park operations. Given the compounding stresses of increasing park visitation, growing water demands, and aging infrastructure, it is increasingly critical to ensure that parks have adequate water supplies. Recognizing this, NPS policy emphasizes proactive planning that integrates future climatic conditions into resource management and investment decisions (NPS, 2012; NPS, 2015; NPS, 2024a).

Situated in the Jemez Mountains of north-central New Mexico, Valles Caldera National Preserve features a large volcanic caldera characterized by extensive grassland meadows, forested volcanic domes, abundant wildlife, and meandering streams, while also preserving Native American homelands and a rich ranching history. The preserve was established in 2000 and has been managed by the NPS since 2014. As a relatively new NPS unit, Valles Caldera is planning an expansion of visitor services and infrastructure, including a new visitor center, new roads, and utility upgrades. A key component of this project involves replacing the aging surface water supply with a new groundwater supply (PMIS 327780; FEA, 2022; FEA, 2024). These improvements are expected to both generate and coincide with increased future visitation and water demand, requiring careful planning to ensure long-term water supply adequacy.

This water supply vulnerability assessment (WSVA) evaluates the susceptibility of Valles Caldera's proposed water supply system to the effects of hydroclimatic change and related stressors. Employing a scenario-based approach, the assessment incorporates a range of plausible future conditions by examining the system's exposure and sensitivity to climate-driven changes in water budgets, storage requirements, droughts, water quality, and fire regimes along with estimated changes in water demands. Vulnerability is quantified by comparing historical and projected factors related to supply, storage, and demand across these categories. The report summarizes vulnerability findings and provides actionable recommendations to inform both short- and long-term water resource management decisions at the preserve. This report is part of a broader "Water for People" project aimed at increasing the security and sustainability of NPS water supplies.

Proposed Water Supply at Valles Caldera

Valles Caldera is planning to develop a new groundwater water supply system to replace the aging surface water diversion that currently sources water from La Jara Creek. These upgrades are necessary to meet projected increases in water demand associated with park development and to address substantial operational challenges and excessive maintenance of the existing system. Proposed upgrades will include a supply well, water treatment facility, and 100,000-gallon water storage tank, all located near the current system in western Valle Grande (Figure 1).

The original water supply at Valles Caldera was constructed in the 1960s as an infiltration gallery diversion system along La Jara Creek. However, in 2013, flash floods following the Thompson Ridge wildfire washed out the gallery, leaving the preserve without a viable water supply. In March 2014, an existing well with a functional pump was located nearby and brought into service as an interim supply. This well, however, proved



unsustainable due to a high sediment load, a long groundwater level recovery period, and biofouling of the well screen. This led to the reinstatement of the surface water system in 2017. Today, water is directly diverted from La Jara Creek using a submerged pipe and partially-functioning settling tank. The new, proposed water supply will serve as a more reliable long-term groundwater source that is less susceptible to surface contamination, flooding, fires, and other water quality and quantity concerns (Connors, 2015; Rice, 2015a).

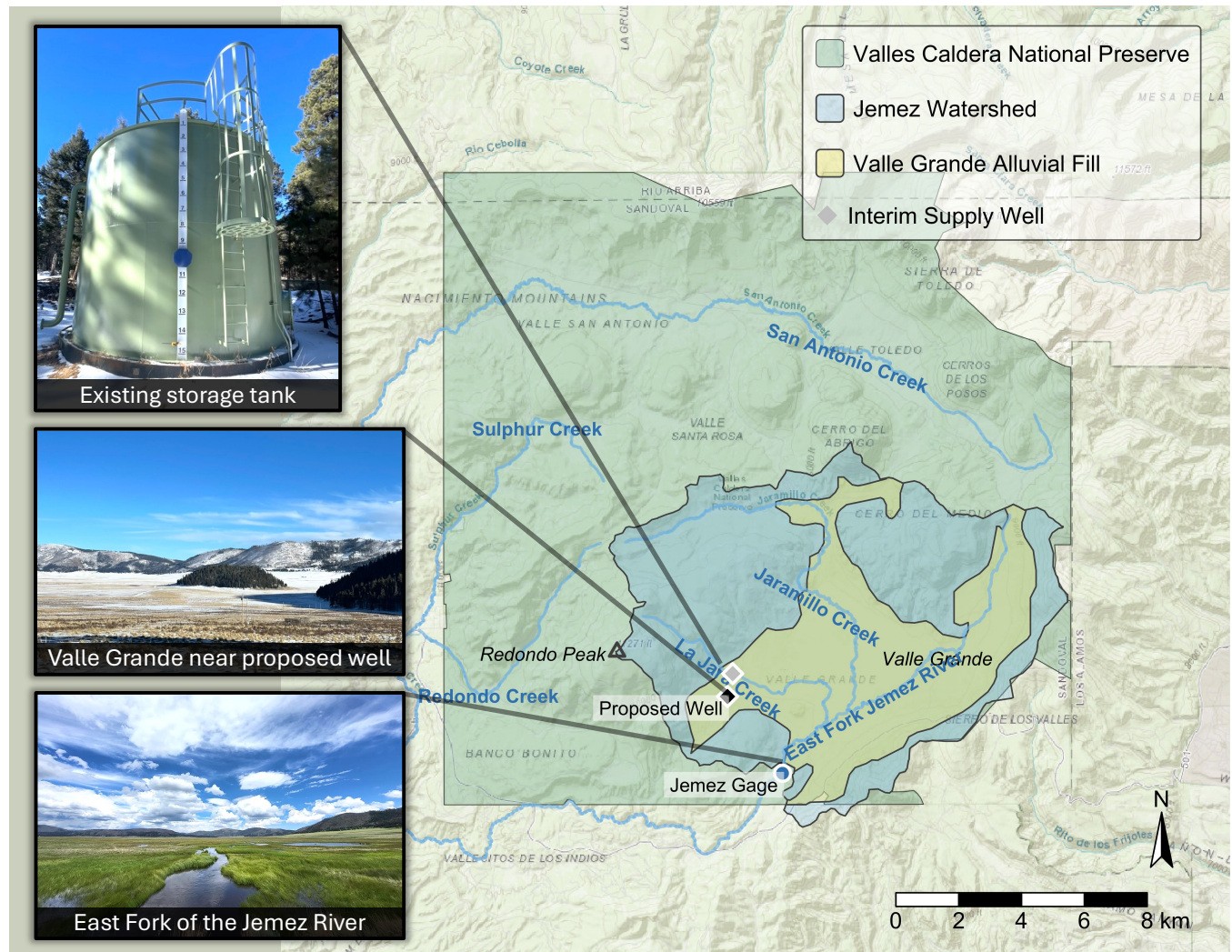


Figure 1: Map showing the location of the proposed supply well within the preserve.

The proposed well site in western Valle Grande was selected based on its proximity to existing infrastructure and the likelihood of suitable hydrogeologic conditions based on geophysical surveys and locations of nearby faults (Rice, 2017; Rice, 2018). Prior to drilling the final supply well, however, a test well should be drilled to verify that hydrogeologic conditions are adequate for the required pumping rates (Rice, 2018). The preserve’s General Management Plan is currently in “draft” form, indicating the proposed infrastructure locations, including the well site, remain subject to change (January 2025 conversations with park staff). Despite the tentative nature of the precise well location, its completion within Valle Grande is highly probable.

Physical Setting

Valles Caldera is in the Jemez Mountains of northern New Mexico at the intersection of the Rio Grande Rift and the Jemez Lineament fault. The collapsed caldera formed from a massive eruption approximately 1.25 million years ago, with subsequent volcanism producing a large, resurgent dome (Redondo Peak) and multiple post-resurgence rhyolite domes within the caldera interior. Upland volcanic domes are separated by intermontane grassland valleys. Valle Grande, the largest of these valleys, features multiple creeks draining adjacent uplands along with various springs, wet meadows, and wetlands. Upland areas, including the caldera rim and volcanic domes, are forested with ponderosa pine and Douglas fir.

This region's semi-arid climate is marked by significant variability in temperature and precipitation, influenced in part by the area's complex topography. Between 2004 and 2024, the weather station in western Valle Grande (USW00003062) recorded annual precipitation ranging from 11.3 to 33.4 inches with an average of 23.9 inches. Snow depth, logged from 2014 to 2024, records annual maximum depths ranging from 3.75 to 37 inches per year. Nearby SNOTEL sites at Garita Peak (Site ID: 1173; located in the northern central part of the preserve) and Quemazon (Site ID: 708; located just outside the preserve east of Valle Toledo) record annual snow water equivalent (SWE) ranging from 2.3 to 13.7 inches and 1.4 to 10.4 inches respectively for years 2016 through 2024. The elevation within the preserve spans from around 8,500 feet (ft) in the valleys to 11,250 ft on Redondo Peak. Notably, Valles Caldera's inclusion in the Catalina-Jemez Critical Zone Observatory (CZO) has facilitated extensive research in the area, contributing to the development of local hydrological conceptual models that inform this study.

Surface Water

The East Fork of the Jemez River is the primary surface water drainage for Valle Grande, with several key headwater streams originating along volcanic uplands surrounding the valley including La Jara and Jaramillo Creeks. The East Fork of the Jemez River and its tributaries exhibit snowmelt-dominated hydrographs, peaking in late-March to early-April during snowmelt, followed by a steady recession that continues until the following spring snowmelt (Zapata-Rios et al, 2015; [Figure 2](#)). Stream discharge is flashy, with dramatic increases in flow after snowmelt and monsoon events, as seen in the late-summer and fall hydrograph spikes. NPS staff have observed ice dams near the valley outlet which, upon breaching, have released large water volumes. Many headwater streams originate as springs, with lateral subsurface flow being the primary driver of stream discharge, particularly along La Jara Creek (Liu et al., 2008; Zapata-Rios et al., 2015). The stream gauge for the East Fork of the Jemez River is at the southwest margin of Valle Grande, where the river departs the valley, thereby capturing most of the surface flow leaving Valle Grande. Notably, discharge records from this gauge are discontinuous, with multiple gaps during spring peaks, likely related to issues with ice damming. See [Appendix C, Figure C2](#) for the full discharge record and refer to the subsequent section on water balance for definitions and methods related to runoff, snowmelt, and discharge calculations.



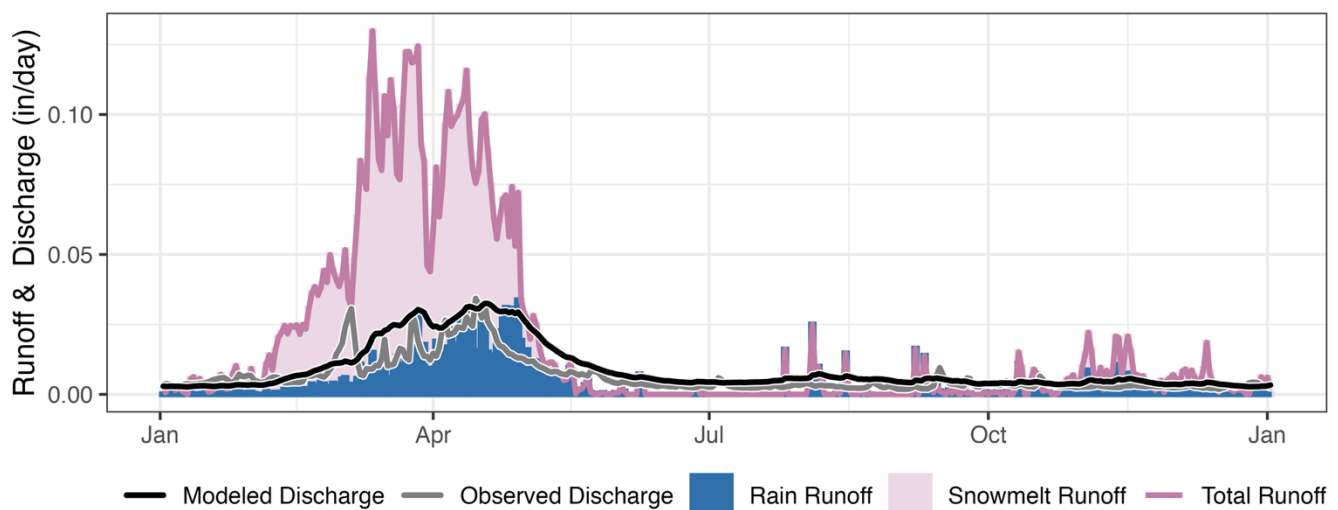


Figure 2: Observed (Aquarius Site: VALL_EFJRHV) and modeled specific discharge (discharge divided by the drainage area), along with rain and snowmelt runoff components, for the East Fork of the Jemez River at the outlet of Valle Grande.

Hydrogeology

Groundwater occurs within shallow-nonthermal and deeper-geothermal systems throughout Valles Caldera. The proposed groundwater supply will access shallow nonthermal groundwater from unconsolidated sediments of Valle Grande. These unconsolidated alluvial and lacustrine sediments overly a thick sequence of volcanic bedrock. Near the proposed well site, upper volcanic units are not explicitly mapped, but nearby cross-sections indicate either Bandelier Tuff or older Miocene volcanics (Goff and Others, 2011). Of the upper unconsolidated sediments, alluvial deposits make up the primary aquifer material, consisting of early Pleistocene- to Holocene-age fine to coarse sand and gravel derived from mass-wasting and streams draining volcanic uplands. Pleistocene lacustrine (lake) deposits interspersed within the alluvium indicate past inter-caldera lakes that formed by volcanic damming and were subsequently backfilled with fine sediments (Goff and others, 2006).

Where present within Valle Grande, lakebed clays function as an aquitard, forming a deeper, confined alluvial aquifer and a shallow perched aquifer throughout much of the valley. Clay thicknesses approach 295 ft (90 meters) in the valley center where strong artesian conditions support numerous springs. Thinner clay sequences are reported near the valley's periphery (Conover et al., 1963). The driller log for the interim supply well, which is located on the valley periphery to the northeast of the proposed well, records 60 ft of clay terminating at a depth of 175 ft and overlying a gray sandy bedrock ([Appendix A Figures A1 & A2](#)). An aquifer test for that well indicates a semi-confined to confined aquifer response and artesian conditions were not reported (Rice, 2015). The presence of a clay unit at this interim well, which sits between the valley margin and proposed well, indicates the clay unit is also likely present at the proposed well site. This estimation is supported by staff observations of a near-surface clay layer between the two well locations and significant water flow atop this clay unit in spring. Depending on the depth of the confining unit and the hydraulic properties of the overlying materials, significant lateral flow may occur within this perched aquifer.

The target depth of the proposed well is approximately 200 ft into alluvial sediments of Valle Grande. Neither the total thickness (depth) of the alluvium or presence/absence of the confining unit are defined at this location (Rice, 2018). Furthermore, direct groundwater depth measurements and aquifer hydraulic properties are generally

unknown for the Valle Grande sediments near the proposed well location. Electrical resistivity imaging conducted in November 2017 estimated groundwater depths ranging from 12 to 18 ft below ground surface at the proposed well site based on subsurface resistivity values (Rice, 2018). However, resistivity values may also reflect changes in lithology, dissolved solids content, and temperature of subsurface materials, leaving considerable uncertainty regarding groundwater conditions. Conover et al. (1963) estimated a hydraulic conductivity of 1 ft/day for the confined aquifer in central Valle Grande where the aquifer is over 800 ft thick and overlain by 300 ft of confining material. The nearby interim supply well has recorded groundwater depths ranging from 15 to 50 ft; however, this well is believed to be completed in fractured bedrock and is significantly closer to Redondo Peak at an elevation approximately 181 ft higher. Therefore, these measurements are likely not representative of conditions near the proposed well site.

Characterizing climate impacts to groundwater availability requires an understanding of how future changes could impact groundwater stores. The lack of groundwater level data near the proposed well site limits the ability to assess how historical climate fluctuations have influenced Valle Grande groundwater storage in the past. Instead, we develop estimates of historical and future groundwater recharge to predict how climate-driven changes in recharge could impact groundwater levels near the well site. This requires a conceptual model for groundwater recharge in Valle Grande.

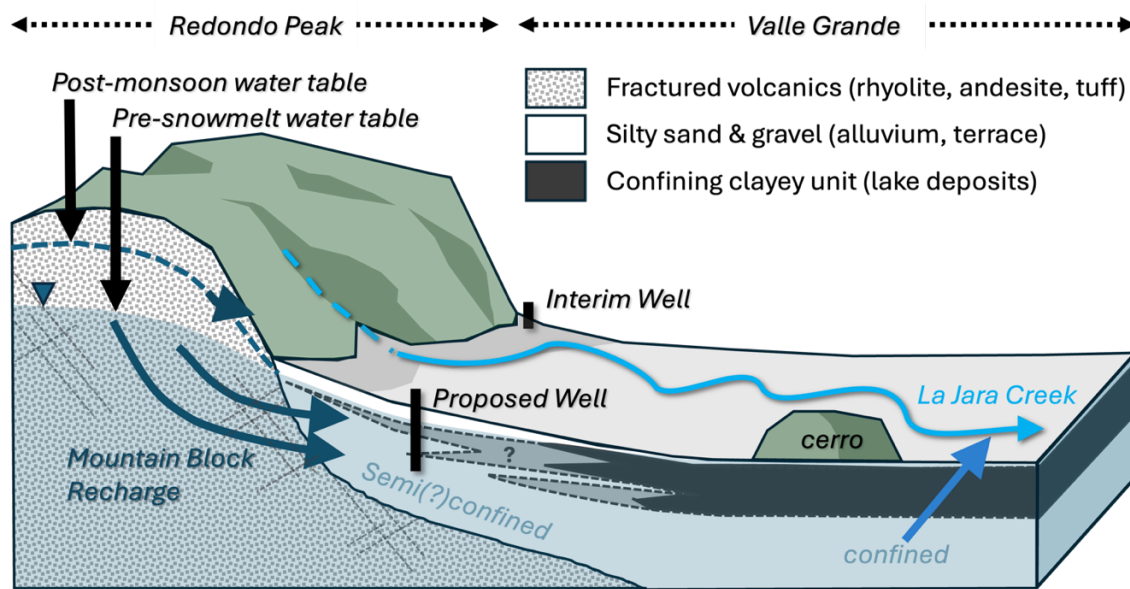


Figure 3: Conceptual model for recharge of the semi-confined to confined Valle Grande aquifer near the proposed well site. The dashed outline and question mark indicate uncertainty in the confining unit extent; the blue arrow from the confined aquifer to La Jara Creek represents deeper groundwater discharge to La Jara Creek.

For upland areas surrounding Valle Grande, infiltrating rain and snowmelt recharge the shallow groundwater table in the fractured bedrock, then flow downgradient towards the valley, with some water returning to the surface as springs, some recharging the shallow valley aquifer, and some recharging the deeper valley aquifer. Within the valley, where the confining unit is present, infiltrating rain and snow directly recharge the shallow, perched aquifer and then flow laterally atop the confining unit, with some fraction discharging to streams as baseflow. Where the confining unit is absent, particularly near the valley margin, infiltrating water may directly recharge the deeper aquifer. However, wherever the confining unit extends to valley margins, recharge to the

deeper aquifer is limited to inflow from the adjacent mountain block, a process referred to as mountain block recharge (MBR). MBR occurs when water infiltrates into the fractured mountain block (i.e., Redondo Peak and other volcanic uplands) and subsequently flows downgradient into the valley aquifer ([Figure 3](#)). Lyon et al. (2008) documented flow in headwater streams on Redondo Peak that closely tracked with groundwater table fluctuations within the highly permeable fractured bedrock. This seasonally fluctuating water table, which rises following snowmelt (March-April) and monsoon (October-November), indicates periods of increased hydraulic gradients between the mountain block and valley aquifer, providing a driving force for MBR into the shallow and/or deeper aquifers of Valle Grande. Localized thinning or absence of the clay layer results in groundwater discharge from the confined Valle Grande aquifer to both the unconfined Valle Grande aquifer and tributaries of the East Fork of the Jemez River.

This conceptual model is supported by previous studies that have used groundwater age tracers to estimate relative ages of different water sources around Valles Caldera. Groundwater tritium concentrations reveal the approximate recharge age of water that infiltrated before or after the 1950s peak in atmospheric tritium generated by nuclear bomb testing. Shallow groundwater on Redondo Peak has tritium concentrations that indicate present-day meteoric water, whereas concentrations downstream in the East Fork of the Jemez River indicate recharge occurred between 20 and 75 years ago; this indicates a mixing of recently infiltrated precipitation with older groundwater moving along longer flow paths before this groundwater discharges to the river (Vuataz and Goff, 1986).

By contrast, tritium from deeper geothermal groundwater indicates residence times ranging from 60 to 10,000 years, with stable isotopes indicating recharge elevations that span the caldera floor to rim and suggesting the caldera depression serves as a recharge basin for the deeper geothermal system (Vuataz and Goff, 1986). These ages support the idea that shallow groundwater stores in Valle Grande are distinct from the deeper geothermal system, and that upland areas are replenished annually with modern-day precipitation. Although tritium concentrations are unavailable for groundwater within Valle Grande, based on the conceptual model, we assume this water would include a mixture of modern water from MBR and valley floor recharge, and much older water from the deeper aquifer that was recharged over a much longer period of time. Either way, we assume that modern recharge is essential for maintaining current storage within the Valle Grande aquifer near the proposed well site.

Projecting Climate and the Water Budget

New Mexico's water resources are anticipated to be significantly impacted by future changes in climate. Global climate models unanimously project warmer temperatures in the future, with average annual temperatures ranging from 1.9 to 7.3 °F warmer by 2050 (NPS CCRP, 2024). Rising temperatures will drive increasing atmospheric water-holding capacity, leading to heightened evaporative demand and overall aridification. While the trajectory of precipitation remains less certain, with average annual changes ranging from -4.9 inches (-18.1%) to + 3.9 inches (14.2%), increased interannual variability is expected, with potential for anomalously wet years interspersed with more extreme droughts.

To quantify the impacts of these changes to the proposed water supply at Valles Caldera, we used a water balance model driven by both historical and projected climate data. Historical (1979-2012) daily temperature and precipitation data were obtained from the 4-kilometer (km) resolution gridded GridMET dataset (Abatzoglou, 2013), which covers the contiguous United States. Future (2025-2100) temperature and precipitation projections



were derived from global climate models (GCM) that simulate Earth’s climate under various future conditions. Specifically, we employed models from the Coupled Model Inter-Comparison Project 5 (CMIP-5; Taylor et al., 2012) downscaled and bias-corrected to GridMET using the Multivariate Adaptive Constructed Analogs (“MACA”) method (Abatzoglou and Brown, 2012) to enhance representation of local conditions.

Temperature and precipitation datasets served as inputs for the National Park Service water balance model (NPS WBM) to generate daily timeseries of various water budget components (Figure 4; Thoma et al., 2020; Tercek et al., 2021; Runyon et al., 2024). The NPS WBM simulates the daily water budget using the general equation:

$$P = AET + \Delta S + RO$$

The model initially parses precipitation (P) into rain and snow. Snow is retained in snow storage until it is released through temperature-dependent melting. Rain and snowmelt then enter soil storage (S) where the effects of evapotranspiration are applied resulting in a change in storage (ΔS). This involves calculating potential evapotranspiration (PET ; Oudin et al., 2005) and then calculating actual evapotranspiration (AET) as the fraction of PET available in soil storage. If excess water is available after AET , then runoff (RO) is generated. Runoff is then partitioned into discharge (streamflow) and groundwater recharge using a runoff routing model for which routing parameters are calibrated to match discharge data from a corresponding stream gauge. For the Valle Grande aquifer, the water balance model was run using gridded temperature and precipitation data that overlap the East Fork of the Jemez River watershed and runoff routing was calibrated to discharge data from the associated stream gauge in southwest Valle Grande (Figure 1). The snowmelt fraction of runoff was calculated by multiplying runoff by the snowmelt fraction of available water (snowmelt + rain) for each timestep. Notably, the runoff term includes water that will become surface flow and groundwater recharge, which is sometimes referred to as excess precipitation. Herein, we retain the term “runoff” for consistency with other NPS WBM publications. A complete outline of the NPS WBM can be found in the appendix of Runyon et al. (2024).

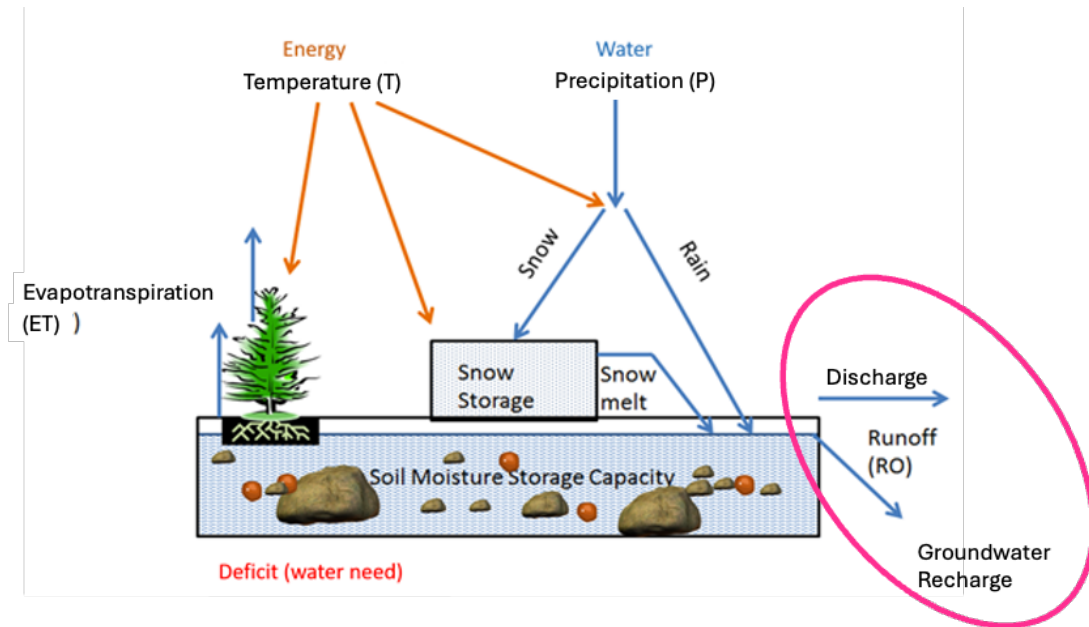
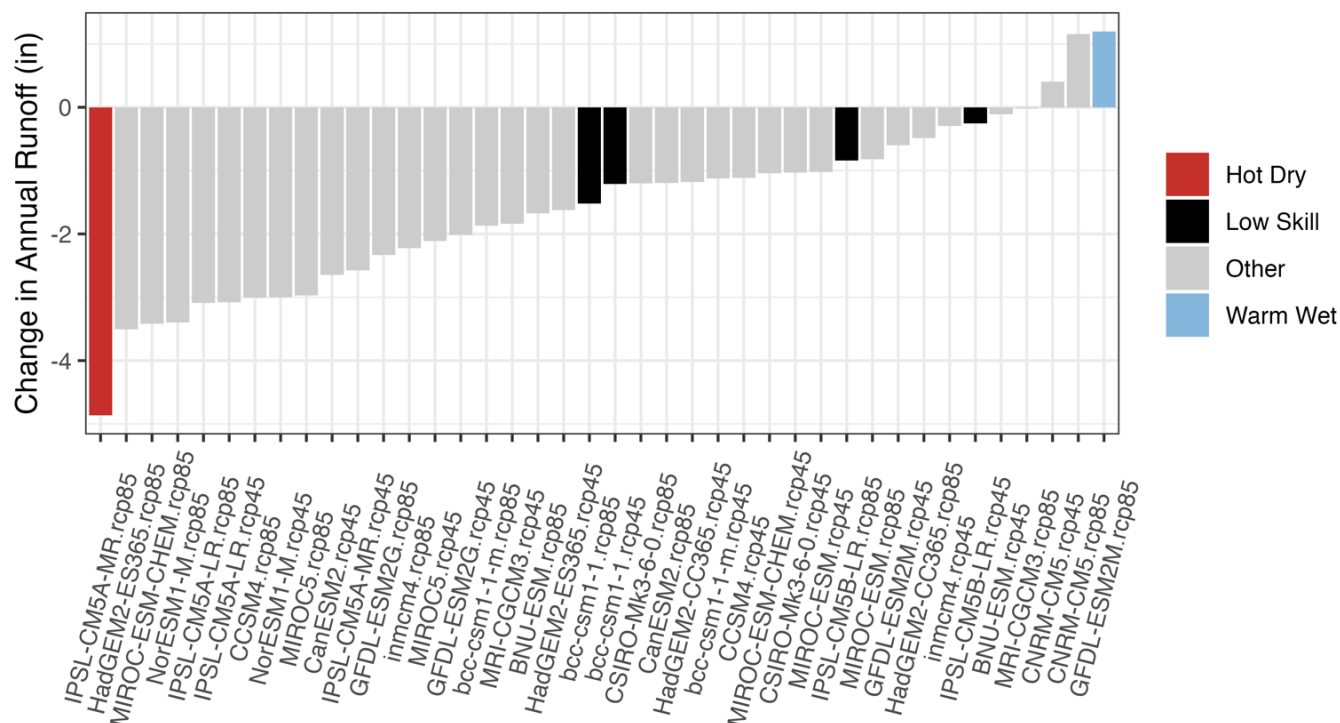


Figure 4: Schematic illustration of the water budget (NPS, 2024b). Runoff, surface flow, and groundwater recharge, key components that relate to the water supply, are circled in pink.

The NPS WBM was run using inputs from 40 CMIP-5 GCM projections, yielding a range of water balance projections that reflect the inherent uncertainty in future conditions. To facilitate decision-making under this uncertainty, we adopted a scenario-based approach, focusing on two divergent yet plausible climate futures for Valles Caldera: the “Warm Wet” (coolest and wettest) and “Hot Dry” (hottest and driest) scenarios (Runyon et al., 2024). These climate futures correspond to the most substantial projected changes in mean runoff (recharge + discharge) between a historical baseline period (1980-2012) and a future management period (2035-2065) (**Figure 5**). These climate futures should be interpreted as plausible and contrasting representations of future uncertainty, rather than definitive predictions. Divergent scenarios are intended to provide decision-makers with a spectrum of potential resource impacts, enabling the development of robust and adaptable management strategies that can be used to prepare for unforeseen events (Lawrence et al., 2021). A related climate futures summary detailing additional climate variables is available for Valles Caldera National Preserve (CCRP, 2024), and further information regarding the scenario and GCM selection process is included in **Appendix B**. Detailed descriptions of the runoff-routing function, calibration, fitted parameters, and performance statistics are included in **Appendix C**.



consistent with other New Mexico park visitation including White Sands National Park (730,000 in 2023), Bandelier National Monument (270,000 in 2021), and Carlsbad Caverns National Park (approximately 400,000 in 2023) (NPS, 2025). For the relatively short period of data availability, Valles Caldera visitation was greatest in August through October and lowest in January through March. This seasonal distribution is expected to change as development includes provisions for winter visitation including a visitor center and paved roads. Bandelier, which shares a northwest border with Valles Caldera and has a longer record of visitation (1980-2024), records peak visitation from May through August.

To project future annual visitation for Valles Caldera, we assumed a linear increase to 500,000 visitors (per the GMP) by 2075, corresponding to an average increase of 8,300 visitors per year starting with approximately 10% annual growth and ending with 1.5% annual growth. Upper and lower uncertainty ranges for future annual visitation were estimated as $\pm$ one standard deviation, estimated as the historical coefficient of variation (CV) multiplied by the projected annual mean. Monthly visitation was projected by applying historical monthly proportions to annual projections, indicating the largest increases would occur during late summer and fall (**Figure 6**). For reference, linear trends in annual visitation at Bandelier for years 2013-2024 (excepting 2020 due to pandemic related visitation decreases) show increases of on average 7,700 visitors per year (**Appendix A Figure A3**).

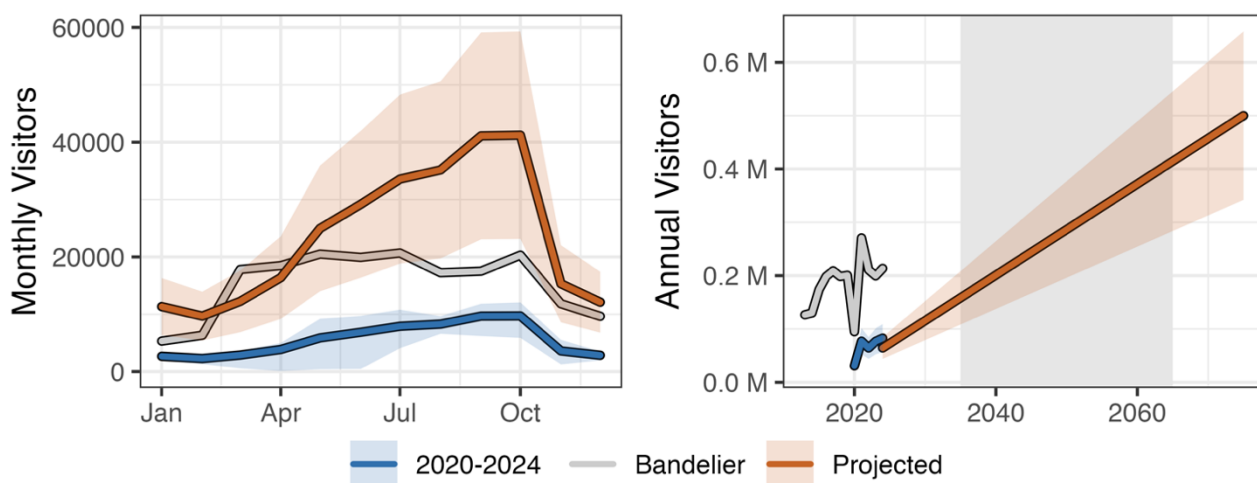


Figure 6: Historical (“2020-2024”) and projected monthly and annual visitation for Valles Caldera with historical visitation at Bandelier (2013-2024) shown for reference. Shaded areas surrounding each curve indicate upper and lower uncertainty bounds and the gray area indicates the focus period for report projections.

Valles Caldera’s water system is currently classified as “non-public”, serving a resident staff of 8-10 individuals and 12-15 daily staff. Potable water is not currently provided to visitors. Manually recorded meter data tracking the total volume of treated water from 2014 through early 2018 was used to estimate pre-expansion water demands. Estimated monthly use ranged from 0 to 128,000 gallons (17,000 cubic feet; CF), averaging 21,500 gallons (2,875 CF) with active operation between March and October (**Figure 7**). Equivalent daily use ranged from 28 to 4,200 gallons (3.5 to 560 CF) and averaged 778 gallons (104 CF). Annual use ranged from 115,000 to 310,000 gallons (15,000 to 41,500 CF). Connors (2015) similarly assessed water demands at the preserve for 2013 and 2014 and estimated an average daily use of 870 to 1,000 gallons (116 to 134 CF) from metered tank data, equivalent to annual use of 212,000 to 240,000 gallons (28,340 to 32,000 CF) assuming active use for 8 months

of the year. They also estimated peak daily use to be 3,675 gallons (503 CF) based on a per-person rate of 75 gallons (10 CF) per day multiplied by an estimated maximum number of occupants per occupied building.

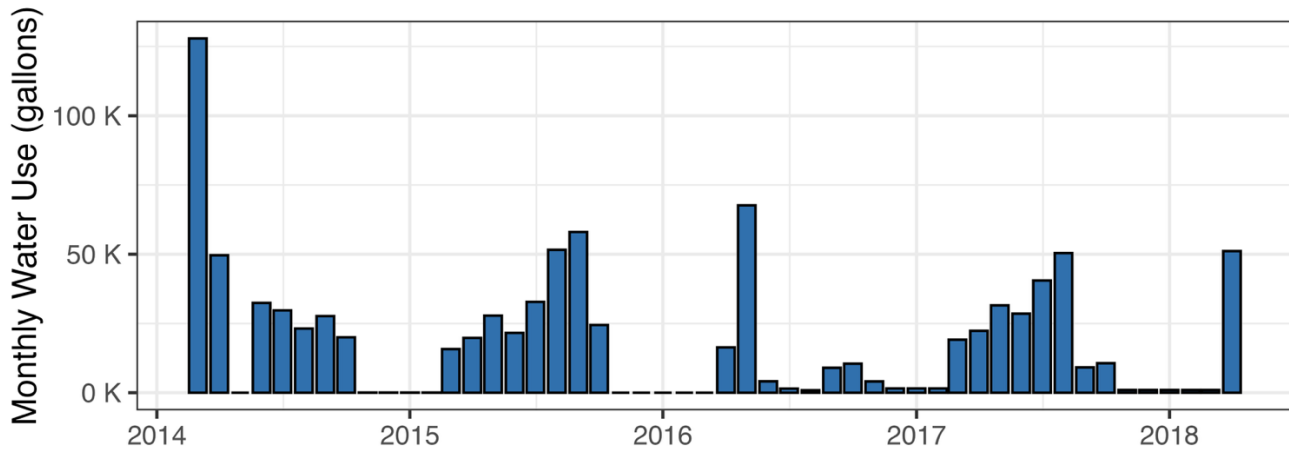


Figure 7: Recorded water use for Valles Caldera National Preserve

The anticipated growth and expansion of water service to visitors, coupled with increased year-round demands for staff, construction, and maintenance, suggests substantial rises in future water demand. These increased demands will require a “public” water supply classification, necessitating stricter treatment, testing protocols, and increased storage capacity. To estimate future water demand, we assumed a per-capita daily use of 5 gallons (0.67 CF) for visitors and 75 gallons (10 CF) for staff and applied these rates to previously described visitor projections. We assume a constant staff-to-visitor ratio of 1:10,000, approximately one quarter of current rates at the preserve, assuming maximum staffing of 50 for the projected 500,000 visitors (**Figure 8**).

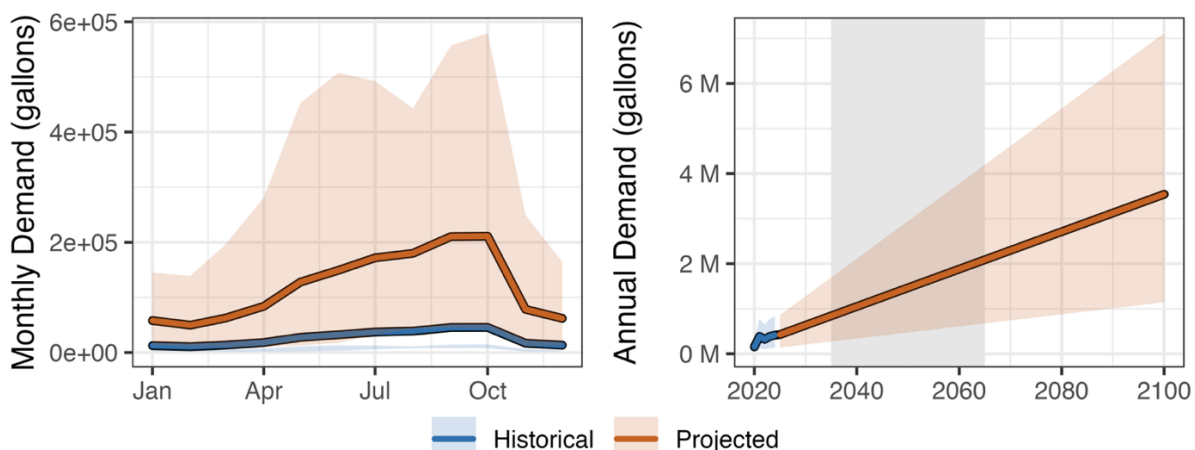


Figure 8: Projected water demand for Valles Caldera National Preserve. Shaded areas surrounding each curve indicate upper and lower uncertainty bounds and the gray area indicates the focus period for report projections.

Projected water demand for 2050 is 1.4 million gallons, with low and high estimates ranging from 0.47 to 2.9 million gallons. Although these calculations assumed that visitor and staff numbers were the primary drivers of future water demand, previous WSVAs have identified a complex relationship between visitation and water use in parks. For example, at Bryce Canyon National Park, monthly water use correlated with visitation, while annual water use showed no correlation with visitation (Cognac et al., 2025). Instead, irregular demands associated with

operations and infrastructure projects (e.g., leaks, construction, fire suppression, and maintenance) were presumed to be the primary driver of year-to-year variations in water use. To account for this non-visitation-related variability, we applied a per-capita uncertainty range of $\pm$ the Bryce Canyon coefficient of variation (CV) of per-capita water use (0.5) multiplied by the mean per-capita use (5 gallons) at Valles Caldera to estimate low and high ranges for future water demand (Figure 8). The CV represents the extent of variability in relation to the mean. In using this metric, we assume a similar relative variability to that found at Bryce Canyon, a national park with detailed water use data. The large uncertainty in projected water demands reflects compounding uncertainty related to both visitation and water use but is expected to provide realistic bounds for future demands. As more data and information becomes available, demand projections should be updated to reflect best estimates.

Vulnerability

In this WSPA, water supply vulnerability is the degree to which the water supply is susceptible to adverse impacts of a changing climate, defined as a function of both exposure and sensitivity (Figure 9). Exposure measures the magnitude or rate of climate-related stress a water supply may face, driven by changes in water availability. Sensitivity measures the degree to which the system will be affected by those stressors, governed by climate-water linkages in the physical system. For example, the water supply faces high exposure when climatic shifts significantly reduce water inputs to the system (i.e., recharge); conversely, the system demonstrates high sensitivity if the supply well cannot sustain park operations through dry periods (i.e., low recharge). In this section, we evaluate factors that define exposure and sensitivity of the proposed water supply to projected changes in climate and hydrology. We specifically focus on how alterations to the water budget could influence the amount, timing, and quality of recharge to the Valle Grande aquifer, and how these changes relate to storage, pumping, wildfire, and projected demands at the preserve.

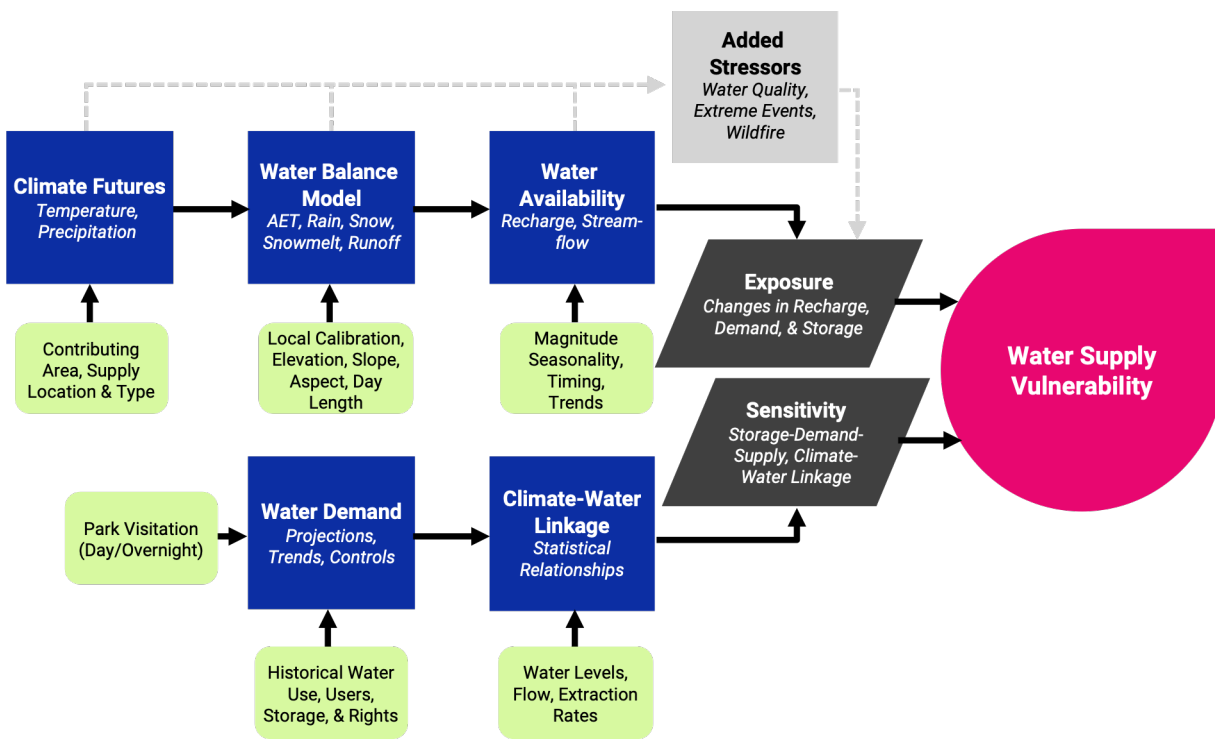


Figure 9: Overview of the water supply vulnerability assessment workflow.

We calculated projected changes using statistics for a historical baseline (1979-2012) and future (2035-2065) time period. These date ranges were selected to maintain statistical accuracy when comparing historical (GridMET) to projected (MACA) climate datasets. They also focus on a planning period relevant for future water development projects, centered around the year 2050. While the text and descriptions are limited to the end of the future period (2065), select figures extend to 2100 to visualize longer-term trends. The following sections include bolded statements highlighting the exposure and sensitivity ratings assigned to each vulnerability category.

Changes in Climate, Water Budgets, and Recharge

Climate-related changes to the water budget indicate the degree to which the hydrologic system—the source for Valles Caldera’s water supply—is exposed to impacts of hydroclimatic change. We compared historical and projected water budget components for the Valle Grande aquifer, focusing on key metrics that indicate exposure for the water system. The water budget was calculated for the watershed area upstream of the East Fork of the Jemez River gauge, which includes Valle Grande and surrounding upland recharge areas (**Figure 1**).

As previously described, temperatures at Valles Caldera are projected to become warmer, whereas precipitation projections vary from dryer (in the Hot Dry future) to wetter (in the Warm Wet future). These changes promote downstream changes to water budget components (**Figure 10**). In the Hot Dry future, rising air temperatures lead to long term increases in potential evapotranspiration (PET) and short-term increases in actual evapotranspiration (AET). However, as water becomes increasingly limited from decreases in precipitation, AET undergoes longer-term decreases. These changes are coupled with reduced snow accumulation and melt and minor increases in rainfall, amounting to a net decrease in runoff; a trend that is also apparent during the historical period. Because stream discharge and groundwater recharge are derived from runoff, these modeled components exhibit highly similar trends. Water balance projections from 37 of the 40 evaluated GCM scenarios also project decreases in runoff, discharge, and recharge (**Figure 5**).

Conversely, the Warm Wet future is projected to experience a lesser rise in temperature alongside an overall increase in precipitation. These changes drive higher rates of PET and AET and decreases in snowmelt, but still amount to an overall increase in runoff, discharge, and recharge. Notably, a mid-century spike in precipitation corresponds to anomalously high rain-, snowmelt-, and runoff-derived components that highly influence statistics for this scenario, but it also reflects a plausible future for Valles Caldera with increased likelihood of large runoff volumes.



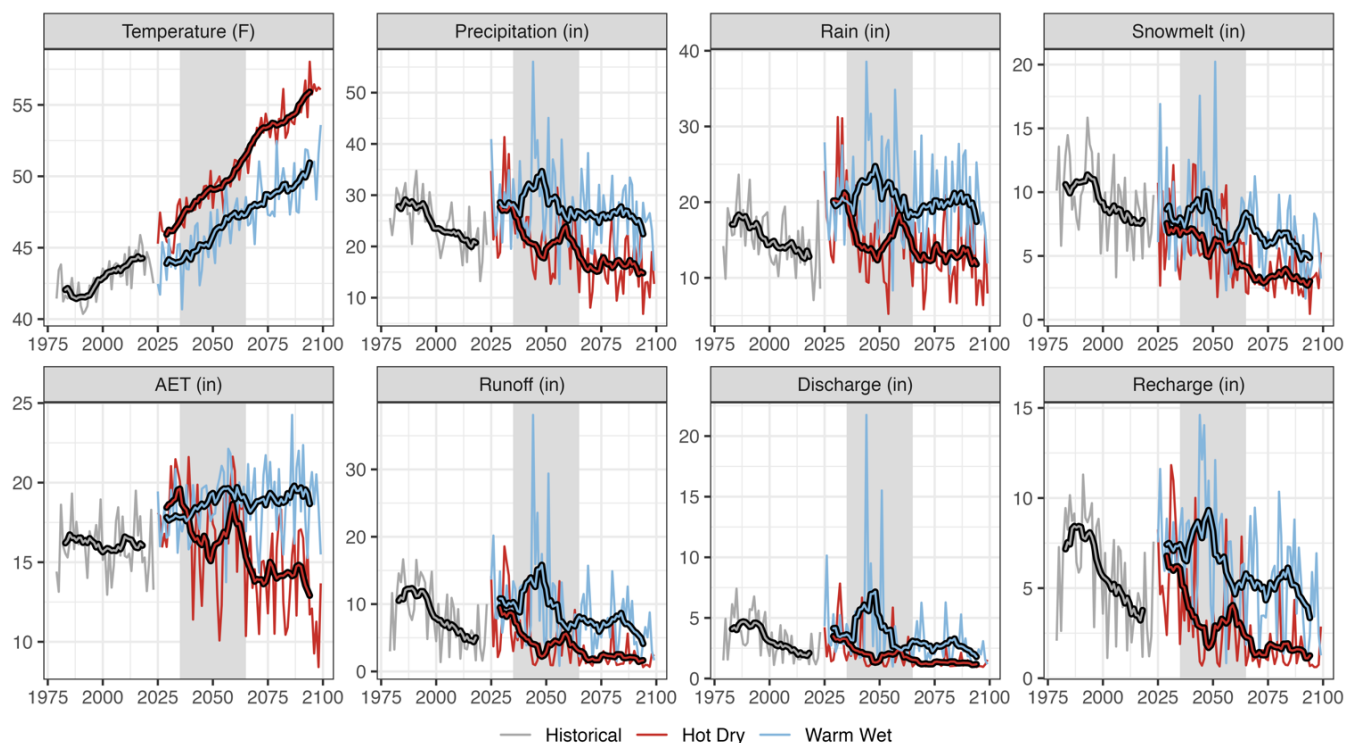


Figure 10: Historical and projected annual climate and modeled water budget components for the East Fork of the Jemez River watershed shown along with smooth 10-year moving average trend lines. The gray area indicates the focus period for report projections.

Runoff, Discharge, and Recharge

Runoff constitutes the primary water input to streams and aquifers of Valle Grande. Consequently, runoff changes are a key indicator of exposure for the proposed water supply. Using runoff-routing functions, we divide runoff into discharge (streamflow) and groundwater recharge, to better characterize impacts to each water source. The proposed groundwater supply will be most directly impacted by changes in recharge.

Projections of runoff, discharge, and groundwater recharge vary from year to year, but generally follow precipitation trends, decreasing in a Hot Dry future and increasing in a Warm Wet future (**Table 1**). Mean annual runoff changes range from -52% (decrease; Hot Dry) to 9% (increase; Warm Wet). Similarly, mean annual recharge change projections range from -50% (Hot Dry) to 8.9% (Warm Wet) and mean annual discharge change projections range from -45% (Hot Dry) to 18% (Warm Wet). The majority of climate and water balance models project future declines rather than increases (**Figure 5**). **A 50% decrease in recharge, as projected in the Hot Dry future, indicates a high level of exposure for the water supply with significant reductions in water available to replenish the aquifer, potentially leading to declining aquifer storage and groundwater levels. By contrast, the wetter projections of the Warm Wet future indicate a low level of exposure, as they suggest increased water input to the Valle Grande aquifer.**

The standard deviation (SD) of annual values provides an indicator of variability between years. Consider high- and low-SD sets of annual runoff values. The two sets have the same mean annual runoff, but the high-SD set includes several dry years interspersed with a couple of very wet years and the low-SD set includes consecutive years with approximately the same wetness. Despite having the same average runoff, the high-SD (i.e., high-

variability) scenario is more likely to lead to water stress from the occurrence of several dry years and offsets in the timing of water availability, storage capacity, and demand. SD values are projected to decrease under a Hot Dry future and increase under a Warm Wet future for all three components (**Table 1**), suggesting that year-to-year fluctuations may become more pronounced in a Warm Wet future and less pronounced in a Hot Dry future. Therefore, the increased variability associated with the Warm Wet future indicates the possibility of this water supply being impacted even in a generally wetter climate.

Table 1: Mean, median, and standard deviation (SD) of annual runoff for historical and future periods and percentage (%) change from the historical to future periods.

	Component	Historical	Hot Dry	Warm Wet	Hot Dry % Change	Warm Wet % Change
Mean (in)	Runoff	9.3	4.5	10.5	-52	13
	Recharge	6.5	3.3	7.1	-50	8.9
	Discharge	3.6	2.0	4.3	-45	18
Standard Deviation (in)	Runoff	4.4	3.3	8.1	-26	85
	Recharge	2.7	2.4	3.4	-13	25
	Discharge	1.7	1.3	4.4	-25	157

Projected decreases in recharge are consistent with regional studies. Meixner et al. (2016) projected a general decline in groundwater recharge across the western United States, with findings particularly relevant to Valles Caldera in their projections for the Wasatch Range of Utah. This region, characterized by similar high-elevation and valley terrains, was projected to experience overall declines in groundwater recharge. Reductions were attributed to: (1) diminished diffuse valley-floor recharge driven by increased evapotranspiration (ET) linked to rising temperatures and reduced spring precipitation; and (2) reduced mountain front and mountain block recharge driven by warmer temperatures, higher ET, reduced spring precipitation causing lower snowpack and snowmelt, and shallower snow levels. Meixner et al. (2016) emphasized that “subtleties in the response of the water budget to changes in precipitation and ET cannot be teased apart without numerical simulation of feedback between processes,” underscoring the complexities involved in accurately predicting highly dynamic recharge processes. Therefore, while our projections of groundwater recharge and stream discharge trends closely follow projections of runoff, the complexities of a given hydrologic system may result in recharge or discharge being disproportionately affected by changes in runoff.

Extreme Runoff Events

Extreme runoff events are characterized by increases in runoff frequency (how often extreme runoff events occur) and intensity (the amount of runoff during a given event). Extreme runoff events can expose the water supply system to risks associated with both water scarcity and excess water. Herein, we analyze extremes in annual runoff (wet and dry years) and individual runoff events (3-day sums) to assess these risks.

Projections for the Hot Dry future indicate notable increases in the frequency and persistence of dry years, defined as years with total runoff less than the historical 10th percentile. These low-runoff years are projected to occur three times more often than in the historical period (**Figure 11Error! Reference source not found.**). This increased frequency is compounded by a greater likelihood of consecutive dry years. While rare historically, successive dry years are projected to occur in 25% of years, with a maximum span of three years. Over the full



projection period through 2100, the maximum duration of consecutive dry years could extend to 12 years. Conversely, high-runoff years (total annual runoff greater than the historical 90th percentile) are not projected to occur in the Hot Dry future. In contrast, the Warm Wet future projects a decrease in low-runoff years, which are expected to occur approximately 0.25 times less often than in the historical period. High-runoff years are projected to be 1.3 times more frequent, with the wettest years reaching up to 2.3 times the historical annual runoff. This scenario is not projected to experience consecutive dry years. Although not shown here, stream discharge and groundwater recharge follow nearly identical trends.

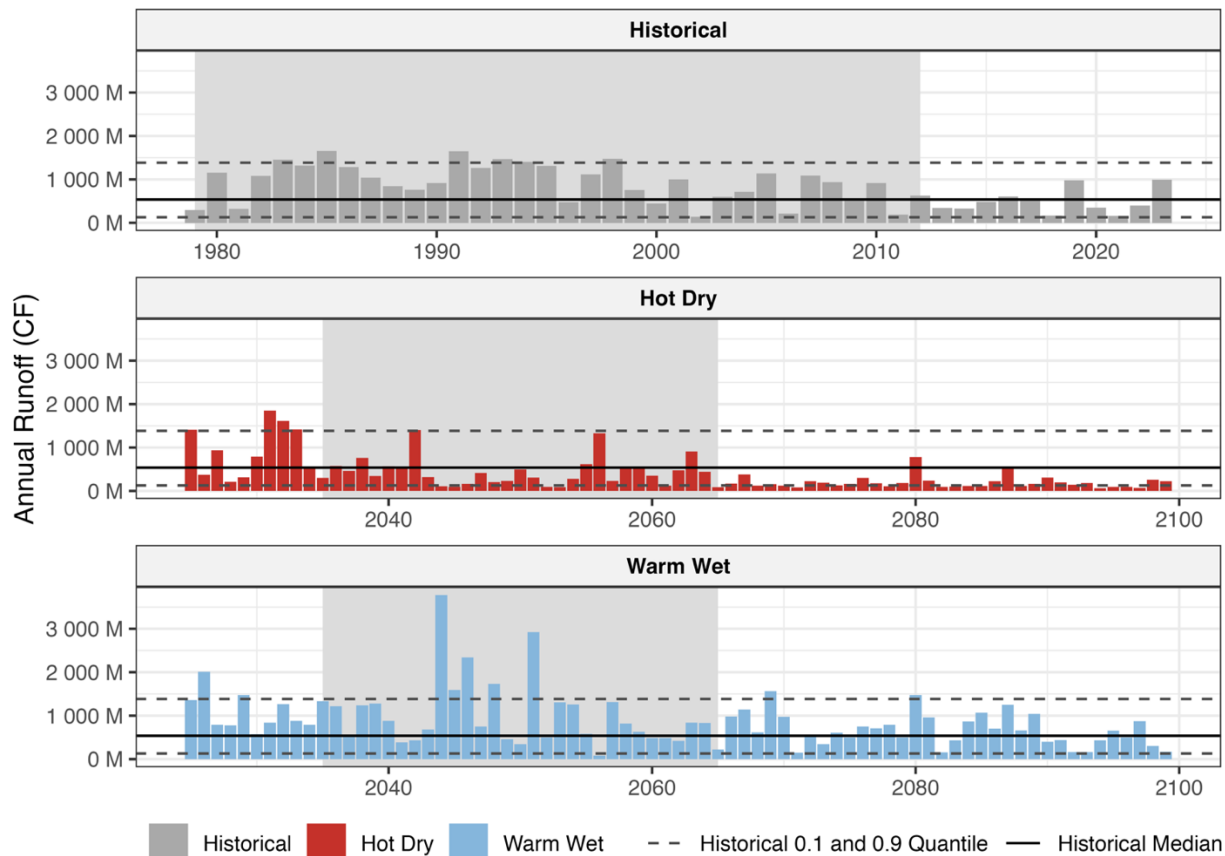


Figure 11: Annual runoff variations for the historical period and Hot Dry and Warm Wet climate futures. Gray area indicates the period used for historical and future statistics. The solid and dashed lines indicate the historical median and 10th and 90th percentiles, respectively.

Both climate futures project a moderate increase in large-magnitude precipitation events, defined as the three-day precipitation sum at or above the historical 99th percentile (**Figure 12**). The frequency of these events is projected to increase 1.4-fold (40%) in the Hot Dry future and twofold (100%) in the Warm Wet future. The intensity of these events is also projected to increase, with the maximum three-day precipitation sum being 10% greater in the Hot Dry future and up to 150% greater in the Warm Wet future compared to the historical period. In contrast, moderate to low changes are projected for large runoff events (three-day sum at or above the historical 99th percentile (**Figure 13**). These events are projected to increase 23% in the Warm Wet future and decrease by 71% in the Hot Dry future. This diminished runoff response compared to precipitation extremes is attributed to significant increases in evapotranspiration which temper the conversion of large precipitation

volumes into runoff. The impacts of low-magnitude extreme runoff events are separately considered using drought metrics that better represent the time-integrative nature of hydrological and groundwater droughts.

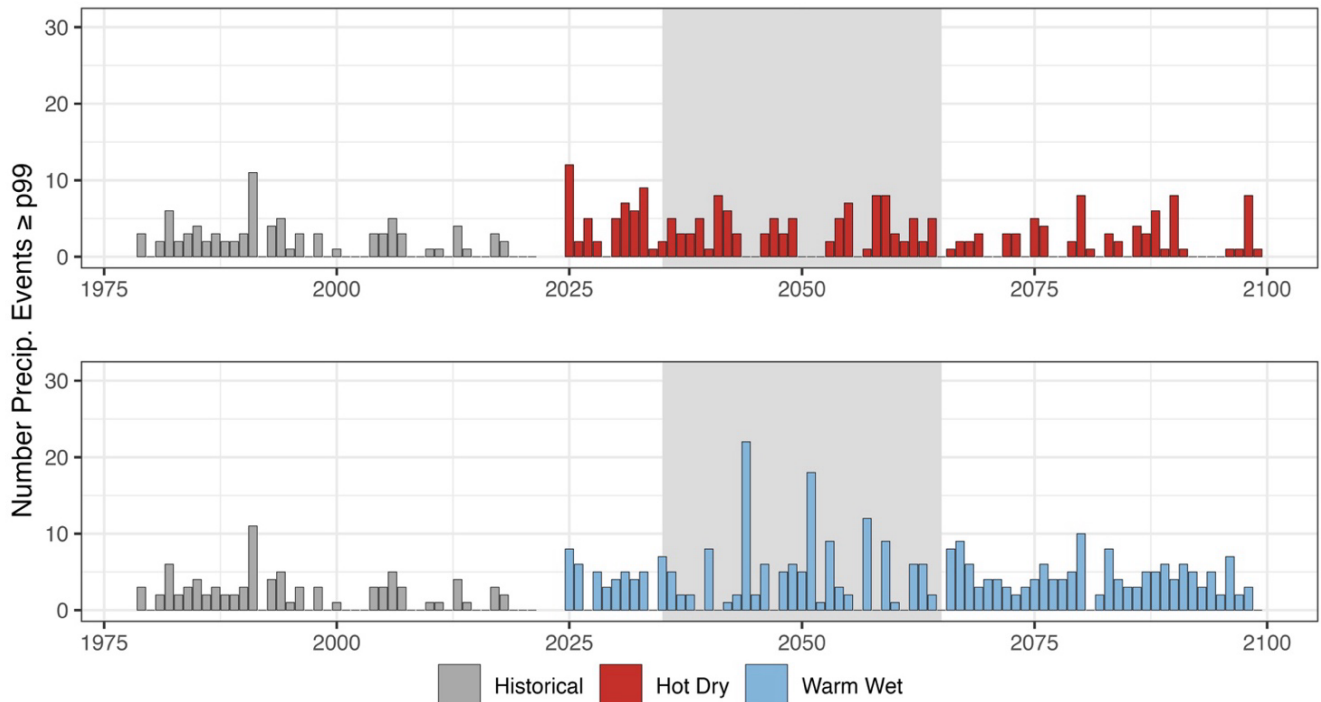


Figure 12: Number of extreme precipitation events ($\geq$ 99th percentile (p99) of historical 3-day moving sum of precipitation) for historical period and climate futures.

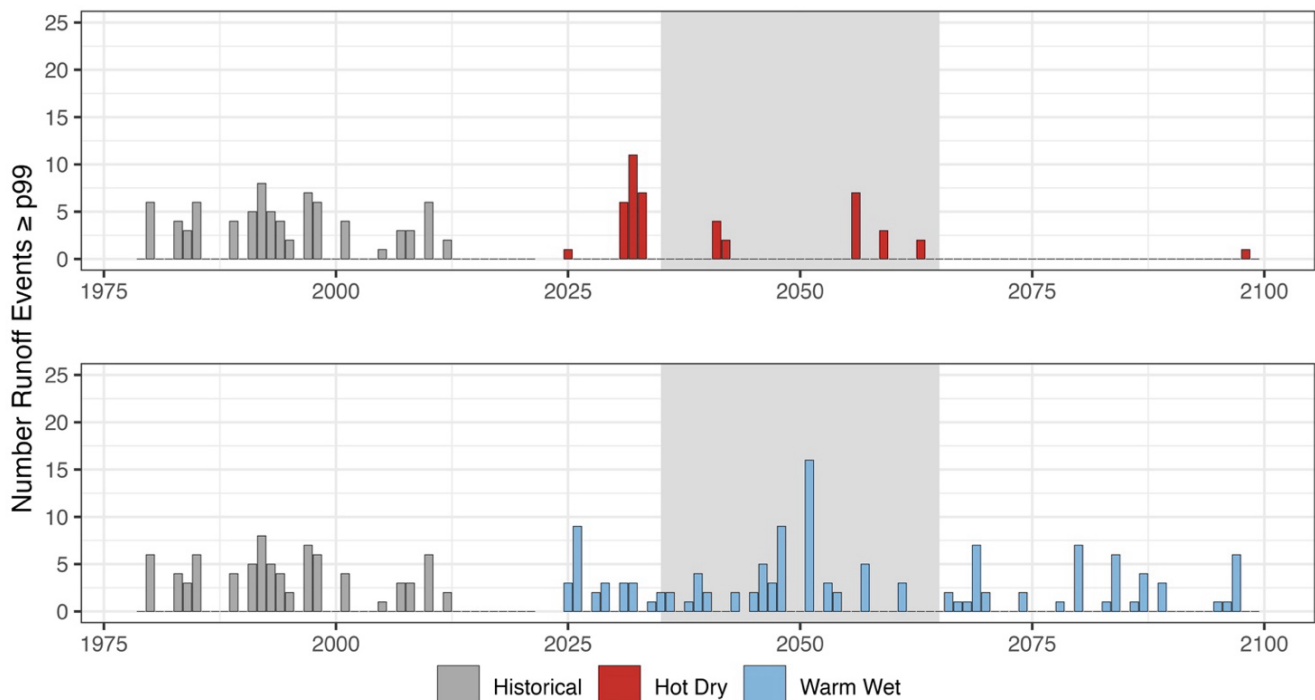


Figure 13: Number of extreme runoff events ($\geq$ 99th percentile (p99) of historical 3-day moving sum of runoff) for historical period and climate futures.

Overall, these changes indicate moderate exposure to extreme events for both climate futures. The Hot Dry projections indicate more frequent and consecutive dry years, posing a risk for water scarcity. Conversely, the Warm Wet projections indicate more wet years with larger individual runoff events that pose risks for flooding, contaminant loading, and infrastructure damage. Historically, the surface water diversion system has been sensitive to large runoff events.

Runoff Seasonality

Temporal shifts in the water budget can alter the timing of water availability, potentially leading to mismatches between availability and demand that expose the system to added stress (Figure 14). At Valles Caldera, runoff timing is particularly important for recharging the valley aquifer. The MBR conceptual model indicates that fluctuating mountain groundwater levels are critical for driving water into the adjacent alluvial valley (Figure 3). Past studies suggest that mountain block water tables are highest following the snowmelt (spring) and monsoon (late-summer) peaks (Lyon et al., 2008). Consequently, diminished spring and fall runoff could reduce these high water table periods, leading to less flow into the adjacent valley and disproportionately impacting groundwater recharge to the alluvial aquifer. Spring runoff is especially critical as it precedes the preserve's period of peak water demands, ensuring adequate aquifer storage when pumping needs are highest.

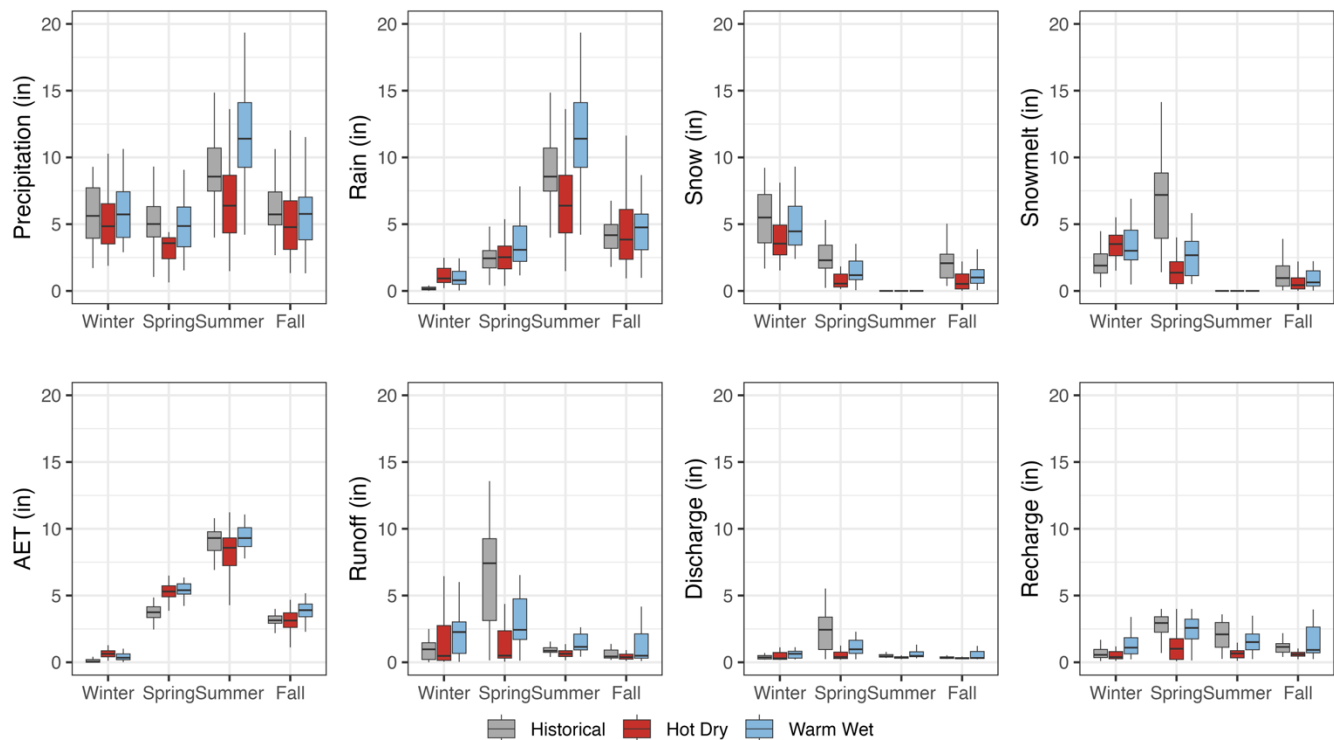


Figure 14: Seasonality of historical (1979-2012) and projected (2035-2065) precipitation, rain, snow, snowmelt, actual evapotranspiration (AET), runoff, discharge, and recharge for winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November).

Under both climate futures, spring runoff is projected to decline. Conversely, summer, fall, and winter runoff show minor decreases in the Hot Dry future but minor increases in the Warm Wet future. Discharge and recharge exhibit similar trends. Historically, 57% of runoff occurred during the spring. In the Hot Dry future, this is projected to decrease to 33% (a 42% reduction), and in the Warm Wet future, to 37% (a 35% reduction). These spring runoff declines are attributed to reduced snowmelt and temperature-driven increases in AET that

outweigh minor increases in rainfall. **These changes in runoff seasonality represent moderate exposure for both climate futures due to the strong concentration of changes during spring and the disproportionate impact this could have on aquifer recharge.**

Snow to rain

Rising temperatures will increasingly drive decreases in snow accumulation and melt ([Figure 10](#); [Figure 14](#)), processes that control stream discharge and groundwater recharge at Valles Caldera (see [Figure 3](#)). In high-elevation southwestern catchments, snowmelt has been found to contribute disproportionately large fractions of groundwater recharge relative to its share of annual precipitation (Earman et al., 2006). For instance, at a nearby monitoring site in Los Alamos, snowmelt-derived recharge was estimated to be 7% to 13% higher than the total snow fraction of average annual precipitation. This regional shift from snow to rain, coupled with earlier melt onset (Clow, 2010) is linked to declining annual stream discharge across the western U.S. (Hammond et al., 2018), and may be linked to declining rates of recharge.

Historically, snow has accounted for 39% of the total precipitation in the contributing area for Valle Grande, serving as the primary driver for seasonal recharge and discharge. However, both climate scenarios project significant shifts towards more rain and less snow, with rain increasingly sourcing recharge and discharge ([Figure 15](#)). By 2050, the snowmelt fraction of runoff is projected to decline to 27% in the Warm Wet future (29% reduction) and 28% in the Hot Dry future (26% reduction), a downward trend that continues through the end of the century. This sustained downward trend underscores a long-term transition toward a rain-dominated system.

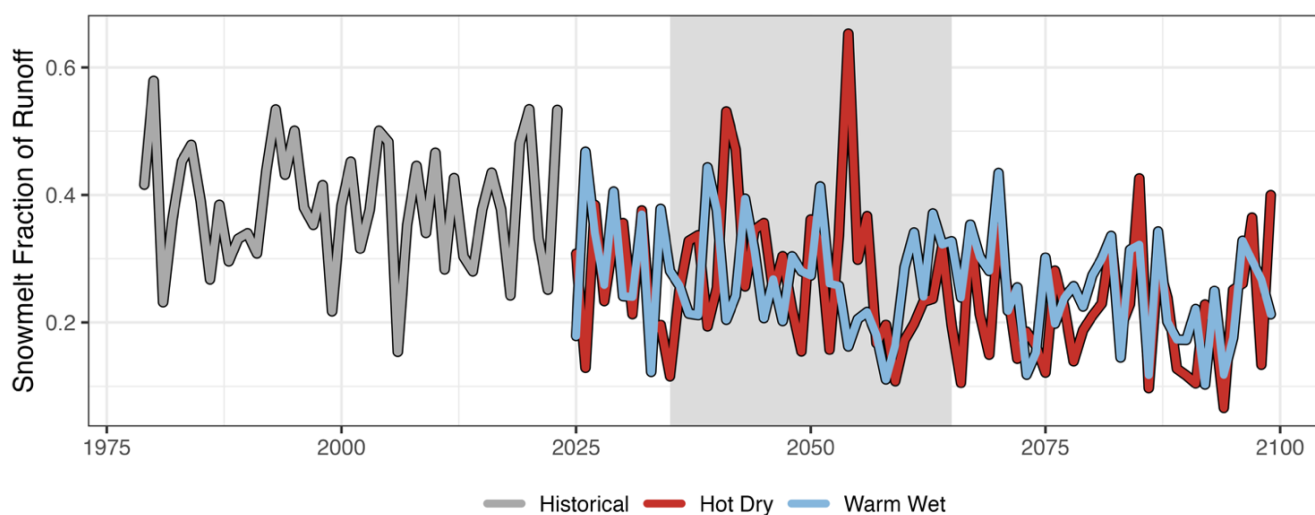


Figure 15: The snowmelt fraction of runoff plotted through time with gray area indicating period for which future statistics were summarized.

Infiltration rates of rain and snowmelt vary related to differences in event intensities and antecedent moisture conditions, with higher precipitation intensity and wetter soil tending to produce greater infiltration (Hammond et al., 2019). Although daily rain events typically have greater intensity than snowmelt, accumulated snow can melt in concentrated pulses that tend to occur when the soil is saturated and PET is low, often culminating in greater infiltration than rain events if the ground isn't frozen (Loik et al., 2004; Hammond et al., 2019). Although monsoonal rains can be high intensity with potential to generate high stream discharge (Hammond and Kampf,

2020), because they occur during the late-summer and fall when PET is higher and antecedent soil conditions tend to be drier, infiltration capacity may be reduced. Decreased snow cover can also reduce the insulating effects of snow, causing frozen ground that prevents infiltration during subsequent melt events, thus reducing recharge and increasing overland flow (Hyman-Rabeller and Loheide II, 2022).

The NPS WBM accounts for changes in PET and soil moisture with functions that coarsely approximate processes governing infiltration and runoff efficiency. However, various other factors influence these processes (e.g., vegetation, erosion, and sublimation) that are not included in the NPS WBM. For example, sublimation, where solid snow or ice changes directly into water vapor, can strongly affect the water budget, particularly in alpine catchments (Strasser et al., 2008). Sublimation reduces snow cover and in turn snowmelt available for runoff and recharge. Incorporating the full suite of factors that influence these processes would require far more complex physically based models that extrapolate future vegetation and soil conditions, often adding uncertainty to results. Previous studies that have implemented more complex models (e.g., Loik et al., 2004; Hammond et al., 2019) have identified complex responses to shifts in snowmelt related to soil properties, vegetation, and other factors. Unfortunately, soil and vegetation conditions in the cited studies differ from those in Valle Grande.

Additional monitoring will be required to fully characterize groundwater response to changes in snow cover and melt at Valles Caldera. **However, based on explanations above, we estimate that even if total annual precipitation were to stay the same, the projected decline in snowmelt is likely to result in lower infiltration and recharge. Given this expected impact on groundwater recharge, projected 25% to 30% reductions in snowmelt runoff for the Hot Dry and Warm Wet climate futures indicate moderate exposure to risks of decreased water supply.**

Aquifer Sensitivity

The absence of groundwater monitoring data presents a significant limitation in assessing the sensitivity of the Valle Grande aquifer to projected hydroclimatic changes. Substantial uncertainty exists regarding aquifer properties and groundwater behavior near the proposed well site, including depth, confining unit extent, hydraulic properties, and groundwater levels. For instance, seasonal groundwater level data could have been correlated with historical climate variables to indicate aquifer response to wet and dry years. Likewise, a lithology log would help to estimate aquifer properties and the extent of any confining units, which are crucial for predicting water level response to recharge and pumping. Ultimately, this lack of data fundamentally limits the certainty with which conclusions can be drawn about potential impacts to the aquifer.

Despite these limitations, we can still estimate the aquifer's sensitivity to hydroclimatic changes using the conceptual model and the following assumptions: a) the primary water source for the well is groundwater resulting from MBR, which is driven by a seasonally fluctuating mountain block water table, and may be particularly vulnerable to springtime recharge reductions, and b) the aquifer is thinner near the valley margin, resulting in lower transmissivity and therefore greater water level fluctuations in response to recharge changes. Reductions and seasonal shifts in recharge are likely to have immediate, negative impacts on groundwater levels and pumping capacity at the proposed well, indicating moderate sensitivity. This sensitivity assessment applies to the subsequent section on drought as well.



Drought

Projections for reduced snowpack, earlier snowmelt, and increased evaporative demand suggest a future characterized by greater aridity compared to historical conditions. Prolonged dry periods can lead to diminished stream discharge, decreased aquifer recharge, and long-term reductions in aquifer storage, exposing the proposed water system to significant stress. To monitor and quantify these changes, drought indices provide a standardized, objective measure of drought severity, spatial extent, and temporal evolution across regions and time periods. The Standardized Precipitation Evapotranspiration Index (SPEI) is a cumulative drought index that utilizes a normalized climatic water balance (precipitation minus potential evapotranspiration) and has demonstrated strong correlations with hydrological variables (Serrano et al., 2010), making it a robust metric for evaluating hydrologic drought. Negative SPEI values indicate drier than average conditions, whereas positive values indicate wetter than average conditions. Six-month SPEI values were computed using the SPEI R package (Beguería, 2023), assuming a log-logistic distribution with the entire historical period (1980-2023) serving as the reference period for normalization (Beguería, 2014) (**Figure 16**). Drought severity was classified based on negative thresholds wherein $\text{SPEI} < -1.0$ indicates moderate drought, $\text{SPEI} < -1.5$ indicates severe drought, and $\text{SPEI} < -2.0$ indicates extreme drought (Yildirim et al., 2022).

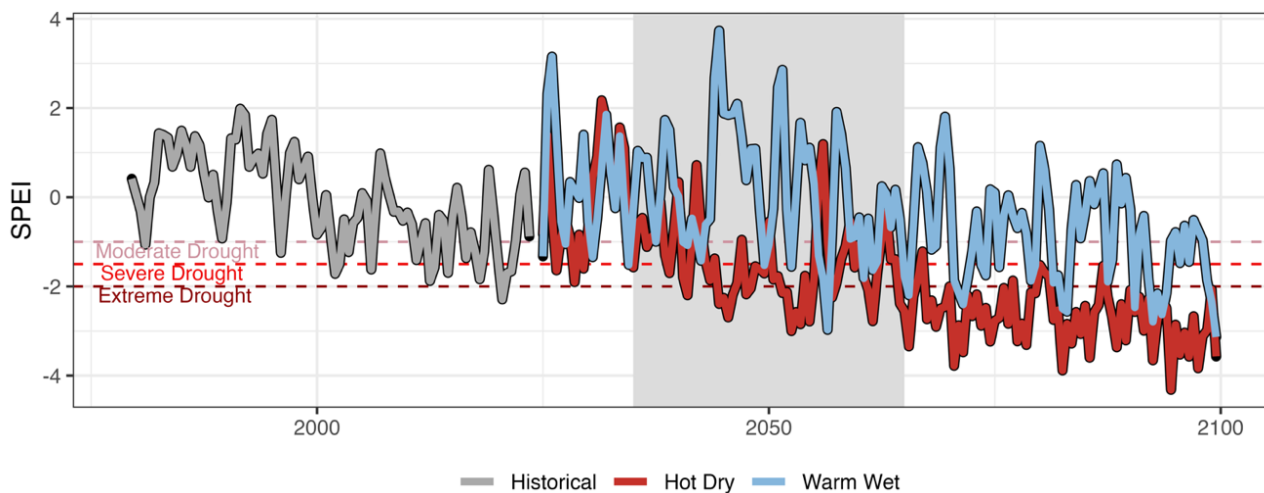


Figure 16: Six-month Standardized Precipitation Evapotranspiration Index (SPEI) for the East Fork of the Jemez River watershed. Gray area is the summary period for future statistics.

To quantitatively assess the severity and duration of climate-driven changes in dryness, we compared SPEI summary statistics for moderate, severe, and extreme drought across the historical baseline and future periods (**Table 2**). The overall mean and median SPEI values reveal a clear shift towards more negative values under the Hot Dry future, indicating a pronounced drying trend. Conversely, the Warm Wet future exhibits more positive values during the future summary period, suggesting generally increased wetness. Notably, **Figure 16** suggests that although the future summary period (2035-2065) appears wetter, the full projection period (2035-2100) demonstrates overall drying for both climate futures. The overall standard deviation of SPEI values projected for both Hot Dry and Warm Wet futures is greater than historical, suggesting greater variability and potentially more extreme wet and dry events (**Table 2**).

SPEI statistics for individual drought categories show increases in drought frequency in the Hot Dry future, with moderate, severe, and extreme droughts occurring 3, 4.5, and 19 times more often, respectively (see “% of Period”, **Table 2**). By contrast, drought frequency in the Warm Wet future is projected to remain similar to

historical conditions. Drought duration is projected to increase for all severity categories in both climate futures. Critically, Hot Dry projections suggest potential for extensive, multi-decadal droughts characterized by severity and durations considerably exceeding those observed during the historical period. **These findings under the Hot Dry future indicate significant exposure to intensified and prolonged drought that could lead to water scarcity. Conversely, the Warm Wet future demonstrates low exposure to drought stress, with generally similar drought frequency to historical conditions and only minor increases in event duration.** Notably, the lack of groundwater data (e.g., groundwater levels and flow from the confined aquifer to the overlying unconfined aquifer) limits the ability to link historical droughts to aquifer conditions, a critical component for assessing the sensitivity of the aquifer to drought. This limitation highlights the need for aquifer characterization and future monitoring of aquifer conditions to assess potential impacts. Furthermore, this data will be crucial for detecting and mitigating drought impacts into the future.

Table 2: SPEI drought summary metrics for the historical baseline and future periods.

Category	Statistic	Historical	Hot Dry	Warm Wet
Overall	Mean (SPEI)	-0.09	-1.12	0.20
	Median (SPEI)	-0.08	-1.39	0.029
	Standard Deviation	1.02	1.14	1.34
	n (# of 6-month periods)	89	80	80
Moderate	% of Period	20.2	58.8	20
	Mean (SPEI)	-1.47	-1.8	-1.66
	Mean (Duration)	0.82	4.5	0.98
	Median (Duration)	0.5	1	1
	Maximum (Duration)	2	36.5	2.5
Severe	% of Period	10.1	45	8.75
	Mean (SPEI)	-1.75	-1.97	-1.92
	Mean (Duration)	0.75	3.5	1
	Median (Duration)	0.5	1	0.75
	Maximum (Duration)	1.5	32.5	2.5
Extreme	% of Period	1.1	21	1.3
	Mean (SPEI)	-2.3	-2.6	-2.5
	Mean (Duration)	0.5	3.33	0.93
	Median (Duration)	0.5	2	1
	Maximum (Duration)	0.5	12.5	2

Water Demand

Demand-to-Supply Ratio

Future changes in climate may cause a decrease in water availability while increased visitation could lead to increases in water demand. The demand-to-supply ratio (D:S) quantifies the intensity of water use at the park relative to available supply and bridges the current state of the system and its future risk. A low D:S indicates a surplus of water after demands are met that can serve as a buffer for future climate-related stresses. A high D:S indicates less of a buffer and therefore greater water stress. For example, a greater D:S represents a system with a



higher likelihood of not meeting demands during drought. A $D:S < 0.2$ is considered to indicate a sustainable system, while 0.2-0.4 indicates medium to high stress and $D:S > 0.4$ indicates severe water limitation (Vorosmarty et al., 2000). We calculated $D:S$ as annual water demand divided by annual water supply:

$$D:S = \frac{\text{Demand}}{\text{Supply}}$$

$D:S$ values calculated using historical supply and demand provide a primary indicator of baseline sensitivity. High baseline $D:S$ values suggest that even a small exposure to a decrease in recharge could have a disproportionately large impact on the system, with less buffer capacity during droughts or periods of increased demands. Future projections of $D:S$ (calculated using projected supply and demand), measure exposure of the system to future stress. For example, projected increases in $D:S$ due to decreases in supply or increases in demand indicate added stress on the system and less buffer capacity during droughts or peak demand.

Historical water use at the preserve has been limited to staff and operations, whereas future water use will be expanded to visitors. To better compare the baseline and future $D:S$, we calculated $D:S$ for near-future (2025-2035) and future projected (2035-2065) periods, both accounting for expanded water service to visitors. For demand, we input values for average- and high-demand from 2050 using the annual mean and upper uncertainty limit of projected water demands (Figure 8). For supply, we input the 2050 annual mean and minimum groundwater recharge, representing average and low-recharge years. Together, high-demand and low-recharge years are referred to as “high-stress” scenarios.

Previously in this report, we calculated runoff and recharge for the entirety of Valle Grande, allowing for direct comparison to observed streamflow at the East Fork stream gauge. However, for this analysis, we also considered a constrained supply limited to the fraction of groundwater recharge occurring near the proposed well site specifically supplied to the confined aquifer as a better representation of available supply to the well. To calculate this, we employed a Darcy’s Law-based approach to partition simulated recharge between perched and confined aquifers. First, we calculated the fraction of MBR supplied to the confined aquifer versus the perched aquifer using Darcy’s law:

$$Q = K \cdot b \cdot w \cdot i$$

where Q is the flow rate (ft^3/day), K is hydraulic conductivity (ft/day), b is aquifer thickness (ft), w is the width of the contact between the mountain block and valley aquifer (ft), and i is the hydraulic gradient (-). Assuming aquifer thicknesses of 5 ft (perched) and 100 ft (confined), a hydraulic conductivity ratio of 10:1 (perched: confined), and equivalent hydraulic gradients and contact widths, we determined that 67% of MBR enters the confined aquifer. Then, using simple area calculations, we estimated that mountain block areas contributing recharge near the well site make up 13% of the East Fork of the Jemez River watershed (Figure 6). Combining these fractions (0.67×0.13), we estimate that 8.8% of total recharge is supplied as MBR near the well site. $D:S$ values were calculated as previously described except with total recharge multiplied by this fraction (0.088).

Resulting $D:S$ values, even for high-stress conditions with fractional recharge, are well below the 0.2 threshold, indicating a sustainable water supply under future climate scenarios (



Table 3). For D:S to surpass the threshold of 0.2, either a) the recharge fraction would need to be $\leq 4\%$, or b) projected demands would need to increase 12-fold. Although a recharge fraction $\leq 4\%$ may seem low, sensitivity analysis assuming a hydraulic conductivity ratio of 100:1 yielded a significantly lower recharge fraction of 2.2%, highlighting the substantial uncertainty inherent in these estimates. Applying a recharge fraction of 2.2%, the D:S threshold would be exceeded in the Hot Dry future in average and high-stress conditions, and in the Warm Wet future during high-stress conditions.

Importantly, D:S ratios increase substantially from the near- to future-period across all scenarios. Under average conditions, D:S increases by 181% in the Warm Wet scenario and 407% in the Hot Dry scenario. Under high-stress conditions, increases are even more dramatic: 1,823% for Warm Wet and 889% for Hot Dry. These projections demonstrate how decreased supply and increased demand can expose water supply to added stress. Given that there is still significant uncertainty about hydrologic conditions and viable extraction rates from the proposed well, the actual volume of annual supply remains unknown, and the exposure represented by these increasing D:S ratios is a concern.

Based on these estimates, the annual supply of water is likely to exceed demand under Hot Dry and Warm Wet futures, and therefore the sensitivity of the system to water supply shortages is low. However, it's critical to note that water availability will be defined by extraction rates from the proposed well, differing from the combined storage and recharge volumes presented here. Fine-grained sediments may limit the flow of water into wells, resulting in large drawdowns that limit viable pumping rates. Aquifer conditions at the proposed well site, including depth, remain unknown. If the aquifer is significantly shallower or hydrologically disconnected from the productive confined aquifer in the center of Valle Grande, the available water supply may differ. If the estimated available supply is in fact significantly lower than presented herein, the current D:S ratio could be much lower. Projected increases in D:S are significant, ranging from 180% to 1,800%, and indicating significant exposure. Lastly, long-term pumping may cause local storage depletions, limiting water availability at wells.

Table 3: Demand, supply, and demand-to-supply ratio (D:S) estimates for near-future (2025-2035) and future (2035-2065) time periods. All values are reported in millions of gallons.

	Years	Scenario	Demand	Supply (fractional)	Supply (total)	D:S _{Fract}	D:S _{Total}
Warm Wet	2025-2035	Average	0.61	490	5500	0.0011	< 0.001
		High-Stress	1.60	390	4400	0.0039	< 0.001
	2035-2065	Average	1.40	460	5300	0.0031	< 0.001
		High-Stress	4.10	55	620	0.0750	0.007
Hot Dry	2025-2035	Average	0.61	450	5100	0.0013	< 0.001
		High-Stress	1.60	160	1800	0.0096	< 0.001
	2035-2065	Average	1.40	210	2400	0.0068	< 0.001
		High-Stress	4.10	43	490	0.0950	0.0084

Notes: The average scenario was calculated using mean demand and mean supply for all years during each period. The high-stress scenario was calculated using maximum demand and minimum supply for all years during each period.



Storage-to-Demand Ratio

We used storage-to-demand ratio (S:D), the ratio between the proposed storage tank capacity (100,000 gallons; 13,400 CF) and park water demand, as a sensitivity indicator to measure the park's capacity to provide water during future short-term supply interruptions or spikes in demand. A low S:D indicates a limited storage capacity for providing a buffer during periods of drought, pumping shortages, or increased demand, indicating greater sensitivity of the system to changes in either supply or demand. Conversely, a high S:D represents ample storage and lower sensitivity. S:D was calculated as total storage capacity divided by demand over a defined time period:

$$S:D = \frac{\text{Storage}}{\text{Demand}}$$

We calculated S:D ratios for projected peak monthly and daily demands. Monthly peak demand was set as the mean and upper limit of uncertainty ("high") for projected October demand for each period (**Figure 8**). Daily peak demand was calculated by dividing monthly peaks by the number of days in the month and then multiplying by a factor of two, assuming that daily use is not uniformly distributed. This resulted in average maximum daily use values of 7,300 gallons (2025-2035) and 20,000 gallons (2035-2065). Daily peak values represent 100% and 250% increases over the 2015 estimate by Connors (2015) of 3,675 gallons, which is reasonable given that revised estimates include visitors in addition to staff.

Monthly S:D for the future period (2035-2065) ranges from 0.17 to 0.34, indicating that the proposed tank will hold approximately 5 to 10 days' worth of the water demand during peak monthly usage (

Table 4). Similarly, daily S:D for the future period ranges from 2.7 to 5, indicating that 2.7 to 5 days' worth of water at peak demands would be stored in a full tank. Notably, these calculations don't account for water stored for fire suppression (typically, fire suppression requires a minimum volume of water to always be stored in tanks). With wildfires expected to become increasingly prevalent, as discussed in later sections of this report, related storage requirements may increase in the future. If half of the proposed tank storage were dedicated to fire suppression, S:D ratios would effectively be halved, resulting in 2.5 to 5 days' worth of storage during peak monthly demands and 1.3 to 2.5 days' worth of peak daily demands. Daily and monthly S:D ratios for the nearer term (2025-2035) are greater due to lesser demand. **Projected S:D values indicate moderate sensitivity of the system to future changes in supply and demand, with potential for disruptions or inadequate water availability during fire suppression efforts.**

Table 4: Summary table of water use, storage tank size, and storage-to-demand (S:D) ratio with volumes reported as thousands of gallons (kGal).

	Use period	Demand (kGal)	Storage (kGal)	S:D (-)	Days of supply
2025-2035	Monthly	110	100	0.91	28
	Monthly High	210		0.47	15
	Daily	7.3		14	14
	Daily High	14		7.3	7.3
2035-2065	Monthly	300		0.34	10
	Monthly Max	580		0.17	5.4
	Daily	20		5.0	5.0
	Daily High	37		2.7	2.7



To assess potential vulnerabilities, we also evaluated interactions between water demand, storage capacity, and pumping rates. Utilizing projected demand scenarios, the proposed storage tank volume, and a range of potential pumping rates for the proposed supply well, we compared the maximum daily pumping volume against peak daily demand and storage capacity (

Table 5). At a constant pumping rate of 5 gallons per minute (gpm) and a daily water demand of 20,000 gallons, the tank would be depleted within 8 days, assuming an initially full tank. Conversely, a constant pumping rate of 25 gpm would result in a net gain of 1,600 gallons per day.

Table 5: Projected annual, monthly, and daily water demands compared to maximum pump volumes for hypothetical pumping rates. Volumes are reported in thousands of gallons (kGal).

	Demand (kGal)		Storage (kGal)	Pumped volume at given pump rate in GPM				
	<i>Average</i>	<i>High</i>		<i>5 gpm</i>	<i>10 gpm</i>	<i>25 gpm</i>	<i>50 gpm</i>	<i>100 gpm</i>
Annual	1,400	4,100	100	2,600	5,300	13,000	26,000	53,000
Monthly	300	580		220	430	1,100	2,200	4,300
Daily	20	37		7.2	14	36	72	140

Projected increases in high-flow events (under the Warm Wet future) and wildfire frequency (discussed in subsequent sections) elevate the risk of future well outages. We considered a well outage scenario using data presented in

Table 4 and

Table 5. The storage tank provides approximately 2.5 to 5 days’ worth of water during peak-daily demands depending on whether fire suppression storage is left in the tank. A well outage lasting 2 to 5 days would therefore either drain the tank or place the tank at critically low levels during peak demands. To reduce this vulnerability in the future when daily demands are large compared to tank storage, the preserve should explore options to add a second supply well or to increase on-site storage.

Determining the ideal storage capacity for the water supply system often requires balancing conflicting operational and water quality interests. We recommend consulting with water resource engineers and hydrologists who can perform a detailed analysis based on specific site conditions and water demands. Herein, we focus on climate-change related vulnerability of the water system related to its storage capacity as a single component of this engineering analysis.

Wildfire

Wildfires are a natural and necessary part of many western landscapes. At Valles Caldera, fire plays a dominant role in shaping the landscape, influenced by the dry climate, frequent lightning strikes, abundant flammable fuels, and complex topography (NPS, 2024c). At least 77% of the East Fork of the Jemez River watershed has been burned since 1970 (**Appendix A Figure A5**), particularly the volcanic uplands where the recharge water for the Valle Grande aquifer originates (**Figure 17**). **The wildfire hazard potential (WHP), an index of potential high-intensity wildfire (Dillon et al., 2023), ranges from “very low” to “very high” across the East Fork of the Jemez River watershed, with higher values concentrated in upland forested and shrubland areas**



and lower values in herbaceous and wetland lowlands. The sensitivity of the water supply system to wildfire impacts is therefore high.

Across the western US, changing weather and drought have been key drivers in increasing the risk and extent of wildfires. Increases in fire weather (Zuang et al., 2021) have enhanced the drying of organic matter, doubling the number of large fires between 1984 and 2015 (Abatzoglou and Williams, 2016). Wildfire impacts are intensifying as a result of larger, more severe, and more frequent fires (Wasserman and Mueller, 2023).

Projected increases in temperature and evapotranspiration are expected to reduce soil moisture and water availability for plants, adding more fuel in the future for wildfires. Gao et al. (2021) assessed current and future wildfire probabilities across the contiguous United States, focusing on regions with similar fire regimes (pyromes) and using the same set of climate models referenced throughout this report. **The Southern Rockies pyrome, which encompasses Valle Grande and the East Fork of the Jemez River watershed, is projected to experience increases in wildfire probability under both the Warm Wet and Hot Dry futures of 24.4% and 6.97% respectively, indicating moderate exposure to wildfire impacts from climate change.** The lesser increase for the Hot Dry future may seem counterintuitive but is common in the southwest as fuels become increasingly limited from dry conditions (Gao et al., 2021). Across all GCMs, increases in wildfire probability for the Southern Rockies pyrome range from 1.1% to 41%, with warmer and wetter scenarios tending to have greater increases. Furthermore, in northern New Mexico, cool-season moisture, monsoons, and wet conditions in previous years have been found to exert a strong influence on wildfire occurrence (Margolis et al., 2017). As patterns of wetness and dryness shift, so too may patterns of wildfire occurrence. This increased wildfire potential exposes the water supply to direct threats of contamination from ash and sediment runoff, altered watershed hydrology, and infrastructure damage.

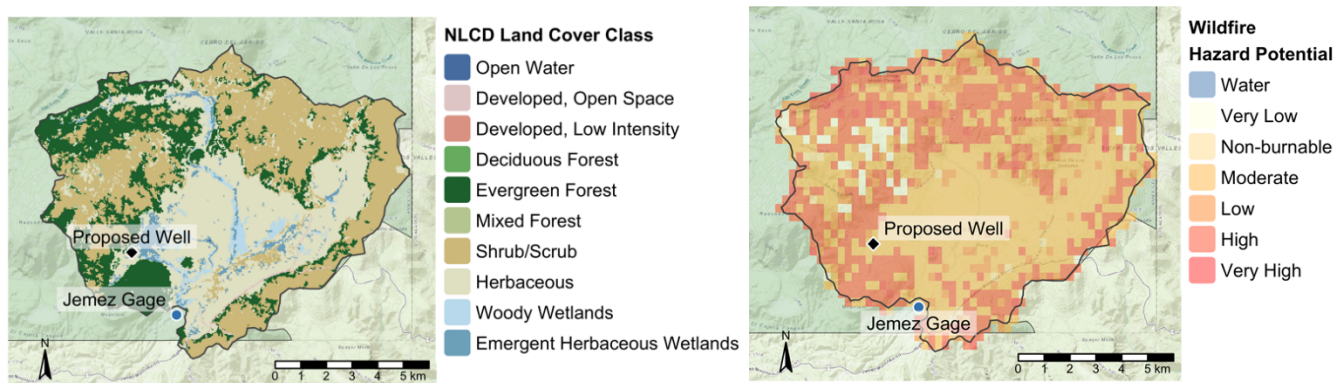


Figure 17: National Landcover Dataset (NLCD, 2021) land cover (left) and wildfire hazard potential classes determined by Dillon (2023) (right) for the East Fork of the Jemez River watershed.

The proposed change to a groundwater supply system at Valles Caldera, as opposed to the historical surface water system, greatly reduces the overall sensitivity of the water supply to wildfires. Surface water can experience high sediment loads and water quality issues following wildfire, while groundwater tends to be more resilient due to natural filtration processes that occur during recharge. As noted previously, a post-fire flood event severely damaged the La Jara infiltration gallery located in a forested area uphill from the proposed well. The proposed location for the supply well is in grasslands, characterized by lower wildfire hazard potential than forested uplands, and in turn, a lower risk of infrastructure damage and well outages (Figure 17).



Figure 18: Southwest-facing aerial image showing wildfire-burned upland areas surrounding the proposed well site in Valle Grande (image by Greg Kendall/ladailypost.com).

Overall, the proposed water supply is likely to experience impacts from future wildfires. Areas most likely to experience wildfire are concentrated in forested uplands surrounding Valle Grande where infiltration (recharge) occurs (**Figure 17 & Figure 18**). Research has shown that burned locations can experience increased surface runoff, reduced infiltration and recharge, reduced interception by plants, changes in ET, and changes in soil hydraulic conductivity (Guzman-Rojó et al., 2024). These complex interactions can lead to either increased or decreased rates of recharge, depending on factors like fire intensity, vegetation recovery, and local hydrological conditions. Some studies report drops in groundwater levels following wildfire (Ice, Neary, & Adams, 2004), while others have found the reduction in vegetation may lead to increases in soil infiltration (Boisramé et al., 2019). Notably, water balance changes due to fire can be short- or long-term, depending on the intensity and extent of fire impacts (Guzman-Rojó et al., 2024). Continued monitoring of groundwater and surface water levels will be critical for determining future impacts to the water supply from wildfires. The impacts of fire on rates of recharge are challenging to predict but given the large volume of recharge compared to future demands, wildfires are unlikely to present significant challenges related to supply volumes.

Water Quality

Although groundwater offers increased resilience compared to surface water, climate change-driven water quality impacts remain a threat to Valles Caldera's proposed water supply. Due to limited water quality data directly linking historical climate to shallow groundwater in Valles Caldera, we summarized available surface water and groundwater data along with climate-related mechanisms that could affect groundwater quality.

Available water quality data: Previous sampling for routine Environmental Health and Safety reporting found no evidence of nitrate or bacterial contamination at the interim supply well (Connors, 2015). However, historical surface water impairment has been documented in Valle Grande, primarily due to road runoff, rangeland grazing,

and wildlife (JWG, 2005). These impairments could worsen as increased visitation leads to greater road traffic, which is especially relevant because the new road alignment will likely be near the proposed well. Although restoration efforts have successfully reduced elevated stream temperature, turbidity, and aluminum levels, water quality data from the New Mexico Environment Department's Surface Water Quality Bureau indicates that *Escherichia coli* (*E. coli*) is still commonly detected in both La Jara Creek and the East Fork of the Jemez River. A related report described water in the upper reaches of the Jemez River and its tributaries to be of good quality, with the greatest exceedance of quality standards in aluminum, which was believed to originate from weathering of the highly aluminiferous Valles Caldera volcanic geology. Aluminum concentrations tended to be higher during times of high flow. Other parameters found above state water quality standards included arsenic and boron associated with certain hot springs, which occur outside of Valle Grande.

Increased wildfire risks: Both the Warm Wet and Hot Dry futures project increased wildfire risk, which can substantially impact water quality. Research demonstrates that post-wildfire runoff and erosion events can elevate concentrations of contaminants such as nitrates, arsenic, and dissolved organic compounds in drinking water systems. Furthermore, dissolved organic matter can generate toxic disinfection byproducts during chlorination (Hohner et al, 2020, Chen et al., 2020, Pennino et al., 2022). Wildfire can directly impact groundwater chemistry, with preferential and diffuse flows delivering ash, fire retardants, nutrients, metals, and other chemicals of concern to groundwater following fire (Walvoord et al., 2025). Given that the Valle Grande aquifer is recharged in upland areas especially prone to fire (Wallace et al., 2021), wildfire-related water quality impacts are a distinct possibility, though more information about groundwater flow conditions and chemistry are necessary to determine specific impacts to the proposed well.

Changes in recharge: Depending on the climate future, runoff and groundwater recharge are projected to either increase or decrease. These changes imply potential for less recharge and/or more sporadic recharge characterized by large pulses followed by dry periods with minimal recharge. Recent research indicates that hydroclimatic extremes, such as extended droughts or prolonged heavy precipitation, can degrade groundwater quality (Schroeter et al., 2025). For example, flooding may promote rapid transport between surface ecosystems and subsurface waters, bypassing critical filtration processes, and thus threatening groundwater quality (Schroeter et al., 2025). Again, infiltration occurs in headwater areas that have minimal anthropogenic influence and existing surface water contamination, but these areas are expected to see increased contaminant loading due to fires and fire suppression efforts.

Changes in water temperature: Across all climate futures, air temperature at the park is expected to rise, and recharge is projected to be increasingly sourced from rain. These changes will likely lead to warmer groundwater temperatures (Benz et al., 2024). Increases in water temperature can alter microorganism activity, biogeochemical processes, and mineral weathering (Dao et al., 2024), which in turn, could impact water quality.

These factors highlight potential risks to water quality, though more information is needed to characterize climate impacts to water quality. A baseline analysis of groundwater chemistry at the proposed well site is essential for determining any existing issues and potential changes. Regular water quality monitoring can be used to establish links between climate and water quality and to identify concerning trends and treatment modifications in a timely manner. Further, improved characterization of recharge mechanisms and aquifer properties are essential to determining contaminant pathways into the aquifer.



Despite this uncertainty, **based on the recharge conceptual model and potential water quality impacts described in this section, the sensitivity of the groundwater source to water quality impacts from climate change is generally low while the exposure to increased contaminant loading from fires, fire suppression, extreme events, and temperature changes are moderate.**

Water Rights

New Mexico operates under a system of prior appropriation, with groundwater and surface water rights administered by the Office of the State Engineer (OSE) (<https://www.ose.nm.gov/WR/WRindex.php>). Prior to use, the proposed supply well will require a valid water right (or multiple consolidated water rights) to meet annual water demands at the preserve. Demand projections range from 4.5 (average) to 9 (maximum) acre-feet (AF) in 2050 to upwards of 12 AF in 2065. A review of the New Mexico OSE points of diversion database (https://gis.ose.state.nm.us/gisapps/ose_pod_locations/) and Jemez River adjudication files identified many water rights with points of diversion located throughout the preserve. One of these points of diversion conditionally allows the preserve to divert up to 3 AF per year from the proposed well. Several additional diversion points are in Valle Grande and might become eligible for use at the proposed well via water right change applications, however they are not eligible at this time. A comprehensive assessment of existing water rights and the feasibility of filing change applications to support anticipated water demands should be conducted to determine the legal vulnerability of the proposed Valles Caldera water supply.

The majority of Valles Caldera, and all of Valle Grande and contributing areas, are within the fully appropriated Middle Rio Grande Basin. The Middle Rio Grande is the most densely populated region in New Mexico and contains more than half of New Mexico's population, most of whom live in the cities and towns of Albuquerque, Santa Fe, Rio Rancho, Belen, and Socorro. Valles Caldera is in the headwaters area, upstream of all major population areas. As climate change intensifies and temperatures continue to rise, increasing aridification is projected to drive a 25% to 30% decrease in surface water availability for New Mexico by 2050, prompting increased reliance on groundwater across the state. This increased stress on water resources will drive competition for senior water rights and may drive calls for curtailment on junior rights. Particularly in a Hot Dry future, decreased water availability could lead to priority calls within the Middle Rio Grande basin. Therefore, even though water may physically be available within the Valle Grande aquifer, a priority call could temporarily curtail the preserve's water use if a water shortage prevents senior water rights from being satisfied. An assessment of the priority status of water rights should be completed to determine the risk for curtailment.

In summary, the current allowable diversions (3 AF) are less than future estimated demands (upwards of 4.5 AF), indicating that future changes to water rights will be necessary to secure adequate water. Given the prerequisite nature of water rights, the future need to modify water rights, and that the fully appropriated basin is projected to experience additional strain on water availability, the preserve is considered to have both high sensitivity and high exposure to stresses from water rights constraints. This water rights summary is not intended to provide a comprehensive review of water rights but rather highlights the need for further legal assessment to ensure adequate rights to water for Valles Caldera. An assessment of Valles Caldera water rights is being conducted by the NPS's Water Resources Division and the Department of the Interior's Office of the Solicitor. Results of this assessment and recommendations for water rights management will be provided to the preserve in a forthcoming report. **More information is needed to determine the exact water rights requirements that will determine water rights-related exposure and sensitivity.**



Conclusions

We assessed multiple water supply vulnerability factors for two contrasting climate futures, "Warm Wet" and "Hot Dry", to evaluate the climate-related vulnerability for the proposed water supply at Valles Caldera National Preserve. Vulnerability is determined by exposure, defined as the degree to which the water system will be subjected climate-related stresses, and sensitivity, defined as the degree to which the water system is affected by those stresses. Indicators across six major categories (i.e., water budget, drought, water demand, wildfire, water quality, and water rights) were rated as either "Low," "Moderate," "High," or "More info needed" based on quantitative projections from water balance modeling, wildfire probability assessments, demand projections, and comprehensive literature review.

Results indicate the Hot Dry future presents higher overall vulnerability due to severe reductions in groundwater recharge (up to 50%), intensified drought conditions (severe droughts occurring 4.5 times more frequently), and reduced springtime water availability coinciding with peak demand periods. Conversely, the Warm Wet future shows less vulnerability to hydrologic stresses but maintains moderate exposure to extreme precipitation and runoff events and significant snowmelt declines. Regardless of the climate future, Valle Grande will be faced with high exposure to demand increases (over 550% visitation growth) and institutional vulnerabilities related to insufficient water rights. Here we provide a detailed summary of the key factors contributing to Valles Caldera's water supply vulnerability.

Water Budget Vulnerability: Projections for runoff, stream discharge, and groundwater recharge show diverging trends between climate futures. The Hot Dry future projects runoff and recharge reductions of up to 50% (high exposure) while the Warm Wet future projects an increase of 13% (low exposure). Both futures project greater frequency and intensity of extreme precipitation events, but in the Hot Dry scenario, evapotranspiration largely offsets these events, leading to a 71% decrease in extreme runoff events (low exposure). In contrast, the Warm Wet future projects a 23% increase in extreme runoff events (moderate exposure). Both futures project substantial declines in spring runoff, from 35% to 42% (moderate exposure), that could disproportionately impact aquifer recharge that largely occurs during spring snowmelt. Spring reductions are compounded by shifts from snow to rain that impact natural water storage and release cycles. The absence of groundwater monitoring data presents a key limitation for assessing the sensitivity and impact of projected shifts on the Valle Grande aquifer. Significant uncertainty exists regarding groundwater behavior (e.g., whether water level fluctuations occur following snowmelt), confining unit extent, aquifer depth, and hydraulic properties, especially at the proposed well site along the western margin of Valle Grande. This uncertainty limits the ability to draw conclusions about aquifer impacts from changes in climate. A qualitative assessment based on the system conceptual model leads to the assumption that a 50% reduction in recharge could have immediate, negative impacts on groundwater levels and pumping capacity at the proposed well site, leading to a ranking of moderate sensitivity.

Drought Vulnerability: Drought was assessed using the Standardized Precipitation-Evapotranspiration Index (SPEI), a normalized drought index that is well suited to hydrologic droughts. The Hot Dry future is projected to have more frequent, severe, and prolonged droughts, indicating high exposure. Conversely, the Warm Wet future projects increased wetness and less severe drought. Again, due to the limited availability of groundwater data, the aquifer's response to drought is not well understood. Given potential drawdown risks and seasonal recharge dependencies, the system likely exhibits moderate sensitivity to drought conditions.



Demand, Supply, & Storage Vulnerability: Water demand at Valles Caldera is projected to increase substantially by 2050 and beyond due to infrastructure development and rising visitation. Demand-to-supply ratios (D:S) were calculated as indicators of future stress due to mismatches between supply and demand. Despite projected decreases in recharge, D:S range from 0.001 to 0.09, indicating supply (recharge) exceeds projected demands under both climate futures. Notably, recharge does not solely determine sustainable pumping rates at the supply well and additional hydrogeologic testing is needed to constrain plausible extraction rates. Importantly, peak water demands at Valles Caldera are expected to occur following spring recharge reductions, meaning lower groundwater levels and limited pumping rates may coincide with times of highest demand.

Storage-to-demand ratios (S:D) were calculated as indicators of future stress due to mismatches between storage and demand. Calculated S:D values suggest a storage capacity of approximately 2.7 to 5 days' worth of water demand during projected peak daily use, and less when wildfire water storage requirements are factored in. Notably, structural and wildfire water storage requirements will need to be determined and factored into S:D projections. Well outages could lead to critically low tank levels and issues with meeting water demands. Our findings emphasize the need for continued monitoring of water use.

Wildfire Vulnerability: Valle Grande and the surrounding area are projected to experience a rise in wildfire probability under both the Warm Wet (24% increase) and Hot Dry (7% increase) futures (moderate exposure). Wildfire can alter soil and water dynamics and may reduce rates of infiltration and recharge, potentially leading to water quantity and quality impacts, though impacts to infiltration rates are challenging to predict. Wildfire hazard potential is rated as "high" or "very high" for 51% of the contributing watershed area (high sensitivity). While the proposed groundwater system is less susceptible to wildfire impacts compared to the current surface water system owing to natural filtration during infiltration, the recharge areas in forested uplands remain highly vulnerable to fire impacts that can alter infiltration rates and introduce contaminants.

Water Quality Vulnerability: Climate change presents several pathways for water quality degradation, including heightened wildfire risk, extreme hydroclimatic events, and rising temperatures. Post-wildfire runoff can introduce harmful contaminants like arsenic and dissolved organic compounds, which can lead to the formation of toxic disinfection byproducts. Increased drought and heavy precipitation events can reduce natural filtration processes, while warmer groundwater temperatures can alter biogeochemical reactions. Exposure to increased contaminant loading from fires, fire suppression, extreme events, roadside runoff and other potential contaminant sources, and temperature changes is therefore moderate. Conversely, the new groundwater supply is expected to be significantly less sensitive to these impacts than the current surface water system. Sensitivity to water quality impacts is therefore low.

Water Rights Vulnerability: The current allowable diversions (3 AF) are less than future estimated demands (4.5-9 AF). Given the necessity of water rights for legally diverting water, the preserve is considered highly sensitive to water rights constraints. Furthermore, the substantial gap between available rights and projected future demands creates high exposure to legal constraints that could limit water access regardless of physical water availability. This exposure represents a critical constraint on the system's ability to meet demands under any climate future.

Recommendations



Management actions may offer capacity to mitigate some climate change impacts. The proposed water supply at Valles Caldera is in the initial stages of planning, marked by uncertainty in many aspects of hydrology and water demand that limit the ability to accurately assess threats. For example, future water demands from park staff and operations remain relatively uncertain. Also, aquifer properties and seasonal and annual groundwater level responses to changes in climate remain unknown for the proposed well site. This limits the ability to project groundwater levels and aquifer storage response to future changes in climate. Herein, we present recommendations that offer potential to mitigate and monitor climate change impacts while reducing gaps in understanding.

Advance hydrogeologic understanding: Our primary recommendation is to advance the understanding of hydrogeologic conditions near the proposed well site. Determine the aquifer depth, hydraulic properties, and seasonal changes in groundwater levels that may be due to fluctuations in recharge or water balance. Construct and evaluate a test well to inform supply well design: Prior to constructing the permanent supply well, a less-expensive test well should be constructed at the proposed well location to confirm adequate groundwater availability and favorable aquifer conditions exist. Observations made during drilling and yield-testing will inform supply well and water system design and construction. Groundwater samples should be collected from this test well during yield-testing and analyzed by an accredited laboratory to determine water treatment requirements.

Real-time water level and use monitoring: Invest in hourly continuous water level, pumping rate, and pumping volume monitoring at the proposed supply well. This data will enable efficiency tracking and provide drawdown response data necessary for registering changes in supply. Consider installing monitoring wells or retrofitting existing wells to measure groundwater levels outside the influence of pumping. Upgradient monitoring wells could also be used to evaluate seasonal fluxes associated with MBR to the valley aquifer, potentially providing an early predictor for seasonal conditions at the supply well. Daily water use data, including metadata describing place of use, would also greatly improve the understanding of present and future water demands and would allow the park to meet reporting requirements.

Inspect and maintain wells: Once the well is installed, regular video inspection (at least every 5 years or more frequently if iron bacteria is discovered) should be conducted to gauge the well's condition, estimate remaining lifespan, and plan for well rehabilitation. Well performance commonly declines over time, leading to increases in drawdown and unnecessary stress on well pumps. Because inspection will require temporary removal of well pumps, it should occur well in advance of or following known periods of high water demand. Additionally, depending on observed video inspection results and well performance, consider periodic well rehabilitation (e.g., development, brushing, or bailing) to improve and maintain well performance.

Data-driven decision making: Once supply or monitoring well data are collected regularly, simple models can be developed that relate seasonal water supply to well conditions to allow for proactive adjustments to water management that ensure resilience against climate variability. For example, if groundwater levels are heavily impacted by low snowmelt years, tracking of snowmelt can instigate proactive water conservation measures to ensure demands are met throughout the following year.

Water storage monitoring: Continue to monitor storage and demand to determine whether storage capacity is sufficient. Increased storage capacity provides a buffer against seasonal variability in water availability, especially



during peak demand periods and will ensure adequate water to address the increased risk of wildfires. Storage capacity should be designed according to projected demands, seasonal supply variability, and well yield.

Alternative supplies: Although runoff and recharge are projected to decline substantially in a Hot Dry future (50%), previous investigations indicate ample water volume in Valle Grande as a whole, with aquifer depths in the central valley exceeding 1,000 ft (Conover et al., 1963). These deeper sources are less vulnerable to impacts of decreasing supply, drought, and fire. The potential to tap into this alternative water source indicates capacity to mitigate climate-related impacts. Furthermore, relying on a single supply well presents vulnerability in the case of well damage, outages, insufficient well yield, or slow aquifer recovery. In the future, installing an additional supply would help to ensure demands are met even in the case of a well outage. Verifying that hydrogeologic conditions are appropriate and adequate water rights are available prior to supplemental well installation would be critical. Although not as effective, a less-expensive option for increasing water system resiliency is to store a spare pump, motor, submersible cabling, and drop pipe at the preserve. This will decrease the outage time required for replacing a failing pump or other downhole equipment but will not address issues related to declining well yield or slow aquifer recovery.

Fuel management: Continuing to utilize fuel reduction treatments in forested areas in the water supply's contributing area will help to reduce fuel loads, thereby minimizing the likelihood of intense wildfires and structural damage.

Enhance infrastructure resilience: Projected increases in wildfire and extreme runoff events pose risk to water supply infrastructure. Although the well is in grasslands, the proposed storage tank and piping will likely intersect with areas at risk of damage due to wildfires and flooding. Invest in retrofitting and reinforcing pump houses, water treatment buildings, storage tanks, and their surroundings to withstand these risks.

Open Science Policy

We are committed to open science principles, ensuring transparency in our research process. All analyses described in this report are available at our official GitHub repository for this project:

https://github.com/Water-Vulnerability-Analytics/VALL_WSVA.

Provisions

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, US Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the US Government.

Acknowledgements

This report benefited significantly from the knowledge and experience of National Park Service staff and partners, who provided invaluable insights into park resources and management challenges. We extend our sincere thanks Matt Ross, Stephanie Kampf, Jonathan Allbach, Jorge Silva-Bañuelos, Travis Kraft, Andrew Erwin, Steve Rice, and other reviewers and NPS staff for their thoughtful feedback and suggestions.



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Appendix A

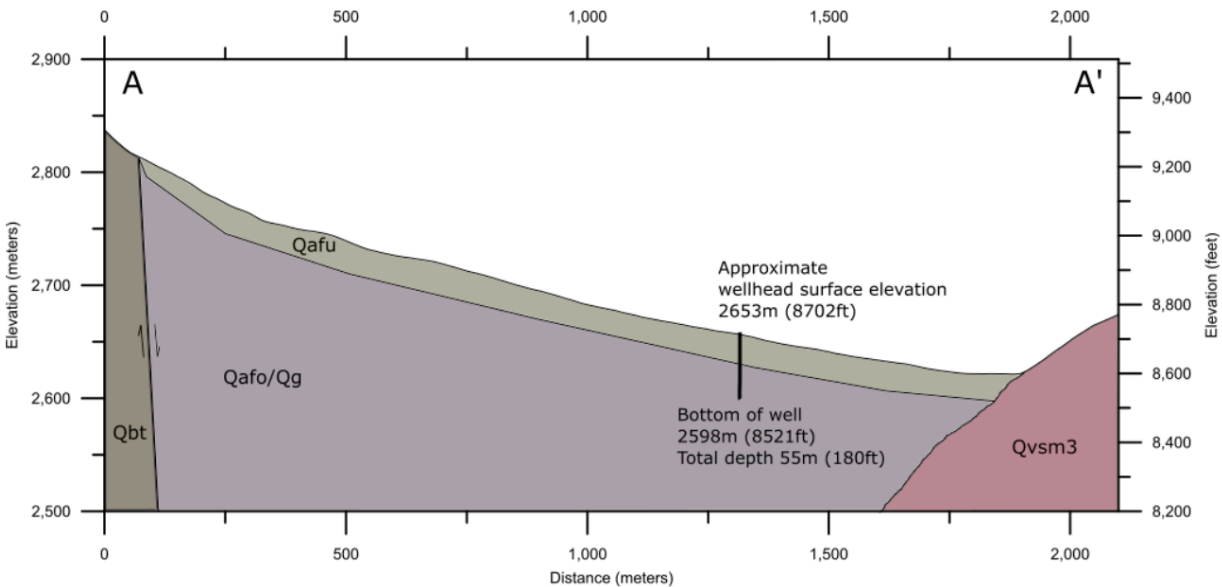


Figure A1: Simplified interpretation of subsurface conditions near proposed well location [from Rice, 2018] including Quaternary Age alluvial fans (young: Qafu, old: Qafo), gravels (Qg), Bandelier Tuff (Qbt), and the South Mountain Member of the Valles Rhyolite (Qvsm3).

Depth in Feet		Thickness in Feet	Color and Type of Material Encountered
From	To		
0	6	6	surface dirt
6	115	109	decomposite red granite
115	160	45	grey sandy silt clay
160	175	15	yellow-green clay
175	280	105	grey sandy rock

Figure A2: Driller boring log for the interim supply well filed under New Mexico well permit RG-55866.



Bandelier Visitor Growth since 2013

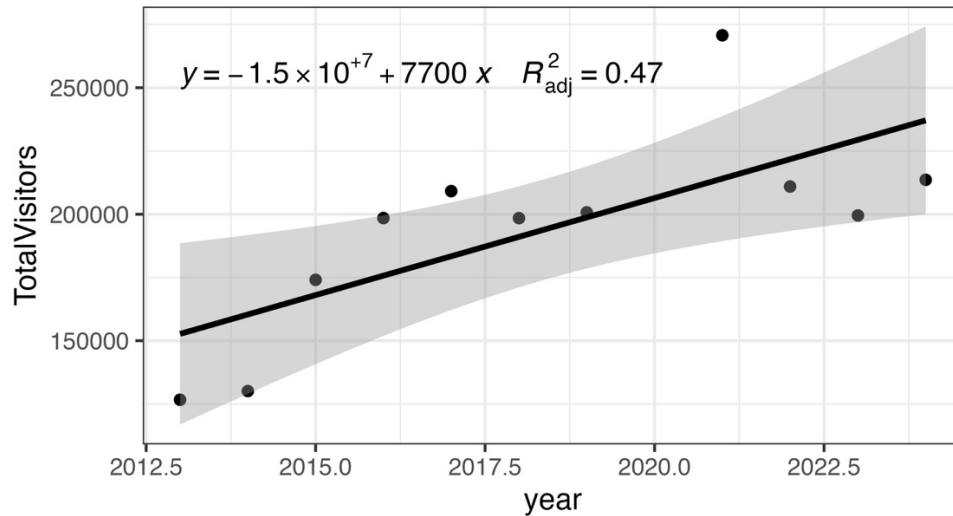


Figure A3: Bandelier visitor growth since 2013.

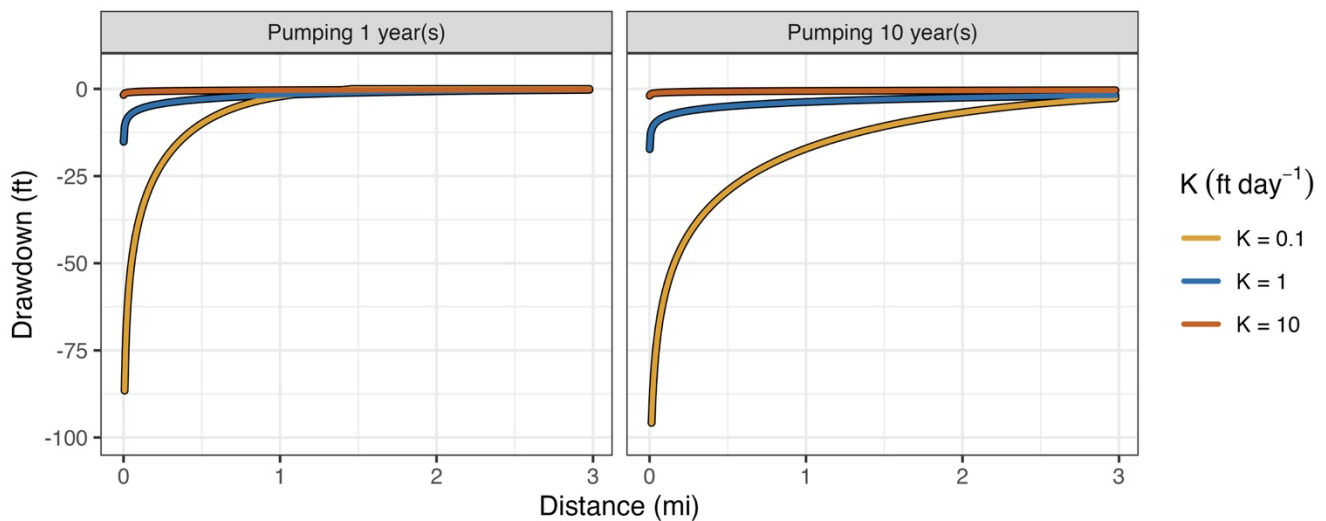


Figure A4: Well drawdown after one and ten years of pumping as determined by the Theis equation with assigned pumping rate of 50 gallons per minute, confined aquifer thickness of 300 feet, storativity of 0.005 (-), and hydraulic conductivity (K) ranging from 0.1 to 10 feet per day. Note, hydraulic parameter values were based on Conover et al. (1963) which estimated Valle Toledo storativity to be 0.005 (-) and Valle Grande transmissivity to be 25,000 gallons per day per foot which translates to a hydraulic conductivity of 1 foot per day for the aquifer thickness of 800 feet where their aquifer test was conducted.

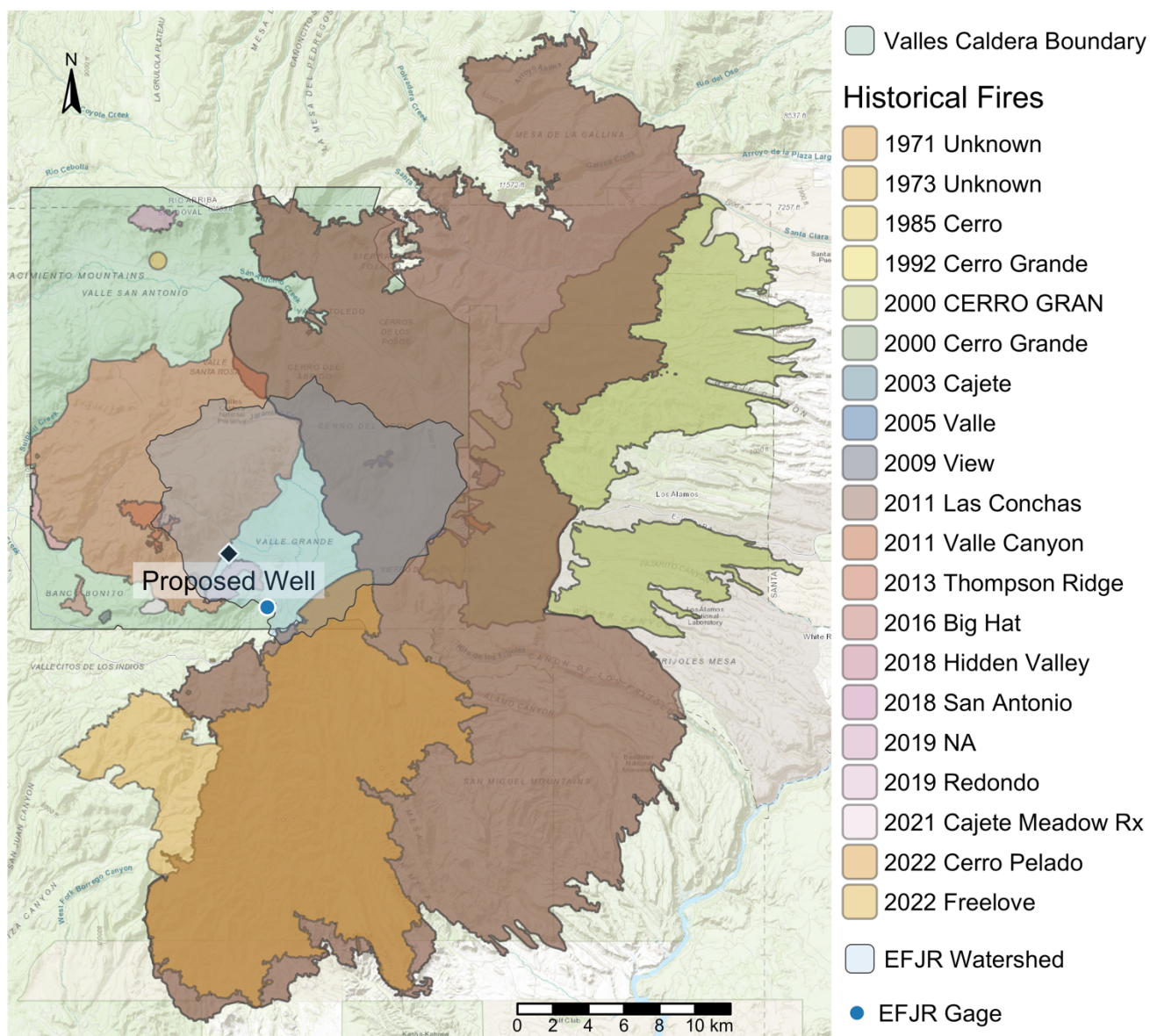


Figure A5: Historical fire perimeters that intersect with Valles Caldera National Preserve obtained from the National Interagency Fire Center (2024).

Appendix B

This report uses methods developed by the National Park Service's Climate Change Response Program (CCRP) to select "Hot Dry" and "Warm Wet" climate futures described in this report (Runyon et al., 2024). This appendix includes adapted and excerpted text from [Runyon et al., \(2024\)](#) describing the approach.

Climate future selection involved obtaining historical climate records and 40 climate projections - 20 GCMs (Global Climate Models) and 2 RCPs (Representative Concentration Pathways) - for each park centroid for a select time period relevant to water resource planning. Because GridMET was used to train the MACAv2-METDATA downscaling process, we could directly compare historical data to projections without having to perform additional bias corrections. For this analysis, we used 1979-2012, the reference period used to train the MACA data, to characterize the historical period and the average centered around 2035-2065 (2050) to define a mid-century future planning period. We calculated average annual temperature and precipitation change of each of the 40 projections relative to the historical period, as illustrated in Figure B1.

Although RCP 8.5 has received scrutiny as an increasingly unlikely emissions trajectory under current and projected decarbonization trends (Hausfather and Peters, 2020; Van Vuuren et al., 2026), it remains a valuable planning scenario for infrastructure decisions with long time horizons: its temperature and precipitation changes represent plausible upper-bound physical conditions that the Valle Grande system could face, and designing water infrastructure against a high-end scenario provides a margin of resilience that a moderate-emissions scenario alone would not. We therefore retain RCP 8.5 alongside RCP 4.5 in the 40-model ensemble and note that the Hot Dry and Warm Wet scenarios selected from this ensemble (Table B1) should be interpreted as a stress-test of system resilience under severe but physically plausible conditions rather than as the most probable future outcome.

We then applied the individual-projection approach to select a small set of projections that characterized the broadest range of uncertainty over this space. This approach used principal component analysis on the change values (from the 1979-2012 baseline) of temperature and precipitation to select the most divergent projections from principal components 1 and 2 based on the loadings on the first two principal components (circled projections in Figure B1). Selected models and associated temperature and precipitation change values are presented in Table B1.

While all projections represent plausible climate futures, some have better skill in representing historical conditions than others. To ensure the individual GCMs selected to represent a climate future have appropriate skill, we used the approach adopted for the US Forest Service 2020 Resource Planning Act. We used rankings of GCM skill based on 19 performance metrics for three climate regions and applied them to parks within the corresponding regions. Only models that ranked in the top 90% of GCM skill were considered for individual projections.

CCRP typically uses two to four divergent climate futures that bracket the range of climate variation relevant to the resource-management decision of interest. For most resources, they focus on climate futures that represent a "best/worst case" or "most/least change" contrast; typically, these climate futures fall on diagonally opposite quadrants shown in Figure B1. "Warm Wet" and "Hot Dry" are one set of contrasting climate futures, where a Warm Wet climate future could lead to more precipitation and flood potential, and a Hot Dry climate future could indicate more drought or conditions conducive to fires. Depending on the resource of interest, these scenarios may have differing impacts.



- Changes in climate means in 2050 by GCM run

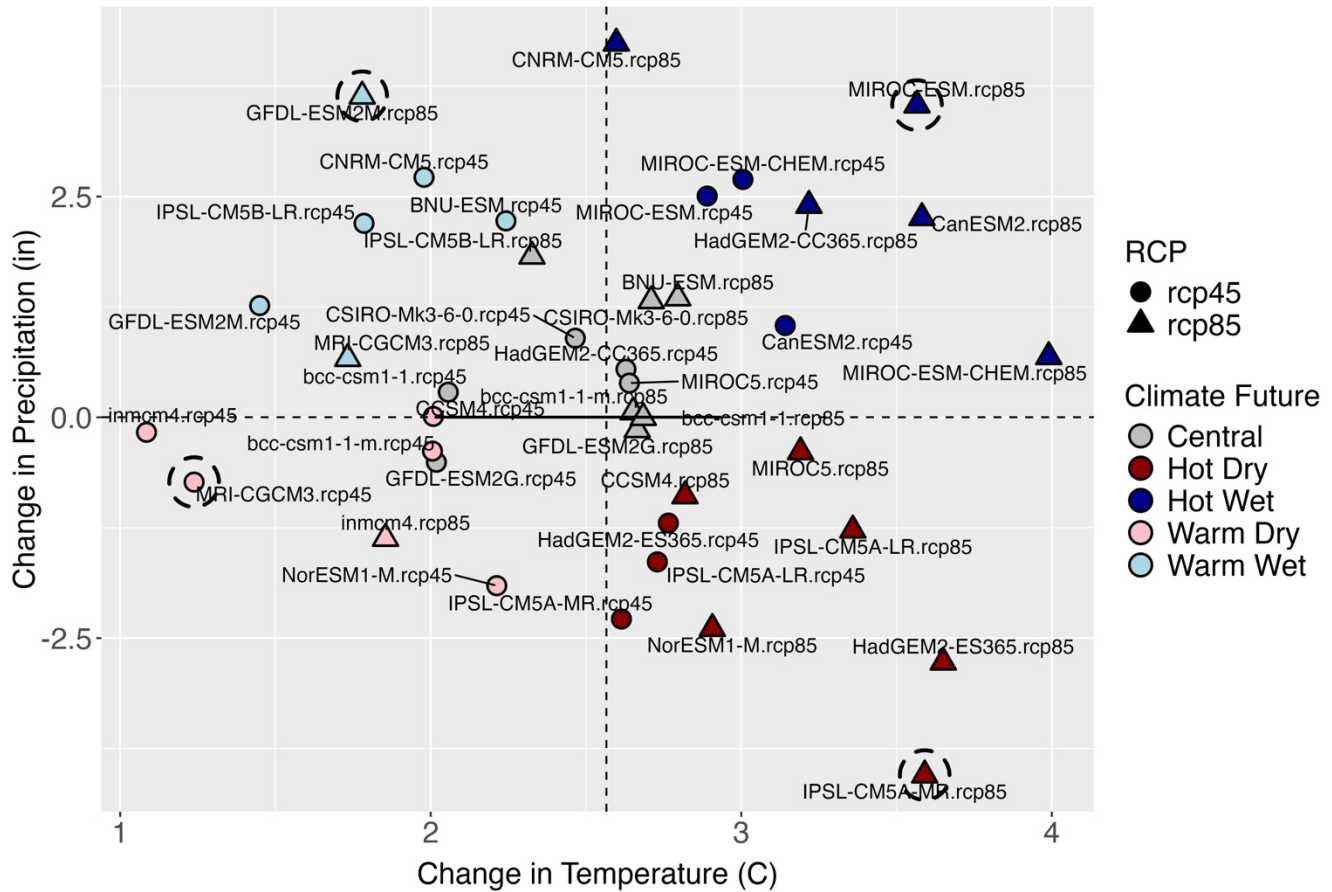


Table B1: Selected climate models for WSVA scenarios

Climate Model	Emissions Scenario	Climate Future	Temperature Change (C)	Precipitation Change (in)
IPSL-CM5A-MR	RCP 85	Hot Dry	3.59	-4.05
GFDL-ESM2M	RCP 85	Warm Wet	1.78	3.64

Appendix C

A routing function was used to convert runoff from the NPS WBM into surface water and groundwater components. The routing function is derived from unit hydrograph theory which states that stream discharge at the basin outlet is linearly related to the amount and duration of effective precipitation (or in our case, runoff) in the contributing basin. The applied routing function, modeled after the IHACRES method (Jakeman and Hornberger, 1993), includes two parallel, linear stores describing direct runoff (quickflow; Q_q) and baseflow (slowflow; Q_s), wherein the sum of Q_q and Q_s components gives the total stream discharge (Q_{sw}). A fraction of slowflow (f_{gw}) was partitioned to groundwater recharge (Q_r) and consequently not added to stream discharge. A constant baseflow component (Q_{bf}) was also added to total stream discharge representing fossil groundwater not derived from effective precipitation. The resulting routing function is summarized in the following set of equations:

$$Q_q = \beta_q u_k - \alpha_q x_{k-1} \quad \text{where} \quad \alpha_q = e^{-\frac{1}{\tau_q}} \quad \text{and} \quad \beta_q = v_q(1 - \alpha_q)$$

$$Q_s = (1 - f_{gw})(\beta_s u_k - \alpha_s x_{k-1}) \quad \text{where} \quad \alpha_s = e^{-\frac{1}{\tau_s}} \quad \text{and} \quad \beta_s = v_s(1 - \alpha_s) \quad \text{and} \quad v_s = 1 - v_q$$

$$Q_r = f_{gw}(\beta_s u_k - \alpha_s x_{k-1})$$

$$Q_{sw} = Q_q + Q_s + Q_{bf}$$

Where v_q and v_s [unitless] are the fractions of effective rainfall that go to Q_q and Q_s respectively, and τ_q and τ_s [time] are time constants governing the rate of recession for Q_q and Q_s . Time constants represent the time required for the Q_q and Q_s responses to fall to $1/e$ of their initial values after an impulse of effective precipitation. As such, these are subject to the condition $\tau_q < \tau_s$, given that Q_q should recede more quickly than Q_s .

Values for the six unknown parameters (v_q , τ_q , τ_s , f_{gw} , and Q_{bf}) were determined using an automated calibration routine designed to minimize errors between modeled and observed stream discharge at the East Fork of the Jemez River gauge. During calibration, parameters were varied within pre-defined ranges until the best-fit, defined as producing the maximum Nash-Sutcliffe Efficiency index (NSE) between modeled and observed stream discharge, was achieved. Visual inspection and mass balance checks were also performed to ensure model accuracy. Parameter ranges were set based on theoretically plausible ranges (Table C1). The range for fossil groundwater was capped at 5 CFS based on the observed upper limit of seasonal low flows at the Valle Grande gauge that may be attributed to fossil groundwater discharging from the artesian aquifer. Calibration was performed using a subset of the available stream discharge data for a period with limited data gaps spanning from May 1, 2008, to July 2, 2015. The best-fit parameters resulted in an NSE value of 0.507 for daily stream discharge and 0.826 for monthly stream discharge for the calibration period (Figure C1) and an NSE value of 0.56 and 0.64 for daily and monthly stream discharge respectively for the full data period (Figure C2).

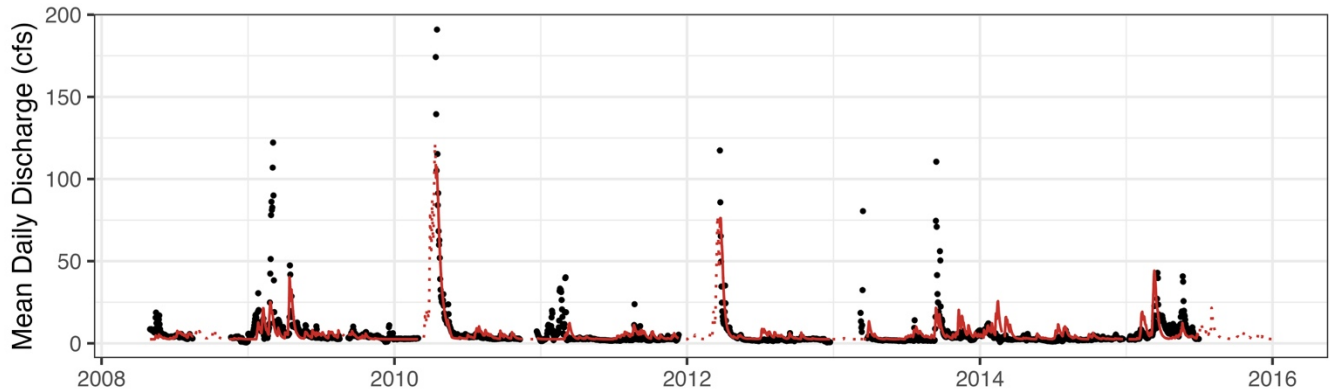
Table C1: Calibrated routing function parameters

Parameter	Description	Calibration Range	Calibrated Value
τ_q	Quickflow recession coefficient	1 – 40 days	5.6 days
τ_s	Slowflow recession coefficient	40 – 350 days	40 days
v_s	Fraction of effective precipitation routed to quickflow ($v_q = 1 - v_s$)	0.01 – 0.99 (-)	0.81
f_{gw}	Fraction of slowflow partitioned to groundwater recharge	0.01 – 0.99 (-)	0.94
Q_{bf}	Fossil baseflow contribution to stream discharge	0.01 – 5 cfs (cubic feet per second)	2.16 cfs

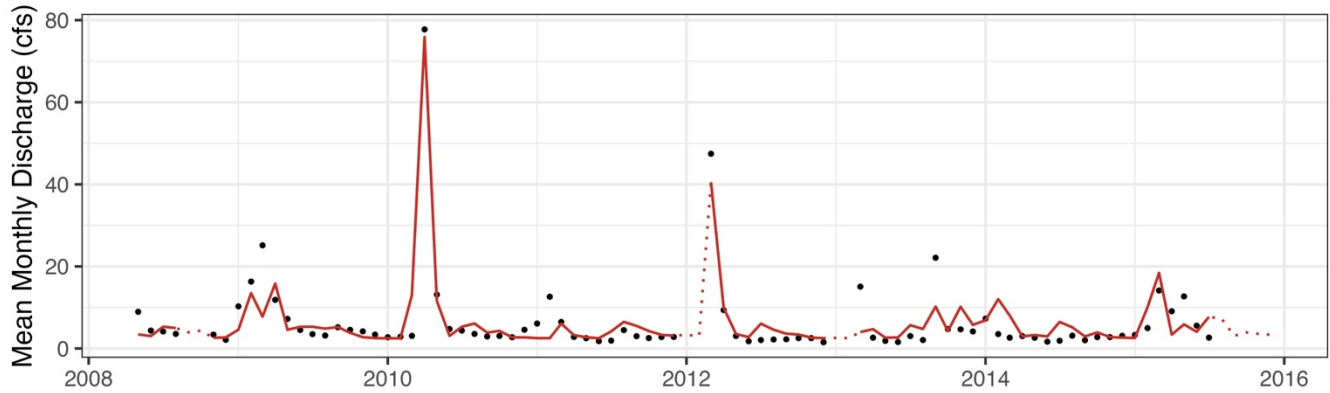


East Fork Jemez River

NSE: 0.54969 RSR: 0.04



NSE: 0.84267 RSR: 0.38

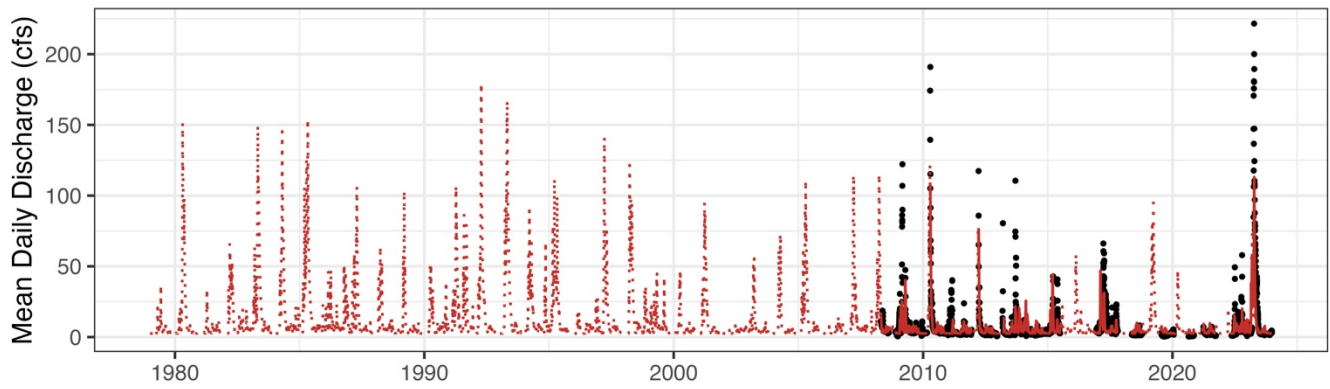


• Observed — Simulated

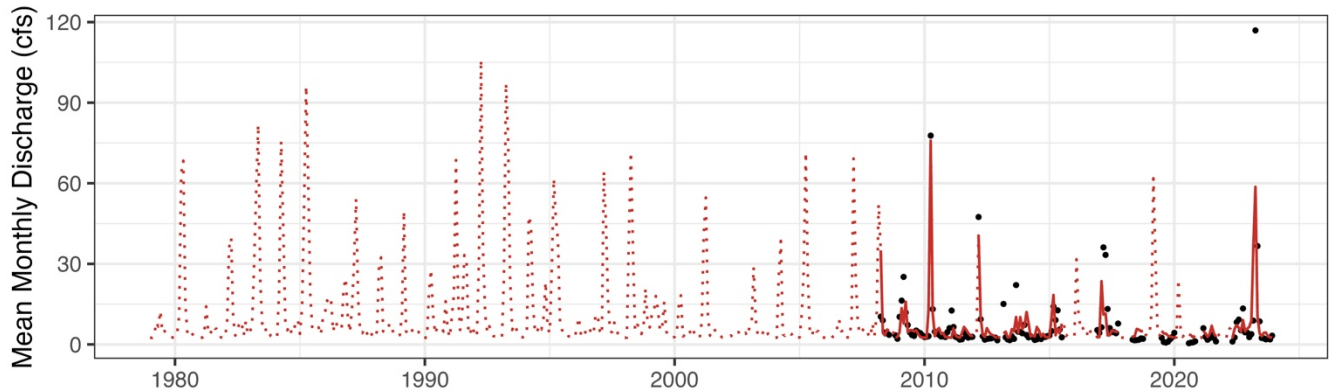
Figure C1: Measured and modeled stream discharge (or streamflow) at the East Fork Jemez River stream gauge for the calibration period.

East Fork Jemez River

NSE: 0.55574 RSR: 8.55



NSE: 0.64498 RSR: 2.56



• Observed — Simulated

Figure C2: Measured and modeled stream discharge (or streamflow) at the East Fork Jemez River stream gauge for the full simulation period and period of stream gauge records.