A Remote Sensing Investigation of Surprise Canyon Creek Wild and Scenic River
Panamint Valley, California

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ABSTRACT

A remote sensing investigation was conducted to characterize groundwater dependent ecosystems (GDEs) in the Surprise Canyon Creek Wild and Scenic River area. An understanding of how variations in climate, hydrologic conditions, land management policy, and natural disturbances influence GDE communities is imperative to efforts to manage these systems. The Wild and Scenic River corridor’s (WSRC) remote setting and harsh environment have largely precluded the collection of in-situ data, rendering remote sensing an ideal approach for this effort. The status, trends, variability, and water use of riparian and other groundwater dependent vegetation along, and in proximity to, the Surprise Canyon Creek WSRC were quantified using 36 years (1985 – 2021) of Landsat satellite imagery. Field data were collected to ground truth and interpret satellite-based results.

Results indicate that most GDE areas show positive trends in vegetation vigor, with the greatest increases observed in Surprise Canyon Creek WSRC and valley floor mesquite bosque areas. Vegetation vigor in upland areas is trending more positively than in GDE areas. Varying degrees of groundwater dependence are observed at different sites along the WSRC, as evidenced by differing sensitivities of vegetation vigor to interannual climate variability. The coincidence of the official road closure (2001), ongoing tamarisk removal on BLM lands (2007-2010), and decreased climate variability after 2008 confounds efforts to identify causal factors of changes in vegetation vigor, though there is reasonable evidence to suggest that increases in vigor in the Chris Wicht reach may be due to removal of a water diversion in 2006.

Estimated median annual water use by vegetation within the WSRC over the period of record amounts to 99 acre-ft in the NPS portion and 68 acre-ft in the BLM portion, with 55% and 70% of this provided by groundwater. Estimated median annual water use within the mesquite bosque amounts to 1684 acre-ft, with 60% of this provided by groundwater. Results from this study provide a baseline against which future impacts to and changes within the GDEs can be compared and may help to guide resulting monitoring and management decisions. Moreover, this study provides a first approximation of the water required to sustain the system in its “free-flowing condition”, which is critical to fulfilling management mandates associated with Wild and Scenic River designations.
## CONTENTS

Abstract ......................................................................................................................................... iii
List of Figures ............................................................................................................................... vi
List of Tables .............................................................................................................................. viii
Introduction ................................................................................................................................. 10
Management History .................................................................................................................. 11
Approach ..................................................................................................................................... 11
Results and Discussion ................................................................................................................ 14
   Synthesis of Vegetation Analysis Results at the basin and GDE Area scales .................... 14
      Plausibility of GDE Community Extents based on Groundwater Levels .................... 14
      Vegetation Status, Climate Sensitivity, and Trends ..................................................... 15
   Site-Specific Results ............................................................................................................ 23
      Vegetation Status, Climate Sensitivity, and Trends ..................................................... 23
      Estimated Water Use of Surprise Canyon WSRC and Surrounding Mesquite Bosque .... 29
Summary of key findings............................................................................................................ 32
References .................................................................................................................................... 34
Appendix A – detailed methods ................................................................................................. 38
   Study Area .............................................................................................................................. 38
   Datasets ................................................................................................................................... 38
      1) Gridded Climate Data ............................................................................................. 38
      2) Landsat Archive Data ............................................................................................ 39
      3) GDE Area Boundaries ............................................................................................ 40
      4) LANDFIRE Existing Vegetation Type Database .................................................. 41
      5) Groundwater Level Databases ................................................................................ 41
   Basin-Scale GDE Vegetation Analytical Approach ............................................................... 42
      Plausibility of GDE Community Extents based on Groundwater Levels .................... 42
      Vegetation Status, Climate Sensitivity, and Trends ..................................................... 42
   Site-specific Areas of Interest (AOIs) Analytical Approach .................................................. 45
      Landsat and Climate Data Summaries ......................................................................... 46
      GDE Evapotranspiration ............................................................................................... 46
      Field Investigations ........................................................................................................ 49
Appendix B – AOI Vegetation and Climate Timeseries, Trend Maps, and Field Images ... 50
   NPS River Corridor AOIs ..................................................................................................... 51
   Upper Panamint Spring ........................................................................................................ 51
LIST OF FIGURES

Figure 1. Selected HUC-10 hydrographic comprising the overall study area potential groundwater discharge areas (i.e., phreatophyte areas) therein. Note the added Surprise Canyon area displayed in orange, the valley floor AOIs in pink, and the mesquite bosque ET area in green. ............................................................................................................................................. 13

Figure 2. AOIs Along the BLM Portion of the Surprise Canyon Creek WSRC. ......................... 14

Figure 3. Surprise Canyon Study Basin 1985 - 2021 Annual NDVI Trend Map.......................... 16

Figure 4. Vegetation status, as indicated by 2012-2021 average ranges of late-summer NDVI, for select LANDFIRE vegetation types within GDE boundaries. Horizontal lines are shown for NDVI values = 0.2, and 0.35 as references. ....................................................................................................................... 17

Figure 5. Surprise Canyon Study Basin 1985 - 2021 NDVI-PWD Correlation (Pearson's R) ....... 18

Figure 6. Sensitivity of late-summer NDVI to interannual variations in climatic conditions (measured as the Pearson correlation coefficient between annual median July-Sept NDVI and water year PWD) for select LANDFIRE vegetation types within GDE areas. ............................................. 19

Figure 7. Distribution of climate-adjusted trends in late-summer NDVI for pixels within non-GDE areas (Hydrographic Area) vs. those in the GDE areas (phreatophyte Area) for the entire study area. ..................................................................................................................................... 21

Figure 8. GDE Area Climate-adjusted 1985 – 2021 trend slope magnitude and direction by LANDFIRE group for vegetation types within GDE boundaries. Note that positive trends dominate most classes, and a greater proportion of moderate-large magnitude trends are seen in riparian/wetland groups. ................................................................................................................. 22

Figure 9. Annual timeseries of late-summer NDVI and water year potential water deficit for NPS areas of interest along Surprise Canyon Creek ............................................................................. 26

Figure 10. Annual timeseries of late-summer NDVI and water year potential water deficit for BLM areas of interest along Surprise Canyon Creek. ......................................................................................... 26

Figure 11. Annual timeseries of late-summer NDVI and water year potential water deficit for BLM valley bottom areas of interest. ..................................................................................................................... 27

Figure 12. Relations between annual late-summer NDVI and potential water deficit for the Chris Wicht reach of Surprise Canyon Creek before and after removal of the upstream water diversion in 2006. Higher NDVI values and a lack of overlap of regression confidence intervals (gray shading) indicate statistically significant increases in vegetation vigor post-removal. ................ 28

Figure 13. Relations between annual late-summer NDVI and potential water deficit before and after tamarisk removals by the BLM from 2007-2010. Differences in NDVI values and a lack of overlap of regression confidence intervals (gray shading) indicate locations where statistically significant changes in vegetation vigor occurred post-2010, that could be attributed to tamarisk removal, but insufficient data exist to make a final determination on this. .................. 28

Figure 14. Relations between annual late-summer NDVI and potential water deficit before and after the official road closure in 2001. Differences in NDVI values indicate locations where changes in vegetation vigor occurred post-2001, but these are not statistically significant given the presence of overlapping confidence intervals (gray shading). ......................................................... 29
Figure 15. Sum of water year annual total evapotranspiration and evaporation supplemented by surface and subsurface water (ETG) across all areas of interest on NPS and BLM lands in the Surprise Canyon Creek corridor and the mesquite bosque.......................... 30

Figure A-1. NDVI – ET* plot with upper/lower 90% confidence and prediction intervals. Modified from Minor (2019). .......................... 48
LIST OF TABLES

Table 1. Summary of observed impacts based on field observations from April 2022 and 36-year trends in NDVI and PWD (see Table 2). Sites are ordered from upstream to downstream. 24

Table 2. Zonal statistics for AOIs, ordered from upstream to downstream. Minimum, maximum, and mean NDVI values are from the annual late summer median NDVI time series. NDVI sensitivity is the Pearson correlation coefficient between NDVI and annual PWD. Climate-adjusted NDVI trend is the Sen’s slope estimate of NDVI residuals (1985 – 2021), accounting for the influence of annual water deficit. Climate trend is the Sen’s slope of water year PWD (1985 – 2021). Blue or red shading indicate statistically significant positive or negative trends or correlation, respectively (p < 0.05). ......................................................... 25

Table 3. Total (ET) and groundwater-supplemented (ETG) evapotranspiration summary table. Surprise Canyon AOIs are presented ordered from upstream to downstream. Annual minimum, maximum, and median values are based on the 1985 – 2021 dataset. Volumetric sums are provided in acre-feet for the NPS and BLM portions of Surprise Canyon WSRC. Metric values are provided in the geodatabase that accompanies this report. ......................................................... 31

Table A-1. NDVI value ranges typical of broad landcover types within the Mojave ecoregion. Threshold values are based on: 1) Albano et al., 2021; 2) Albano et al., 2020; McGwire, 2019; 4) Jones et al., 2008 .......................................................... 43
INTRODUCTION

Surprise Canyon Creek, a spring-fed perennial stream originating in the seemingly inhospitable Death Valley National Park, was established as a Wild and Scenic River (WSR) by Congress in March 2019. Surprise Canyon Creek’s year-round flows represent a scarce resource in this exceptionally arid setting. The creek’s water supports lush riparian vegetation, which provides habitat for numerous avian, reptile, and mammal species, and provides exceptional scenic and recreational opportunities. Part of the protection afforded to an area by Wild and Scenic River status is the creation of a federal water right to protect the “outstandingly remarkable” characteristics of the river and its immediate environments. In order to establish this water right, however, the volume of water required to sustain the system in its “free-flowing condition” must be quantified.

Processes that influence the hydrologic and hydrogeologic conditions in Surprise Canyon are important to understand as they directly influence the crucial groundwater dependent ecosystems (GDEs) that make the area so exceptional. Unfortunately, Surprise Canyon’s remoteness has resulted in exceptionally limited hydrologic data collection, and this lack of in-situ data renders characterizing the system and GDEs in the area challenging. Management actions such as closing the road and removing invasive species have improved hydrologic conditions in Surprise Canyon, but there is no quantitative evidence of the extent or degree of these improvements, or for that matter the baseline condition prior to this improvement. In addition, interannual climate variability, longer-term climate change, and natural disturbances such as flooding can have profound impacts on the system’s hydrology. A quantitative understanding of the influence these actions and events have on the system is imperative to establishing an appropriate water right to protect the creek’s natural character.

The primary goal of this study is to quantify Surprise Canyon Wild and Scenic River corridor’s (WSRC) water requirements, and to provide an assessment of the system’s response to management actions, climate variability and long-term trends, and natural and anthropogenic disturbances. Numerous GDE communities spread throughout the Panamint Valley area beyond Surprise Canyon Creek are similarly poorly understood. This study aims to characterize the dynamics of these more widespread GDEs in addition to the primary WSRC-related goal(s). Given the dearth of in-situ hydrologic data, remote sensing approaches are ideal for this analysis. Results from this study will help develop an understanding of vegetation dynamics in response to variations in climate and management activities. Results will also provide an invaluable baseline assessment which can be used to gauge future impacts to and changes within the GDEs, and guide resulting monitoring and management decisions.

Specific objectives of the study are to:

- Characterize the status and trends of vegetation along the Surprise Canyon Creek riparian corridor and the role that variations in climate, hydrology, disturbance regime, and land management have on these systems.
• Develop satellite-based estimates of water use by riparian vegetation within the Wild and Scenic River corridor and within the surrounding mesquite bosque.

• Develop, document, and make available datasets derived from this study to facilitate future assessments and monitoring.

MANAGEMENT HISTORY

The Surprise Canyon area has a lengthy history of anthropogenic involvement and impacts. For thousands of years the canyon served as a trail for Native Americans, likely drawn to the area by the abundant water and relative ease the canyon offered for traversing the Panamint Mountains (BLM, 2022). Silver was discovered in the isolated canyon by white settlers in 1872 (Durham, 1998). Within two years of the discovery, Panamint City, a bustling but short-lived boom town of some 2,000 people was thriving 7 miles upstream of, and 4,000 feet above, Panamint valley’s floor (Palazzo, 2014). With no viable alternative access route, a road was constructed right up Surprise Canyon despite the perennially flowing creek and rugged terrain. This road remained in active use for over 125 years, save for brief periods of impassability caused by the road’s repeated destruction by violent flash floods through the canyon. Surprise Canyon Road was officially closed in 2001 following the Passage of the 1994 California Desert Protection Act. A preliminary list of disturbance events and management actions that may be detectable using the Landsat archive are listed below:

• 1984: Flash flood “stripped the canyon down to the bedrock” destroying the road (Romney, 2003)

• 1989: Road rebuilt by “off-road enthusiasts” (Romney, 2006)

• 1990: Satellite imagery shows evidence of flash flood between Aug 11 – 18, news reports corroborate (Flinchum, 2005)

• 1995: Big January flood event ( Mentioned in 3/8/22 meeting with NPS/BLM, but no obvious signs of flood observed in Landsat imagery)

• 2001: May 29th, Gate installed to prevent off-roading access, road closed to vehicle traffic (OFR, 2001)

• 2001: Satellite imagery shows evidence of flash flood between Sep. 1 – 9

• 2005: High precipitation year, reports of flash flood fatalities in park

• 2006: Removal of small water diversion associated with Chris Wicht Camp.

• 2007-2010: BLM tamarisk removal efforts begin. More than 80 large trees, as well as, saplings, seedlings, and re-sprouts were removed. Removal began at Chris Wicht Camp down to the first jeep crossing and then up from Chris Wicht Camp to Limekiln and Brewery Springs (with NPS).

APPROACH

This section briefly describes the analytical approach and datasets used. A more comprehensive description of methods is provided in Appendix A. The study area described in this report includes the Surprise Canyon Creek WSRC, its associated catchment area, and catchments relevant to GDE areas across the valley floor below (Figure 1). To assess status,
variability, and trends in vegetation, gridded climate and Landsat satellite data from 1985 – 2021 were compiled, as was readily available groundwater data. The area potentially comprised of groundwater dependent vegetation (GDE boundaries) was identified based on the Natural Communities Commonly Associated with Groundwater (NCCAG) Dataset (CDWR, 2022). The NCCAG dataset did not include the majority of the Surprise Canyon Creek riparian area. The riparian corridor along the WSRC of Surprise Canyon Creek was manually digitized and added to this extent using high resolution aerial imagery and preliminary boundary datasets provided by agency partners. Beyond this, no additional modifications were made to the GDE boundary. Groundwater data available through March 8th, 2021, was used to assess the accuracy of the GDE boundary.

The current status, climate sensitivity, and climate-adjusted trends of GDE vegetation were assessed for each 30-meter (m) Landsat pixel within the study area using annual median late-summer (July 15th – September 15th) Normalized Difference Vegetation Index (NDVI). NDVI is a metric that accurately tracks the chlorophyll content in vegetation (Gitelson & Merzlyak, 1997), and chlorophyll serves as an excellent proxy for overall vegetation vigor (Gitelson et al., 2014). The primary productivity (vigor) of vegetation in the greater Death Valley area is often water limited, and water availability in the study area tends to be at a minimum during the late summer. Given these water limitations, and that NDVI closely tracks vigor, late-summer NDVI provides a robust and useful measure of plant water availability (Huntington et al., 2016).

GDE vegetation status was characterized as the average of 10 years (2012-2021) of late-summer NDVI. Climate sensitivity was quantified as the correlation between annual late-summer NDVI and water year Potential Water Deficit (PWD; see Appendix A for additional details) over the 1985 – 2021 time period. Trends in annual late-summer NDVI were calculated over the same time period. Adjustments to this trend analysis were made to account for and exclude the influences of interannual climate variability, which has the potential to obscure trends (see appendix A for additional details). LANDFIRE (USGS, 2016) Existing Vegetation Type (EVT) data were used to summarize status, climate sensitivity, and trends for those vegetation communities that commonly occurred within the GDE boundaries.

More detailed analyses were conducted at AOIs along the WSRC (Figure 2). For each of these areas, gridded climate and late summer NDVI time series were compiled. The status, climate sensitivity, and climate-adjusted NDVI trend were calculated for each AOI using the same methods described above and expanded upon in Appendix A. A field investigation was conducted in April of 2022 for purposes of ground truthing and interpreting satellite-based results. Eight AOIs along the WSRC, from Chris Wicht to Brewery Springs, were visited as were four sites on the valley floor, including Post Office Spring, Warm Sulphur Springs, Indian Ranch Road, and a site in the northern portion of the mesquite bosque. Data collected as part of the field investigation can be found in the accompanying database for this report. These include: field photographs and vegetation observations, including relative abundance of GDE categories, degree of mortality observed, and signs of water stress. High-resolution orthomosaic imagery of AOIs (where conditions permitted sUAS flight) are also included in the database.
Annual evapotranspiration (ET) and groundwater evapotranspiration (ET\(_G\)) rates and volumes were estimated for 10 AOIs along the entire NPS and BLM lengths of the WSRC, as well as for the surrounding mesquite bosque, which accounts for a broad area within the valley (Figure 1). The ET and ET\(_G\) analyses performed for these areas followed the latest estimation methods available (Minor, 2019).

Figure 1. Selected HUC-10 hydrographic comprising the overall study area potential groundwater discharge areas (i.e., phreatophyte areas) therein. Note the added Surprise Canyon area displayed in orange, the valley floor AOIs in pink, and the mesquite bosque ET area in green.
RESULTS AND DISCUSSION

In this study, we aimed to characterize the status, trends, variability, and water use of riparian and other GDE vegetation in the study area surrounding the Surprise Canyon Creek WSRC using 36 years (1985 – 2021) of Landsat satellite imagery. Changes in vegetation vigor and ET in response to variations in climate, groundwater conditions, disturbance, and land management are of particular interest. The information and datasets developed here provide an important baseline and can be used to guide future monitoring and assessments of GDEs.

SYNTHESIS OF VEGETATION ANALYSIS RESULTS AT THE BASIN AND GDE AREA SCALES

Plausibility of GDE Community Extents based on Groundwater Levels

The GDE boundary used in this study and all available measurements of depth to groundwater (DTW) in meters below ground surface were juxtaposed to assess whether observed depths to groundwater are within the range expected to facilitate groundwater discharge via evapotranspiration (Figure 3; see Appendix A for more details). Of the 19 wells within the study area boundary, 12 either were inside of the boundary or within 500 m of its outer edge. Of these 12 wells, 10 had DTW less than 10 m. Field observations found the two wells with DTW values greater than 10 m (13 m and 18 m) were both coincident with dense stands of mesquite. Given the field observations of these deep-rooted GDE communities in the immediate and surrounding areas, and the lack of information regarding the quality of the DTW measurements in question, no changes were made to the GDE boundary because of these two DTW values beyond the
Vegetation Status, Climate Sensitivity, and Trends

LANDFIRE EVT vegetation groups were used to summarize basin-scale remote sensing results within the GDE extent (see Appendix A for detailed methods). Organizing results by group allows the current status, climate sensitivity, and trends of differing GDE types within the study area to be considered independently from one another. While LANDFIRE classifications are imperfect and misclassifications are common (McGwire, 2019; Provencher et al., 2009), parsing the results of various analyses by LANDFIRE group provides a practical means of assessing like systems at the basin-scale.

Vegetation Status

The most recent 10 years (2012-2021) of median annual late-summer (July 15 – Sept. 15) NDVI values were averaged for each pixel within the GDE extent to represent the current status of vegetation vigor. Figure 4 illustrates the ranges of NDVI values occurring within each LANDFIRE group within the study’s GDE boundary and provides context for comparing site-specific NDVI values to other GDE areas of the same vegetation type in the study area. It also provides a baseline NDVI value for each LANDFIRE group that can be used to assess future disturbance and change. Pixels with 10-year average NDVI values that are on the fringes of the distribution may indicate areas of disturbance, ecosystem change, and/or misclassification by LANDFIRE. A spatial understanding of where these pixels fall is useful for targeting field investigation to identify the cause of the anomalous NDVI value observed.

Throughout the study area’s GDE extent, 10-year average late summer NDVI values clearly distinguish most dryland vegetation types from those more mesic in nature. Dryland vegetation groups (Desert Scrub, Grassland, Sparse Vegetation, and Developed upland Shrubland, Salt Desert Scrub and Creosotebush Desert Scrub) were characterized by 10-year average NDVI interquartile ranges almost exclusively falling below 0.3, with the majority below 0.2. The interquartile ranges of the dryland vegetation groups were also generally much smaller than those of the wetland and riparian vegetation groups, though Grassland and Pinion-Juniper Woodland showed much broader ranges than other dryland groups. The Pinion-Juniper Woodland group was particularly unique among the dryland groups in that it followed neither of these patterns and more closely aligned with the wetland/riparian groups. NDVI value ranges for the dryland groups broadly align with expectations, though the somewhat elevated NDVI values of the Grassland and Pinion-Juniper Woodland groups stand out somewhat.

NDVI values for wetland and riparian and wetland vegetation groups (Introduced Riparian Vegetation, Western Herbaceous Wetland, and Western Riparian Woodland and Shrubland) were on average much higher than those observed for dryland groups. Interquartile (25th to 75th percentile) NDVI ranges in these wetland and riparian groups were predominantly above 0.4. These groups were also characterized by much broader interquartile ranges than most dryland groups were. The elevated NDVI values in the riparian and wetland groups align with expectations for these vegetation types.
Figure 3. Surprise Canyon Study Basin 1985 - 2021 Annual NDVI Trend Map.
Figure 4. Vegetation status, as indicated by 2012-2021 average ranges of late-summer NDVI, for select LANDFIRE vegetation types within GDE boundaries. Horizontal lines are shown for NDVI values = 0.2, and 0.35 as references.

Vegetation Sensitivity to Climate

Pearson’s Correlation Coefficient was calculated to evaluate the sensitivity of GDE vegetation vigor (as represented by NDVI) to interannual variations in PWD. This analysis was conducted using the entire 36-year record. Figure 6 illustrates the range of correlation values observed in each LANDFIRE group within the extent of the study area’s GDE boundary. Figure 5 illustrates the spatial distribution of the PWD-NDVI correlation results throughout the study area. The difference in the NDVI-PWD relationships between GDE and non-GDE areas are readily apparent when mapped, with non-GDE areas almost universally showing a moderate to strong response (Pearson’s R > 0.35) to interannual variations in climate. These results further corroborate the plausibility of the GDE boundary used in this study, as vegetation within the boundary are clearly less sensitive to climate, indicating dependence on groundwater.
Figure 5. Surprise Canyon Study Basin 1985 - 2021 NDVI-PWD Correlation (Pearson's R)
Figure 6. Sensitivity of late-summer NDVI to interannual variations in climatic conditions (measured as the Pearson correlation coefficient between annual median July-Sept NDVI and water year PWD) for select LANDFIRE vegetation types within GDE areas.

Within GDE areas, pixels classified as wetland and riparian vegetation groups (groups (Introduced Riparian Vegetation, Western Herbaceous Wetland, and Western Riparian Woodland and Shrubland) were found to have Pearson’s $\rho$ values predominantly falling between -0.15 and 0.15. The interquartile ranges of wetland and riparian vegetation groups illustrate the interannual vigor of these vegetative communities depends very little on interannual variations in PWD. Riparian and wetland group results align with expectations for particularly mesic communities in arid regions, as these communities’ demand for consistently available water suggests their relationship with groundwater is closer to obligate than facultative in nature. Their
very existence in this highly arid environment is a strong indication of groundwater dependence, as precipitation is insufficient in quantity, and surface water is too short lived (unless supported by groundwater discharge), to meet these mesic communities ET demands.

Dryland vegetation types occurring within GDE areas were found to have a wider range of sensitivities to interannual climate than riparian/wetland groups. Several groups exhibited particularly broad interquartile ranges (Creosotebush Desert Scrub, Grassland and to a lesser extent Pinion-Juniper Woodland), indicating that the response of vegetation vigor to PWD varied greatly across different areas within these groups. The most sensitive dryland LANDFIRE groups (e.g., Desert Scrub and the two developed groups) were characterized by relatively narrow interquartile (25th – 75th percentile) ranges of Pearson’s $\rho$ values generally falling between 0.4 and 0.75 (Figure 6). Creosotebush Desert Scrub, Salt Desert Scrub, and Pinion-Juniper Woodland groups were considerably less sensitive to PWD than other dryland groups (interquartile ranges roughly -0.25 – 0.25), and Grassland split the difference with its broader interquartile range (approximately 0 – 0.6, see Figure 6).

Most pixels classified as Creosotebush Desert Scrub and Salt Desert Scrub are in GDE communities on Panamint Valley’s floor. The lower overall sensitivity of NDVI to PWD exhibited by Salt Desert Scrub, and the lower end of Creosotebush Desert Scrub’s range are thought to result from their connection to groundwater from the valley’s basin-fill aquifer. This large unconsolidated groundwater reservoir is expected to exhibit less interannual variability in DTW than smaller and/or higher elevation groundwater systems, resulting in the low correlation measure observed.

Dryland groups showing higher NDVI sensitivity to climatic variability could result from either the lack of a connection to groundwater or from connection to groundwater levels that are highly responsive to PWD. Nearly all of the Desert Scrub, roughly half of the Grassland, and a smaller proportion of the Creosotebush Desert Scrub groups’ pixels are in the upper reaches of the Surprise Canyon GDE area. Field observations found most of the area classified as these groups in upper Surprise Canyon to be dominated by facultative phreatophyte species (e.g., Rabbitbrush). The location of these communities within the small and high elevation Surprise Canyon unconsolidated fill aquifer suggests they may be subjected to highly variable DTW values influenced by interannual PWD. Variable depth to groundwater may drive the variability observed in NDVI, providing a potential explanation for the higher-end of the correlation ranges observed in these three groups.

GDE area pixels classified as Pinion-Juniper Woodland (n = 48) and Grassland (n = 24) are relatively uncommon and are spread sporadically throughout both the valley floor and Surprise Canyon Creek riparian corridor. Field observations from areas classified as either group revealed vegetation not congruent with these groupings, suggesting misclassification by LANDFIRE. Areas classified as Pinion-Juniper Woodland were observed to be dominated by relatively dense mesquite bosque and willow/cottonwood GDEs in the valley and canyon locations, respectively. This misclassification of riparian tree GDEs as Pinion-Juniper Woodland explains the similarity of this group to other riparian groups, in terms of PWD-NDVI correlation and recent NDVI (see Vegetation Status section). Similarly, areas classified as Grassland were
observed to be dominated by facultative phreatophyte shrubs both in Surprise Canyon and in the mesquite bosques on the valley floor. The almost equal split of Grassland pixels between these rather different GDE communities explain the broad range of NDVI-PWD correlation and recent NDVI values (see Vegetation Status section) observed.

**Climate-Adjusted Trends in Vegetation Vigor**

Figure 7 compares climate-adjusted trends for areas outside of the GDE boundary with the those observed across the study area’s GDE extent. NDVI trend slopes for pixels outside the GDE areas were, on average, trending more positively than those in GDE areas (Figure 7). Figure 3 illustrates that contrast between GDE, and non-GDE, area trends is particularly apparent in the higher elevation forest and woodland vegetation areas of the Panamint range. One potential reason for this difference is that GDE areas occur at the lowest points in the watershed or basin and are therefore most likely to aggregate the direct and indirect effects of disturbances such as land use change, groundwater pumping, surface water diversion and capture. Another potential reason for the observed difference is that the greening of higher-elevation forest and woodlands is part of the global greening phenomenon driven by increased concentration of carbon dioxide in the atmosphere (Lu et al., 2016; Zhu et al., 2016). Regardless of the cause, widespread vegetation greening in forests and woodlands is indicative of potentially large-scale changes in water balances. The widespread nature of this phenomenon across the study area has implications in terms of hydrologic regimes in the Mojave ecoregion and deserves careful consideration and future research.

**Climate-Adjusted Trend Slope Distribution**

![Climate-Adjusted Trend Slope Distribution](image)

Figure 7. Distribution of climate-adjusted trends in late-summer NDVI for pixels within non-GDE areas (Hydrographic Area) vs. those in the GDE areas (phreatophyte Area) for the entire study area.
Figure 8 shows the relative percentage of binned climate-adjusted NDVI trend slope values in each LANDFIRE group in the GDE area (i.e., including only pixels within GDE area shown in Figure 3 and not the higher elevation surrounding regions). The resulting distributions show predominantly positive (greening) trend slopes across most GDE area groups. A consistent pattern that emerged across GDE areas within the study area was that riparian and wetland pixels (Introduced Riparian Vegetation, Western Herbaceous Wetland, and Western Riparian Woodland and Shrubland) vegetation types consistently had a greater proportion of larger magnitude trends in both positive and negative directions than did the dryland GDE groups.

Figure 8. GDE Area Climate-adjusted 1985 – 2021 trend slope magnitude and direction by LANDFIRE group for vegetation types within GDE boundaries. Note that positive trends dominate most classes, and a greater proportion of moderate-large magnitude trends are seen in riparian/wetland groups.

A large proportion of the pixels characterized by statistically significant trends within GDE areas are found along the Surprise Canyon Creek WSRC. Trends within these areas are examined in greater detail in the Site-Specific Results section (and expanded on in Appendix C). That said, this result is unsurprising given the riparian corridors propensity for flash floods and the relatively recent changes in land management (i.e., the closure of Surprise Canyon Road). Moreover, mesic areas are inherently prone to larger magnitude trends, as their higher baseline NDVI values result in larger incremental changes in NDVI.
SITE-SPECIFIC RESULTS
Vegetation Status, Climate Sensitivity, and Trends

Field observations revealed evidence of ground compaction of roads, channel erosion and incision, invasive plants (tamarisk), and the presence of burros and grazing (Table 1). Perennial, albeit spatially discontinuous, surface flows were observed through significant portions of the more mesic AOIs along the WSRC, including Upper Brewery Spring, and Upper Limekiln Spring (Table 1). The spatial discontinuity of surface water combined with the absence of recent precipitation or snowpack melt that might generate runoff suggests groundwater discharge was the source of observed surface flows and vegetation vigor is substantially higher in these reaches (Table 2).

Potential water deficit (PWD)-NDVI regression relationships (Table 2) show that AOIs in the upper portion of the canyon, extending from the Brewkiln Reach to the Panamint reach, have late summer NDVI values that are strongly influenced by water year PWD. It is possible that the sensitivity of these reaches to climate variability is a consequence of variability in the local (reach-scale) depth to groundwater but more data are needed to determine whether this is the case. In contrast, the lowermost five AOIs on the river corridor, the valley floor AOIs, and the Upper Panamint Spring AOIs have weak and statistically insignificant (p > 0.05) correlations with climate. NDVI variability tends to be lower in the 2008-2021 period as compared to earlier for all AOIs, which may be explained by less variable precipitation (Figures 9-11). Although several significant floods occurred, the effects of these events on vegetation are not obvious. Increased NDVI was observed in most reaches in 1995 and 2005, both wet years when floods also occurred, but not in 1990 and 2001, when floods occurred during relatively dry years. Overall, increasing trends in NDVI are observed in most reaches, with the most substantial increases occurring at the two uppermost and two lowermost reaches and in the valley floor AOIs. A lack of high precipitation and flooding in recent years could explain this, but data are insufficient to determine if this is the case.
Table 1. Summary of observed impacts based on field observations from April 2022 and 36-year trends in NDVI and PWD (see Table 2). Sites are ordered from upstream to downstream. Green and red shading indicate statistically significant positive and negative trends, respectively. Gray shading indicates non-statistically significant trends (p>0.05).

<table>
<thead>
<tr>
<th>AOI Name</th>
<th>Observed Impacts</th>
<th>Indication of Perennial Flow</th>
<th>NDVI Trend</th>
<th>PWD Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Compaction from Road</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brewery Spring Upper Reach</td>
<td></td>
<td></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Brewery Spring Lower Reach</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Channel Erosion/Incision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brewkiln Reach</td>
<td>X</td>
<td></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Upper Limekiln Spring</td>
<td>X</td>
<td>Suspected, not observed</td>
<td>X</td>
<td>+</td>
</tr>
<tr>
<td>Lower Limekiln Spring</td>
<td>X</td>
<td></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Invasive Plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Surprise Canyon</td>
<td>X</td>
<td></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Grazing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surprise Canyon Narrows</td>
<td>X</td>
<td>Suspected, not observed</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Chris Wicht Reach</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Grazing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLM – Riparian Corridor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post Office Spring</td>
<td></td>
<td>Signs of removal</td>
<td>X</td>
<td>+</td>
</tr>
<tr>
<td>Warm Sulphur Springs</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>BLM – Valley Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indian Ranch Road</td>
<td></td>
<td></td>
<td>X</td>
<td>+</td>
</tr>
<tr>
<td>Mesquite Bosque AOI</td>
<td></td>
<td></td>
<td>X</td>
<td>+</td>
</tr>
</tbody>
</table>
Table 2. Zonal statistics for AOIs, ordered from upstream to downstream. Minimum, maximum, and mean NDVI values are from the annual late summer median NDVI time series. NDVI sensitivity is the Pearson correlation coefficient between NDVI and annual PWD. Climate-adjusted NDVI trend is the Sen’s slope estimate of NDVI residuals (1985 – 2021), accounting for the influence of annual water deficit. Climate trend is the Sen’s slope of water year PWD (1985 – 2021). Blue or red shading indicate statistically significant positive or negative trends or correlation, respectively (p < 0.05).

<table>
<thead>
<tr>
<th>AOI Name</th>
<th>1985-2019 Annual Median July-Sept. NDVI (unitless)</th>
<th>NDVI Sensitivity to Climate</th>
<th>Climate Adjusted NDVI Trend</th>
<th>Climate (PWD) Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.  Mean  Max.  Pearson R (unitless)  p-value  Trend (yr(^{-1}))  p-value  Trend (mm/yr)  p-value</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPS - Riparian Corridor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Panamint City Springs</td>
<td>0.42  0.48  0.54  -0.20  0.26  0.003  0.003  -0.18  0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panamint Reach</td>
<td>0.09  0.15  0.20  0.64  0.00  0.001  0.000  -0.17  0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brewery Spring Upper Reach</td>
<td>0.38  0.41  0.47  0.44  0.01  0.000  0.452  -0.14  0.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brewery Spring Lower Reach</td>
<td>0.17  0.25  0.37  0.43  0.01  -0.004  0.003  -0.14  0.14</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BLM - Riparian Corridor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brewkiln Reach</td>
<td>0.09  0.13  0.21  0.6  0.001  0.000  0.454  -0.14  0.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Limekiln Spring</td>
<td>0.4  0.47  0.52  0.14  0.442  0.002  0.014  -0.14  0.14</td>
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<tr>
<td>Lower Limekiln Spring</td>
<td>0.15  0.2  0.26  0.12  0.513  0.000  0.612  -0.14  0.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Surprise Canyon</td>
<td>0.28  0.33  0.39  0.17  0.339  0.001  0.196  -0.13  0.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surprise Canyon Narrows</td>
<td>0.09  0.18  0.21  0.16  0.407  0.001  0.0  -0.08  0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chris Wicht Reach</td>
<td>0.02  0.06  0.09  0.34  0.159  0.001  0.03  -0.08  0.31</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BLM - Valley Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post Office Spring</td>
<td>0.17  0.23  0.31  -0.15  0.40  0.003  0.001  -0.07  0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm Sulphur Springs</td>
<td>0.17  0.21  0.24  -0.23  0.18  0.001  0.000  -0.07  0.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indian Ranch Road</td>
<td>0.25  0.35  0.44  -0.15  0.38  0.004  0.000  -0.06  0.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesquite Bosque AOI</td>
<td>0.14  0.19  0.28  0.19  0.28  0.000  0.894  -0.05  0.41</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 9. Annual timeseries of late-summer NDVI and water year potential water deficit for NPS areas of interest along Surprise Canyon Creek. Years with known flood events are indicated by vertical lines.

Figure 10. Annual timeseries of late-summer NDVI and water year potential water deficit for BLM areas of interest along Surprise Canyon Creek. Years with known flood events are indicated by vertical lines.
In addition to the natural precipitation and flood variability that occurred during the study period, significant management changes along the WSRC include the road closure in 2001, ongoing tamarisk removal between 2007 and 2010 from Brewery Springs to the Chris Wicht reach, and the removal of a water diversion above Chris Wicht reach. The overlap of natural and management disturbances in space and time makes it challenging to identify causes of observed vegetation changes, but comparing late summer NDVI values between years with similar PWD at a given site has the potential to better isolate the effects of management changes (Hausner et al. 2018). For example, increased vegetation vigor is observed in years with similar PWD for the Chris Wicht after the water diversion (Figure 12) and tamarisk (Figure 13) removals, suggesting that one or both of these management actions may have improved site conditions. In contrast, differences between pre- and post- road closure vegetation vigor are more subtle at most of the WSRC sites (Figure 14). In most cases, pre-and post- values have overlapping confidence intervals, meaning differences are not statistically significant. Some differences are observed pre- and post- tamarisk removal, but these are inconsistent, with lower Limekiln and Lower Brewery springs exhibiting reduced vigor post-tamarisk removal, and Upper Limekiln and Surprise Canyon Narrows exhibiting greater vigor post-tamarisk removal (Figure 13).
Figure 12. Relations between annual late-summer NDVI and potential water deficit for the Chris Wicht reach of Surprise Canyon Creek before and after removal of the upstream water diversion in 2006. Higher NDVI values and a lack of overlap of regression confidence intervals (gray shading) indicate statistically significant increases in vegetation vigor post-removal.

Figure 13. Relations between annual late-summer NDVI and potential water deficit before and after tamarisk removals by the BLM from 2007-2010. Differences in NDVI values and a lack of overlap of regression confidence intervals (gray shading) indicate locations where statistically significant changes in vegetation vigor occurred post-2010, that could be attributed to tamarisk removal, but insufficient data exist to make a final determination on this.
Figure 14. Relations between annual late-summer NDVI and potential water deficit before and after the official road closure in 2001. Differences in NDVI values indicate locations where changes in vegetation vigor occurred post-2001, but these are not statistically significant given the presence of overlapping confidence intervals (gray shading).

ESTIMATED WATER USE OF SURPRISE CANYON WSRC AND SURROUNDING MESQUITE BOSQUE

Table 3 summarizes groundwater evapotranspiration (ET\(_G\)) and overall evapotranspiration (ET) results for the Surprise Canyon Creek WSRC as well as the surrounding mesquite bosque area (Figure 2). Analysis results show that annual ET exceeds water year precipitation in all AOIs, indicating the presence of supplemental water sources. The degree of groundwater dependence varies considerably (accounting for anywhere from 41 – 91% of total ET) among AOIs. Reaches with higher annual ET rates and groundwater fractions (Table 3), including Upper Panamint City Spring, Upper Brewery Spring, and Upper Limekiln Spring are in the immediate vicinity of springs and are characterized by extensive areas of dense riparian vegetation including Fremont cottonwood and various species of willow. Despite relatively modest annual ET and ET\(_G\) rates, the Panamint and Chris Wicht reaches account for large ET volumes due to their size. The median annual total volumes of ET are estimated to be 99.3 and 68 acre-feet (122,510 and 83,755 m\(^3\)) for the NPS and BLM portions, respectively, for a total of 167 acre-feet (206,265 m\(^3\)) for the entire WSRC. ET\(_G\) accounts for 55% and 69% of the total ET
on NPS and BLM portions, respectively, for a median total of 101 AFA (124,928 m³/yr). ET rates in the mesquite bosque are lower than in the WSRC but because the area covered is large, the estimated annual ET volume is 1894 acre-feet (2,335,645 m³) with 60% (1144 acre-feet, 1,410,600 m³) of this contributed by ETG. The interannual variability of ET and ETG volumes was found to be considerable, with greater ET occurring in wetter years. A slight increase in ETG is observed over time, which may be explained by the decreasing trend in PWD and fewer wet years after 2005 and thus a smaller proportion of ET coming from precipitation and a greater reliance of vegetation on groundwater (Figure 15).

Figure 15. Sum of water year annual total evapotranspiration and evapotranspiration supplemented by surface and subsurface water (ETG) across all areas of interest on NPS and BLM lands in the Surprise Canyon Creek corridor and the mesquite bosque.
Table 3. Total (ET) and groundwater-supplemented (ETG) evapotranspiration summary table. Surprise Canyon AOIs are presented ordered from upstream to downstream. Annual minimum, maximum, and median values are based on the 1985 – 2021 dataset. Volumetric sums are provided in acre-feet for the NPS and BLM portions of Surprise Canyon WSRC. Metric values are provided in the geodatabase that accompanies this report.

<table>
<thead>
<tr>
<th>Assessment Area</th>
<th>Median ET Rate (mm)</th>
<th>Median ETG Rate (mm)</th>
<th>Median ETG Fraction</th>
<th>ET Volume (Ac-ft)</th>
<th>ETG Volume (Ac-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOI Name</td>
<td>Area (m²)</td>
<td></td>
<td></td>
<td>Min.</td>
<td>Median</td>
</tr>
<tr>
<td>NPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Panamint City Springs Panamint Reach</td>
<td>22,089</td>
<td>937</td>
<td>728</td>
<td>0.78</td>
<td>14.6</td>
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<tr>
<td>Brewery Spring Upper Reach</td>
<td>228,406</td>
<td>360</td>
<td>156</td>
<td>0.43</td>
<td>31.1</td>
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<tr>
<td>Brewery Spring Lower Reach</td>
<td>13,495</td>
<td>1008</td>
<td>837</td>
<td>0.83</td>
<td>9.8</td>
</tr>
<tr>
<td>Total NPS WSRC</td>
<td></td>
<td>272,916</td>
<td></td>
<td>0.55</td>
<td>59.0</td>
</tr>
<tr>
<td>BLM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brewkiln Reach</td>
<td>25,322</td>
<td>335</td>
<td>172</td>
<td>0.52</td>
<td>4.0</td>
</tr>
<tr>
<td>Upper Limekiln Spring</td>
<td>19,378</td>
<td>1094</td>
<td>1000</td>
<td>0.91</td>
<td>15.6</td>
</tr>
<tr>
<td>Lower Limekiln Spring</td>
<td>6,248</td>
<td>491</td>
<td>351</td>
<td>0.72</td>
<td>1.6</td>
</tr>
<tr>
<td>Central Surprise Canyon</td>
<td>26,492</td>
<td>851</td>
<td>645</td>
<td>0.76</td>
<td>15.4</td>
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<tr>
<td>Surprise Canyon Narrows</td>
<td>18,586</td>
<td>442</td>
<td>334</td>
<td>0.76</td>
<td>3.6</td>
</tr>
<tr>
<td>Christ Wicht Reach</td>
<td>90,187</td>
<td>225</td>
<td>93</td>
<td>0.41</td>
<td>8.2</td>
</tr>
<tr>
<td>Total BLM WSRC</td>
<td></td>
<td>186,213</td>
<td></td>
<td>0.69</td>
<td>53.2</td>
</tr>
<tr>
<td>Total BLM Mesquite Bosque</td>
<td>10,948,500</td>
<td>213</td>
<td>129</td>
<td>0.60</td>
<td>1177.7</td>
</tr>
</tbody>
</table>
SUMMARY OF KEY FINDINGS

Objective 1: Characterize the status, interannual climate relationships, and trends of GDEs throughout the study area.

- Plausibility of GDE Community Extents
  - Groundwater levels and field observations of groundwater supported streamflow suggest the GDE boundary used is a reasonable approximation GDE extent

- Vegetation Status within GDE Extent (10-year average late summer NDVI values)
  - Vegetation status values clearly distinguish most dryland GDE vegetation types from mesic GDEs
  - Dryland GDE results mostly align with expectations (NDVI < 0.2), but high NDVI ranges in Pinion-Juniper Woodland and Grassland LANDFIRE groups stood out and may be due to misclassification by LANDFIRE. Field observations corroborated this hypothesis.
  - Mesic GDE (wetland and riparian) results aligned with expectations (NDVI > 0.3) and provide evidence of the groundwater dependence of these groups

- Vegetation sensitivity to climate
  - The basin-wide spatial distribution of sensitivity values (Figure 5) supports the study’s GDE boundary as vegetation within are less sensitive to climate, suggesting groundwater dependence
  - Within GDE areas, sensitivity was generally lower for mesic GDEs types than it was for dryland GDEs
  - The higher sensitivity observed in dryland GDEs may result from connection to a groundwater system that is highly responsive to interannual variations in precipitation, though other plausible explanations exist

- Climate-Adjusted Trends in Vegetation Vigor
  - NDVI trend data showed non-GDE areas were trending more positively than GDE areas. Increasing water use by upland vegetation and decreasing downgradient water supply for GDE areas provides one possible explanation for the more positive trends observed in non-GDE areas, additional investigation of this is needed.
  - Most GDE areas showed positive climate-adjusted NDVI trends over the study period (1985 – 2021)
  - Riparian and wetland vegetation groups within the GDE area had a greater proportion of larger magnitude trends in both positive and negative directions than did dryland vegetation groups.
Many of the largest magnitude positive trends were observed to be occurring in the Surprise Canyon Creek WSRC and valley floor mesquite bosque areas.

**Objective 2:** Characterize the status, variability, and trends of areas of interest along the BLM portion of Surprise Canyon Creek, and assess the influence that variations in climate, hydrology, disturbance regime, and land management policy have on these systems

- **Site-Specific Vegetation Analysis Results for 10 AOIs along the Surprise Canyon WSRC**
  - Annual NDVI-climate relationships were weak for most AOIs, with the exception of reaches extending from Panamint to the Brewkiln Reach. The strong NDVI-climate relationships observed along this section may result from a local aquifer that is highly responsive to interannual variations in precipitation.
  - Given precipitation variability and overlap between natural and human disturbances over the course of the study period, definitive links between management actions and vegetation response are difficult to make.
    - Within the NPS section, a positive trend in NDVI is observed at Panamint Spring and a negative trend is observed at Lower Brewery Spring, but reasons for these trends are not clear.
    - Within the BLM section, differences in NDVI (both positive and negative) are observed following the 2007-2010 tamarisk removal, but the role of this management action could not be determined from field visits. The Chris Wicht reach exhibits positive changes in vegetation vigor after 2006, which may be due to increased flows following removal of a diversion at Chris Wicht Camp.
    - With the exception of the mesquite bosque AOI, which exhibited negative trends and tree water stress upon the field site visit, all other valley floor AOIs exhibit increases in NDVI over the study period. Reasons for these trends could not be determined.

**Objective 3:** Develop satellite-based estimates of water use by riparian and other groundwater dependent vegetation surrounding the Wild and Scenic River Corridor (WSRC)

- **Site-Specific ET and ETg volumes were calculated for 10 AOIs along the Surprise Canyon WSRC and for the surrounding mesquite bosque (See Figure 1).**
  - Throughout the entire NPS portion of the Surprise Canyon Creek WSRC, groundwater is estimated to support 43 – 82 % of total ET. The amount of ET in the wettest year is more than double that in the driest year, with a median annual volume of 99 acre-ft (See Table 3).
  - Throughout the entire NPS portion of the Surprise Canyon Creek WSRC, groundwater is estimated to support 41 – 91 % of total ET. The amount of ET in the wettest year is almost double that in the driest year, with a median annual volume of 68 acre-ft (See Table 3).
Throughout the entire mesquite bosque, groundwater is estimated to 60% of total ET. The amount of ET in the wettest year is nearly double that in the driest year, with a median annual volume of 1894 acre-ft (See Table 3).

REFERENCES


California Department of Water Resources (CDWR), 2014, Sustainable Groundwater Management Act data viewer, accessed [March 8, 2022], at URL [https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer].

California Department of Water Resources (CDWR). 2022. Natural Communities Commonly Associated with Groundwater (NCCAG) tool. Available at: https://gis.water.ca.gov/app/NCDatasetViewer/


Office of the Federal Register (OFR), National Archives and Records Administration (2001). 66 FR 29163 - Closure Order for Motorized Vehicle Use, Surprise Canyon Area of Critical Environmental Concern BLM Route P71, Panamint Mountains, Inyo County, CA


APPENDIX A – DETAILED METHODS

STUDY AREA

The study area includes five administrative hydrographic drainage basins at the watershed or HUC-10 (Hydrologic Unit Code) scale as defined by the United States Geologic Survey’s (USGS) national Watershed Boundary Dataset (Figure 1). The five basins included in the study area boundary are Fish Canyon-Panamint Valley, Jail Canyon-Warm Sulphur Springs, Surprise Canyon-Panamint Valley, Water Canyon-Panamint Valley, and Wildrose Wash. This extent was used to capture the entirety of the Surprise Canyon Creek WSR corridor and the corridor’s associated catchment area as well as areas within Panamint valley where mesquite bosques are known to exist.

These areas were selected because they are not only places where the GDE communities are of high ecological value, but also because they are believed to be potentially vulnerable to impacts resulting from future development.

DATASETS

To address the study objectives the following publicly available datasets were compiled:

- Reference ET (ET0) and precipitation (PPT) from the gridMET gridded climate dataset (Abatzoglou, 2013)
- Collection 2 Level-1 Landsat archive images available through the Google Earth Engine (GEE) cloud computing and environmental monitoring platform (Gorelick et al., 2017)
- The LANDFIRE Existing Vegetation Type database (U.S. Department of Interior, 2016)
- GDE boundaries for Panamint Valley from the California Department of Water Resources (CDWR) Natural Communities Commonly Associated with Groundwater (NCCAG) dataset (https://gis.water.ca.gov/app/NCDatasetViewer/) (CDWR, 2022)

1) Gridded Climate Data

The daily resolution gridMET gridded (~2.5 miles/4 kilometers) meteorological dataset (Abatzoglou, 2013) was used for all climate analyses. This dataset contains interpolated meteorological data that are informed by weather station observations from more than 40 station networks and local geographic factors that influence spatial variations in climate. This dataset was selected because it is used extensively for ecological and hydrologic assessments, and it contains the variables necessary to calculate the ASCE-EWRI Standardized Penman-Monteith
reference evapotranspiration equation for a well-watered grass reference surface (Allen et al., 2005), including solar radiation, maximum temperature, minimum temperature, average dewpoint temperature, and wind speed at 32.8 feet height (10 meters). Wind speeds were logarithmically transformed to 6.6 feet height (2 meters) following Allen et al. (2005) prior to calculation of reference evapotranspiration. Grass reference evapotranspiration is a measure of atmospheric water demand (Hobbins & Huntington, 2016), and is simply referred to as potential evapotranspiration in this report. For vegetation and site-specific analyses, potential water deficit (precipitation minus potential evapotranspiration) was aggregated by water year within each grid cell and analyzed in conjunction with Landsat data.

2) Landsat Archive Data

The Landsat program provides the longest continuous record of earth observations from space, with satellites capturing 30-m spatial resolution since 1972. Images from the Landsat archive were used to generate metrics such as the normalized difference vegetation index (NDVI; an indicator of vegetation vigor) and the normalized difference water index (NDWI; an indicator of vegetation water content) (Gao, 1996) for the study area. NDVI was the primary metric used for analyses in this report because it is one of the more readily interpretable and widely used vegetation indices, does not require parameter calibration, and has been shown to perform well for quantifying vegetation cover in arid environments (McGwire et al., 2000; Wu, 2014).

Landsat data processing for the study area was performed within the GEE environment, largely following methods outlined in Huntington et al. (2016) and Beamer et al. (2013). This study considered scenes acquired by multiple sensors in the Landsat lineage, as follows:

- Thematic Mapper (TM) scenes obtained between 1985 and 2012
- Enhanced Thematic Mapper Plus (ETM+) scenes obtained between 1999 to 2019
- Operational Land Imager (OLI) scenes obtained between 2013 – 2021

Scenes of at-surface reflectance from each of these platforms were obtained from the USGS’s Collection 2 Level-1 dataset. The Collection 2 dataset is comprised of known quality images suitable for pixel-scale time series analysis (Masek, 2020) and corrected to at surface reflectance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Landsat TM, ETM+) and the Landsat Surface Reflectance Code (LaSRC) (Landsat OLI), respectively (Masek et al., 2006; Vermote et al., 2016).

The Landsat archive dataset was narrowed to scenes acquired between Julian days 196 and 258 (June 1st - September 15th, non-leap year) for any given year. This late summer period is optimal for assessing the relationship between vegetation vigor and the interannual availability of groundwater since precipitation and soil moisture is typically at a minimum during that time period in this region (Huntington et al., 2016). This annual period of little to no precipitation combined with abundant solar energy results in a strong contrast in the phenotypic expression of phreatophytic and other GDE vegetation types when compared to xerophytic vegetation lacking
access to groundwater (Groeneveld et al., 2007; Smith et al., 2007; Allander et al., 2009; Garcia et al., 2015).

Image pixels with clouds, shadows, or other sources of atmospheric interference were automatically flagged as using the “PIXEL_QA” quality assessment (QA) band. This QA band is built-in during Landsat Collection 2 scene processing, and all pixels identified as potentially impacted were removed from the analysis. Other variables such as enhanced vegetation index (EVI), NDWI, albedo, surface temperature, and more were used to assist in quality assurance and quality control (QA/QC) of the NDVI time series.

Following spatiotemporal filtering and scene QA, NDVI was computed for all mid to late summer, cross sensor calibrated, Landsat Collection 2 at surface reflectance products as:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$ [1]

The NDVI (and NDWI) images were statistically analyzed to generate a single image per year, representative of that year of phreatophyte vegetation vigor for the mid to late summer target period. To accomplish this, the median NDVI value for a given pixel-year combination was calculated and subsequently aggregated for all pixels into a single scene.

3) GDE Area Boundaries

Many of the vegetation communities within the study basins are comprised of phreatophytes, or plants that rely on shallow groundwater for some of their water requirements. Understanding the extent, composition, and status of phreatophyte vegetation communities is important for effective monitoring and management of these GDEs. Potential GDE area boundaries for the study area basins were obtained from a statewide Natural Communities Commonly Associated with Groundwater (NCCAG) Dataset (CDWR, 2022). The NCCAG dataset is the result of compiling several pre-existing large-scale vegetation and wetland mapping efforts. The resulting compiled dataset was subjected to a QA screening process to remove vegetative communities not commonly associated with groundwater and to determine if the species mapped was likely to act as a phreatophyte in the ecoregion in question. Additional screening was conducted to eliminate areas located on hillslopes and other topographic features where the vegetation would be more likely to rely on precipitation, surface runoff, or other non-groundwater sources.

Potential GDE boundaries obtained from the NCCAG dataset were combined with polygons representing the riparian corridor coincident with the Surprise Canyon Creek WSRC. The Surprise Canyon-specific polygons were adapted from shapefiles received from the BLM in order to cover the entirety of the potential GDE area along the WSRC. The Surprise Canyon-specific polygons were combined with the NCCAG to achieve the final potential GDE boundaries. These boundaries are used in the current study to assess status, trends, and climate sensitivities specific to the phreatophyte area, and to guide field investigations toward groundwater influenced areas where substantial changes in vegetation appear to have occurred.
4) LANDFIRE Existing Vegetation Type Database

The LANDFIRE Existing Vegetation Type Database (Remap/LF 2.0.0. version https://www.landfire.gov/viewer/) was selected to represent different vegetation communities and land uses in the study area so that comparisons in status and trends could be inferred for specific wetland, phreatophytic, and upland vegetation types. These classifications represent vegetation conditions in the year 2016 (the most recent available). We selected 12 vegetation types based on the “Group” level of aggregation. These included the most common natural vegetation types\(^1\) that occurred within the GDE boundary, including:

- Three wetland/riparian groups (Introduced Riparian Vegetation, Western Herbaceous Wetland, and Western Riparian Woodland and Shrubland)
- Two groups composed of predominantly facultative phreatophyte species (Creosotebush Desert Scrub and Sparse Vegetation)
- Four groups composed of predominantly upland species (Pinyon-Juniper Woodland, Grassland, Desert Scrub, Salt Desert Scrub),
- Two groups classified as developed (Developed-Roads, Developed-Upland Shrubland)
- One low intensity agricultural type (Agricultural-Pasture and Haylands) that is common in phreatophyte areas within the state and has the potential to provide functional mesic habitat for wildlife species (Donnelly et al., 2016).

Though a number of these groups suggest little to no dependence on groundwater, they were included due to their location within the study area GDE boundaries.

5) Groundwater Level Databases

Readily available groundwater level data for the study areas were obtained from the USGS National Water Information System database (USGS, 2016) and CDWR SGMA (CDWR, 2014) groundwater level databases. All available groundwater level measurements through March 8\(^{th}\), 2022 (the time at which the data were downloaded) were acquired and subjected to a simple QA process to eliminate spurious measurements. The groundwater level data compiled may not include all groundwater data for the Panamint Valley area, as additional measurements may exist that are not part of the publicly available USGS and CDWR databases.

Water elevation measurements obtained from CDWR and USGS were found for 19 wells in the study area (n = 29). Despite the number of wells, the groundwater level dataset is sparse and only one well in the study area was found to have more than a single measurement through the entire record. Groundwater level measurements at all but this one well were insufficient in quantity to allow for any meaningful statistical analyses to be conducted within the period of the Landsat archive (1985-2021). The final measurement from the lone well record with enough measurements to allow for the computation of Sen’s slope and the Mann Kendall trend test was observed mere months before the start of the Landsat archive. The timing of the record and the

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\(^1\) Links to vegetation type descriptions are provided for the most common Ecological System Type within each LANDFIRE Group-level classification.
lack of a significant slope ($p < 0.05$) in the dataset preclude analysis of the relationship between groundwater elevation trends and vegetation vigor in the area. Nonetheless, the dataset acquired was helpful for verifying that depths to groundwater surrounding potential GDE boundaries were in the range expected to support groundwater ET from GDEs (see Appendix A for more details).

**Basin-Scale GDE Vegetation Analytical Approach**

Basin-scale analyses included assessing 1) the spatial extent of the GDE boundary derived from the NCCAG dataset for the plausibility groundwater discharge using the limited groundwater dataset compiled for this study, and 2) the current status, climate sensitivity, and long-term trends of GDE vegetation within the GDE boundary using three quantitative approaches based on late summer NDVI and climatic (GridMET) data.

**Plausibility of GDE Community Extents based on Groundwater Levels**

A limited dataset of groundwater levels was obtained from the USGS and CDWR groundwater level databases (see Datasets section). While the compiled dataset lacked adequate repeat measurements for meaningful statistical analysis of groundwater elevation trends in the area, the static measurements were used to help assess the plausibility of the extent of the GDE area used in this study. Other than the Surprise Canyon Riparian Corridor, the GDE extent used in this study was derived entirely from the NCCAG Dataset (see Datasets section). This statewide dataset represents the most robust available representation of the extent of GDE communities in the study area. That said, the inherent coarseness of a dataset of its size suggests erroneous inclusions or omissions are possible. Therefore, available depth to groundwater data was used to examine whether the boundaries presented by the NCAAG are reasonable.

GDE communities in the study area are understood to be either facultatively or obligately sustained by varying depths of water table depending on their composition. The rooting depths of Honey mesquite (*Prosopis glandulosa*) and Creosote Bush, two common GDE species within the study basin, were used to determine a functional cutoff depth beyond which groundwater ET is unlikely. Mesquite tap roots have been found at depths of up to 53 m, though their roots more commonly likely do not extend much more than 14 m (Uchytil, 1990). While Creosote Bush, which was observed to be widespread throughout the study area, is not commonly labeled as a phreatophyte it’s tap roots have been documented to commonly reach depths as great as 5 m (Gardea-Torresdey et al., 2001) with anecdotal reports of creosote tap roots reaching much deeper still (25+ m). This deep taproot, and the plants penchant for securing water from multiple sources (e.g., precipitation, runoff infiltration, capillary fringe) render it a facultative phreatophyte for the purposes of this study. Considering both species depth ranges, a depth to groundwater of threshold of $> 10$ m was adopted as a functional cutoff beyond which an areas inclusion in the GDE boundary warrants additional scrutiny.

**Vegetation Status, Climate Sensitivity, and Trends**

**Vegetation Status**

The current status of GDE vegetation groups within the study area was quantified as the average of the most recent 10 years (2012-2021) of the annual late summer NDVI dataset.
Averaging over the most recent decade of available data results in a per-pixel value that is representative of recent conditions while remaining minimally influenced by any single year (interannual variation in climate can result in anomalous NDVI values from year-to-year). Calculation of the current status of GDE vegetation allows for evaluation of past and future changes in vegetation vigor relative to the current status.

NDVI values vary from -1 to 1 according to the spectral characteristics of the pixel. The spectral reflectance of pixels varies depending on the spectral absorbance and areal extents of vegetation canopy, water, and soil, and more. Table 1 summarizes general ranges of NDVI values that are typical for broad landcover types within the Mojave ecoregion. Studies in other arid and semiarid regions of the Western United States have used NDVI thresholds as high as 0.3 to differentiate riparian vegetation from shrublands (Albano et al., 2019; Albano et al., 2021), but the areas analyzed in these were higher in elevation and less arid than the current study area. A NDVI threshold of 0.2 was adopted to differentiate riparian vegetation from less mesic types for this study as this lower threshold has proven accuracy in similar environments (Jones et al., 2008; McGwire, 2019).

NDVI values can provide a first approximation of the vegetation vigor, but ultimately the vegetation vigor depends on several factors beyond water availability. For example, the time of year, color and condition of vegetation and soils, presence of water, the proportion of the pixel that is covered by the vegetation type, as well as many other factors. Within the arid Mojave, pixels with late-summer NDVI values that are outside the range expected for each vegetation type or that are outliers relative to the range of values observed for pixels within a given vegetation type could be a result of misclassification by LANDFIRE. Alternatively, these outliers could indicate places where disturbance (anthropogenic impacts, non-native species invasion, etc.) may have occurred and impacted the observed NDVI value. These observations may be useful for putting site-specific results in context, targeting field investigations and/or identifying areas for more detailed study.

Table A-1. NDVI value ranges typical of broad landcover types within the Mojave ecoregion. Threshold values are based on: 1) Albano et al., 2021; 2) Albano et al., 2020; McGwire, 2019; 4) Jones et al., 2008

<table>
<thead>
<tr>
<th>NDVI Range</th>
<th>Landcover Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.0 – 0.0</td>
<td>Water (clouds, snow, surface water)$^1$</td>
</tr>
<tr>
<td>0.0 – 0.19</td>
<td>Low vegetation/high soil cover (desert scrublands and shrublands)$^{1,2}$</td>
</tr>
<tr>
<td>0.20 – 0.59</td>
<td>Mesic vegetation types in desert regions (mesquite bosques, riparian corridors, etc.)$^{3,4}$</td>
</tr>
<tr>
<td>&gt; 0.6</td>
<td>Dense, green, and healthy vegetation (forest or very dense agriculture)$^1$</td>
</tr>
</tbody>
</table>
Vegetation Sensitivity to Climate

The sensitivity of GDE vegetation vigor to interannual variations in climate was quantified using Pearson’s correlation coefficient as a measure of the correlation between annual late summer NDVI and water year potential water deficit (PWD). PWD is calculated as:

\[ PWD = PPT - ET_0 \]  

Where PPT is northern water year total precipitation (mm/year), and \( ET_0 \) is annual potential evapotranspiration (mm/year). The entire 36-year late summer NDVI record and associated PWD for each year within the NDVI series was considered on a pixel-wise basis. Correlations were summarized for the 12 LANDFIRE vegetation types that occurred within the GDE boundary to identify which vegetation types most strongly depend on water sources derived from near-term precipitation. Pixels and vegetation types with larger magnitude correlation coefficients indicate higher sensitivities to (i.e., greater change in response to) interannual variations in PWD. In general, areas deriving their water from precipitation are expected to exhibit higher climate sensitivity (correlation nearer to 1). More mesic areas with more consistent water availability due to consistent connections with ground or surface water are expected to be less sensitive (correlation nearer to 0), but sensitivity also varies according to adaptations and characteristics of component plant species.

Areas with high sensitivity to climate tend to exhibit highly variable vegetation cover and/or vigor from year to year in response to climate variations. This sensitivity to climate should be taken into consideration when evaluating data collected in field assessments among years. High sensitivity could result from the lack of a strong connection to groundwater (and therefore strong dependence on precipitation) or could result from vegetation water use from a groundwater table that is highly sensitive to precipitation variability. Areas with low sensitivity to climate can result from several factors, including:

- Persistent water availability due to ground or surface water influences resulting in little fluctuation in cover and/or vigor among years
- The presence of surface water (which results in low NDVI) that obscures an otherwise positive NDVI response of vegetation to wet-year conditions
- Disturbance due to non-climate related factors

In this latter case, if an area is disturbed, trending over time, or is heavily managed, the NDVI relation to climate becomes obscured by whatever non-climate factors are influencing changes in NDVI.

Quantifying sensitivity of vegetation to climate is useful because changes in sensitivity over time relative to the historical baseline may indicate changes in species composition, water availability, or disturbance. That said, because causes of a change in sensitivity can be inconclusive, this metric is best interpreted in combination with other metrics. For example, quantifying and accounting for the variation in vegetation vigor attributable to variations in climate helps to clarify the role of other, non-climate factors as determinants of vegetation status and trends (see next section).
**Climate-adjusted Vegetation Vigor Trends**

Trends in vegetation vigor adjusted for the effects of climate (i.e., PWD) are evaluated to identify and characterize vigor changes that are likely attributable to factors other than climate variability. The climate-adjusted trends metric was calculated using the Adjusted Kendall approach described in Alley (1988) and Section 12.3 in Helsel & Hirsch (2002). PWD was calculated for each water year, and an ordinary least-squares linear regression analysis between PWD and annual late summer NDVI values over the 1985-2021 time period was conducted for each pixel.

Sen’s non-parametric slope estimator method (Sen, 1968) was then applied to NDVI regression residuals (observed NDVI minus predicted NDVI) to estimate the monotonic trend of climate-adjusted vegetation vigor over time for each pixel. By assessing the trend in NDVI residuals, interannual variations in NDVI associated with interannual variations in potential water deficit are removed. The resultant climate-adjusted NDVI trends indicate the direction and magnitude of change in vegetation vigor over time that are due to factors other than interannual variations in potential water deficit. This approach allows for the identification of areas of vegetation change due to system disturbance, which in turn helps to guide field investigations and identify potential causes of the observed change.

Climate-adjusted NDVI trends were summarized for pixels within phreatophyte areas and by the 12 LANDFIRE vegetation types. Large proportions of pixels with large positive or negative changes for a given vegetation type may correlate to changes in plant or animal species of concern. Unlike other vegetation analyses that were limited to phreatophyte areas, climate-adjusted NDVI trends were quantified across the entire study basin. Trends of climate-adjusted NDVI in the uplands may provide important context related to changes in watershed condition and water use that have the potential to affect down gradient GDEs. Comparisons in trends were made between pixels grouped in phreatophyte and non-phreatophyte areas and among land ownerships. Due to the very large sample sizes (10s of thousands of pixels) all group differences in means (as tested by ANOVA) were statistically significant with p-values less than 0.001. A raster dataset of the climate-adjusted NDVI trends for each hydrographic basin is included in the database that was prepared for this report.

**SITE-SPECIFIC AREAS OF INTEREST (AOIs) ANALYTICAL APPROACH**

Landsat and climate data summaries and field investigations were conducted for discrete areas of interest (AOIs) along the Surprise Canyon Creek riparian corridor. These AOIs were collaboratively identified with US BLM staff and were deliberately delineated to cover the entirety of the Surprise Canyon Creek Wild and Scenic River Corridor (WSRC). In total, 10 AOIs were delineated along the Surprise Canyon Creek WSRC. The name, order of the AOI along the creek, and the area of each AOI along the Surprise Canyon Creek WSRC are summarized in table 2 and illustrated in Figure 2. Targeted site-specific analyses were conducted for each of the AOIs to gain greater insights into historical changes than could be obtained by analyzing changes at the scale of the entire study basin (i.e., the scale of analyses described in
previous sections). These targeted analyses largely parallel those conducted at the basin scale, with the exception of the ET/ETG analysis.

Landsat and Climate Data Summaries

For each AOI, spatial averages of annual gridded climate and late summer NDVI were compiled and used to calculate vegetation vigor metrics of status, sensitivity, and climate-adjusted trend based on the same methods described above. Other selected vegetation index metrics (e.g., Normalized Difference Water Index; NDWI; Gao, 1996) were also calculated. Annual time series figures of late summer NDVI and PWD were generated to provide a detailed view of the interannual variability and long-term change for each AOI.

Table 2 summarizes each of these metrics through the entire 36-year dataset for the 6 AOIs along the BLM portion of the Surprise Canyon Creek WSRC. For each AOI, Table 2 provides:

- Minimum, maximum, and mean late summer NDVI
- The strength and direction of the linear relationship between late summer NDVI and PWD (as measured by Pearson’s correlation coefficient)
- Climate-adjusted NDVI trend slope
- PWD trend slope

The statistical significance (p < 0.05) of NDVI-PWD correlations, NDVI trends, and PWD trends are shown with blue and red highlighting depending on whether the measure of slope or correlation was found to be positive or negative. P-values for climate-adjusted trends in vegetation vigor were based on the Mann-Kendall trend test modified to account for up to three-years of serial autocorrelation (Hamed & Rao, 1998).

GDE Evapotranspiration

The groundwater evapotranspiration (ETG) and overall evapotranspiration (ET) analysis performed for the current study followed the latest estimation methods available (Minor, 2019). The methods are an extension of the work completed by Beamer et al. (2013) by expanding and updating each of the datasets used in deriving the regression-based empirical model linking ET and ETG to NDVI. Minor’s approach used additional micrometeorological site-years (a total of 54 site-years across 36 station locations) and an expanded set of remotely sensed images to calculate representative annual NDVI values. Rather than using single midsummer Landsat scene in the calculation of NDVI, Minor (2019) considered all cloud-free, high quality, mid to late summer Landsat scenes. Additionally, each image in this set of Landsat images was sourced from the standardized Landsat Collection 2 dataset. Beamer (2013) used images atmospherically and radiometrically corrected following Allen et al. (2007) and Tasumi et al. (2008), a method not widely applied since the release of Landsat collections 1 and 2. The Collection 2 dataset is comprised of known quality images suitable for pixel-scale time series analysis (Masek, 2020) and corrected to at surface reflectance using the Landsat Ecosystem Disturbance Adaptive
Processing System (LEDAPS) (Landsat TM, ETM+) and the Landsat Surface Reflectance Code (LaSRC) (Landsat OLI), respectively (Masek et al., 2006; Vermote et al., 2016).

Minor (2019) extended the work of Groeneveld et al. (2007), and Beamer et al. (2013). All three studies used a normalization approach to allow for the relationships established between vegetation indices and ET to be transferrable through space and time. Normalized evapotranspiration (ET*) for each site year was calculated following Groeneveld et al. (2007) as:

\[
ET^* = \frac{(ET_a - PPT)}{(ET_0 - PPT)}
\]  

Where \( ET_a \) is water year ET measured by a micrometeorological station, \( ET^* \) is normalized \( ET_a \), \( ET_0 \) is water year reference ET. 

After establishing a new regression model derived from the available datasets, Minor verified the accuracy of the approach with GRIDMET gridded climate data (Abatzoglou, 2013) in place of in-situ micrometeorological station-based estimates of water year precipitation and ETo totals (Minor, 2019). Replacing costly in-situ measurements with publicly available gridded datasets allowed for the application of this method to areas across the Western United States.

Discharge by ET and ET\(_G\) was estimated for the BLM portion of the Surprise Canyon Creek WSRC area on an annual basis from 1985 to 2021 with the NDVI-based approach of Minor (2019). Minor’s approach relies on combining NDVI with water year precipitation and ETo totals to normalize ET as ET*.

This analysis considered scenes acquired by multiple sensors in the Landsat lineage, that were temporally filtered to limit scenes to the date range considered most representative for characterizing peak growing season health and vigor of phreatophyte vegetation in the Great Basin (Groeneveld et al., 2007; Smith et al., 2007; Allander et al., 2009; Garcia et al., 2015) (see Datasets section for additional detail).

NDVI was computed for all mid to late summer Landsat Collection 2 at surface reflectance following equation 2 (see Datasets section for additional details). The NDVI images were statistically analyzed to generate a single image per year, representative of that year of phreatophyte vegetation vigor for the mid to late summer target period. To accomplish this, the median NDVI value for a given pixel-year combination was calculated and subsequently aggregated for all pixels into a single scene. Normalized ET was estimated from this single representative median image on a pixel-wise basis following Minor (2019) as:

\[
ET^* = \beta_0 + \beta_1 NDVI
\]  

Where NDVI is a given pixel-year combination’s representative mid to late summer NDIV value, and \( \beta_0 \) and \( \beta_1 \) are regression coefficients with values of -0.035 and 1.1277, respectively (Figure, A-1, Table A-2). Coefficients for upper and lower 90 percentile confidence intervals of ET* for the Minor (2019) approach are listed in Table A-2. Note that the confidence interval (CI) indicates the confidence in mean ET* and the prediction interval (PI) indicates the confidence for
the NDVI and ET* measurement pair to be within a given specified interval, at the 90 percent level of significance.

Table A-2. β-coefficients for estimating ET* from NDVI, 90% confidence interval (CI), and 90% prediction interval (PI). Modified from Minor (2019).

<table>
<thead>
<tr>
<th>Equation</th>
<th>β₀</th>
<th>β₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear (model)</td>
<td>-0.035</td>
<td>1.1277</td>
</tr>
<tr>
<td>Lower 90% CI band</td>
<td>-0.0469</td>
<td>1.0733</td>
</tr>
<tr>
<td>Upper 90% CI band</td>
<td>-0.0231</td>
<td>1.1822</td>
</tr>
<tr>
<td>Lower 90% PI band</td>
<td>-0.1667</td>
<td>1.1118</td>
</tr>
<tr>
<td>Upper 90% PI band</td>
<td>0.0967</td>
<td>1.1437</td>
</tr>
</tbody>
</table>

Figure A-1. NDVI – ET* plot with upper/lower 90% confidence and prediction intervals. Modified from Minor (2019).

ET is estimated on a pixel-wise basis each year by rearranging Equation 3 above, following Groeneveld et al. (2007):

\[
ET = (ET_0 - PPT)ET^* + PPT \quad [5]
\]
Where ET is the estimated evapotranspiration rate, \( ET_0 \) is water year reference evapotranspiration, and PPT is water year precipitation. Subtracting annual precipitation from both sides of the equation gives:

\[ ET_G = (ET_0 - PPT)ET^* \]  \[6\]

Where \( ET_G \) is the estimated groundwater evapotranspiration rate (assumed to be equal to the difference between annual ET and precipitation). To ascertain volumetric estimates of groundwater ET, spatially averaged \( ET_G \) rates can be multiplied by AOI or GDE discharge areas. The total volume of water and groundwater evapotranspired within the AOIs presented in this preliminary report are summarized at the end of the site-specific results section.

The total volumes of water and groundwater discharged via ET and \( ET_G \) respectively presented in the site-specific results section are derived from the entire 36-year ET/\( ET_G \) dataset. The median of each AOI’s ET/\( ET_G \) time series was selected such that a single value reflecting the average conditions over the entire period considered resulted. This approach helps to prevent a single anomalously wet season, or any other temporally limited phenomenon that might impact the results of the Minor (2019) method, from skewing the results.

**Field Investigations**

Field investigations were conducted to document the type and condition of vegetation within each AOI to support interpretation of satellite and climate data, and to establish baseline information for future evaluations. Field investigations were conducted between April 19\(^{th}\) – 21\(^{st}\), 2021. At each site, one or more transects of approximately 100 meters\(^2\) were delineated. Five ground photographs were taken by the surveyors (one in each of the cardinal directions and one facing the ground) at each of four points (0 m, 25 m, 75 m, and 100 m) along the transect. Categorical estimates of percent cover were made at the same four points using the line-transect method (Smith, 1974) for each of the following cover types: 1) greasewood, rabbitbrush, sagebrush, creosote brush 2) riparian trees (cottonwood, willow, wood’s rose, mesquite), 3) bulrush-cattail marsh, 4) graminoids, 5) non-native tree species, non-native noxious species, other species that may affect the greenness signal, 6) open water, 7) bare ground, and 8) cow pies within 16 feet on either side of the transect. A qualitative ranking of water stress was applied to the first four categories (i.e., greasewood, rabbitbrush, sagebrush, riparian trees) based on stem mortality (less than 15% stem mortality = low, 15-49% = intermediate, greater than 49% = high). Additional site observations documenting disturbance or stress were also recorded.
APPENDIX B – AOI VEGETATION AND CLIMATE TIMESERIES, TREND MAPS, AND FIELD IMAGES

The following sections present the following information for each AOI 1) annual timeseries of late-summer NDVI and water year potential water deficit for each AOI with overlays of known flood events and management interventions, and 2) Map of the AOI showing spatially explicit climate-adjusted trends in NDVI (See Appendix A for methods), 3) narrative site descriptions for the AOIs along the BLM portion of the river corridor, and 4) photographs and imagery captured from field site visits. Note that field visits did not include the upper NPS River Corridor AOIs.
NPS RIVER CORRIDOR AOIs

Upper Panamint Spring

Upper_Panamint_Spring_NPS

- **NDVI**
- Potential Water Deficit (PPT-ET0, mm)

Year

Value

- Flood
- Tamarisk Removal Begins

Map showing:
- Upper Panamint Springs City AOI
- USGS Site no. 36071511706301
- USGS Site no. 36071511705201

Legend:
- Spring Locations
- Elevation Contour - 100 ft Interval
- Elevation Contour - 200 ft Interval
- Areas of Interest (AOIs)
  - BLM
  - NPS
  - Upper Panamint City Springs AOI
- Climate Adjusted NDVI Trend (unitsless/year)
  - High: 0.005
  - Low: -0.005

51
Panamint Reach

Panamint Reach NPS

Year

Value

NDVI

Potential Water Deficit (PPT-ETo, mm)

Flood

Tamarisk Removal Begins

Panamint Reach AOI

Brewery Spring

UCGS Site no.
35071511760101

Spring Locations

Elevation Contour - 100 ft Interval

Elevation Contour - 500 ft Interval

Death Valley National Park

Areas of Interest (AOIs)

BLM

NPS

Panamint Reach AOI

Climate Adjusted NDVI Trend (unitless / year)

High : 0.005

Low : -0.005
Brewery Spring Upper Reach
0 m; North—Facing (slight positive trend)

25 m; West—Facing (negative trend)

80 m; West—Facing (negative trend)

<table>
<thead>
<tr>
<th>Transect Field</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95% riparian trees. No stress/mortality observed</td>
</tr>
</tbody>
</table>
BLM RIVER CORRIDOR AOIS

Brewkiln Reach

The Brewkiln Reach AOI is a NE-SW oriented, low-gradient, intermittent drainage and is the highest elevation reach of Surprise Canyon Creek WSRC on BLM land. This reach spans from the border of Death Valley National Park (downgradient of Brewery Spring) to just upgradient of Limekiln Spring and covers the riparian corridor and flood plain area of the relatively narrow canyon. The Brewkiln Reach AOI covers a portion of the Surprise Canyon Creek that field observations suggest is intermittent in nature. Vegetation in the AOI was observed to be almost entirely comprised of upland varieties, with Rabbitbrush being the dominant species and overall vegetative cover being somewhat low (< 30%). There was clear evidence of channel incision, and field observations suggest that this may be in part a consequence of the now closed Surprise Canyon Road (remnant compacted road surface was observed adjacent to incised channel in areas). The vegetation observed within the AOI was mostly consistent with the LANDFIRE classifications of Desert Scrub, Creosotebush Desert Scrub, and Sparse Vegetation. The relatively small area and high elevation of the catchment upgradient of the Brewkiln Reach AOI may result in large interannual swings in groundwater recharge. When combined with the potentially limited storage capacity of the reach’s local groundwater system (likely restricted to shallow unconsolidated sediments along the relatively narrow canyon) this variable recharge volume may result in large interannual swings in groundwater depth/elevation and NDVI (see Table 1 and Appendix C).
Limekiln Spring Upper Reach

The Upper Limekiln Spring Reach AOI stands out from other portions of Surprise Canyon Creek in several ways, not the least of which is the prolific discharge of Limekiln Spring. Surprise Canyon Creek takes a sharp turn to the north along this relatively short but lush reach, likely due to a geologic structure running roughly perpendicular to the overall path of the Creek. The perennial Limekiln Spring appears on a hillside well above the established stream channel approximately halfway through the AOI. This spring discharge supports a lush area of riparian vegetation from its point of eminence on down towards the stream channel. A sharp transition from upland to similarly dense riparian vegetation occurs at the upgradient end of the AOI along the main channel and throughout the floodplain area. This dense riparian vegetation continues along the channel corridor and extends to the terminus of the AOI, about 100 m beyond the intersection of the spring and channel riparian areas.

Streamflow through Upper Limekiln Spring Reach AOI is thought to be perennial through most of, if not the entire, AOI. Significant overland flow was observed in numerous small channels running from the springhead towards the channel. No observations of overland flow in the main channel were made given the density of the vegetation, though the vegetation type suggests a perennial water source. Vegetation in the AOI was observed to be almost entirely riparian in nature, with various willow species and Desert Wild Grape being the dominant species. Overall vegetative cover was rather high (>90%). The density of the vegetation largely obscured the stream channel, but observations of channel incision immediately up- and down-gradient of the AOI suggests that this area is likely impacted as well. As with the Brewkiln reach, this is likely consequence of the now closed Surprise Canyon Road (remnant compacted road surface was observed adjacent to incised channel up- and down-gradient of AOI).
Limekiln Spring - Upper Reach

0 m, East—Facing (negative and positive trend)

25 m, North—Facing (positive trend)

100 m, South—Facing (positive trend)

LK 20-01: AOI

Transect Field Notes
15% desert Baccharis, 30% riparian trees, 15% sage, dominant cover is graminoids
**Limekiln Spring Lower Reach**

Lower Limekiln Spring Reach AOI starts at the downgradient edge of Upper Limekiln Spring AOI and extends roughly 250 m in a E-W direction. Unlike Upper Limekiln Spring AOI, the lower reach is characterized by predominantly upland vegetation. Field observations suggest Creosote Bush is the dominant species and total vegetative coverage is considerably lower than the preceding reach (~ 30%). At the upgradient end of the reach significant mortality of small riparian trees was observed. Whether this mortality was due to tamarisk removal efforts or another cause requires additional investigation. No overland flow was observed through the Lower Limekiln Spring AOI, nor did there appear to be any recent signs of surface water expression. The stream channel through this reach was nearly universally severely incised, though through the middle of the reach the lower gradient appeared to result in less severe incision. Like the preceding reaches, this channel incision is thought to be a consequence of the now closed Surprise Canyon Road in conjunction with naturally albeit infrequently occurring flash floods through the Surprise Canyon Creek hydrologic system.

![Graph: Limekiln_Spring_Lower_Reach](image)
Limekiln Spring - Lower Reach

25 m; East—Facing
(negative and positive trend)

75 m; West—Facing
(negative trend)

100 m; North—Facing
(positive trend)

<table>
<thead>
<tr>
<th>Transect Field</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LK 20-02: AOI</td>
<td>30% desert Baccharis and greasewood with intermediate mortality/stress 5% riparian trees. Cheatgrass observed. 30% bare ground</td>
</tr>
</tbody>
</table>
Central Surprise Canyon Reach

Central Surprise Canyon Reach AOI is a roughly E-W oriented, low-gradient portion of Surprise Canyon Creek. Central Surprise Canyon Reach extends from the downgradient edge of Lower Limekiln Spring Reach AOI to the upgradient edge of the Surprise Canyon Narrows Reach. This AOI covers the riparian corridor and floodplain area of the canyon bottom at over 800 m in length is one of the larger AOIs within the Surprise Canyon Creek WSRC. Field observations suggest streamflow through most of this reach is intermittent, though dense riparian trees towards the downgradient end obscured views of the main channel. Vegetation in the AOI was observed to be relatively dense throughout (75%+ cover), with a spatially segregated but near equal area mixture of upland (phreatophyte) shrub species and riparian trees and shrubs. Rabbitbrush and a mixture of various willow and cottonwood shrubs and trees appeared to be the dominant species in the upland and riparian vegetation areas, respectively. As with the upgradient reaches, there was clear evidence of channel incision to varying degrees throughout the AOI, and remnant portions of the compacted road surface were observed. LANDFIRE appeared to struggle in terms of accurately classifying vegetation within the AOI. The three most common groups within the AOI were Creosotebush Desert Scrub, Pinion-Juniper Woodland, and Chaparral, despite the presence of the relatively dense and mesic riparian vegetation observed to be covering much of the area. The narrow width of the riparian corridor and steep canyon walls likely render this AOI a particularly difficult location for a coarse dataset like LANDFIRE EVT to accurately classify.
Central Surprise Canyon Reach

0 m, North—Facing (negative trend)

25 m, East—Facing (negative trend)

80 m, South—Facing (negative trend)

SC 19-01: AOI

<table>
<thead>
<tr>
<th>Transect Field</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>65% sagebrush/rabbitbrush, intermediate stress/mortality</td>
</tr>
</tbody>
</table>

0m 10m 20m 30m

0m 55m 25m 0m
**Surprise Canyon Narrows Reach**

The Surprise Canyon Narrows AOI differs from other reaches within Surprise Canyon Creek in several ways, the most notable being its unique morphology. Surprise Canyon Creek is characterized by a relatively moderate and consistent gradient from the BLM/NPS land boundary to the start of the Narrows AOI. The channel’s gradient steepens considerably and the canyon itself becomes significantly narrower at the upgradient end of the reach. Exposed bedrock throughout the upper half of this reach appears to force shallow groundwater to the surface. Field observations of surface flows and obligate wetland and riparian vegetation throughout the entire reach suggest that Surprise Canyon Creek flows perennially within the AOI, though additional data collection is needed to verify this. Surface water and shallow groundwater support a richly mesic area of riparian and wetland vegetation from the “choke” at the upgradient end of the AOI on down to the end of the AOI. The exposed bedrock and tight canyon walls (total canyon floor width is as little as 3 – 5 m in areas) at upgradient end of the AOI result in a very narrow riparian corridor through the upper half of the AOI. The gradient becomes milder, and the canyon walls widen significantly through the lower half, facilitating a much wider but equally rich riparian corridor. Vegetation in the AOI was observed to predominantly riparian in nature, with various willow species and Freemont Cottonwood being the dominant species. Wetland species were also observed throughout the AOI and were mostly concentrated along the channel. Total vegetative cover was quite high (< 90%).

The density of the vegetation within this AOI obstructed views of the stream channel through much of the lower half, which made assessing potential channel incision impractical. That said, observations of incised channels up- and down-gradient suggest channel incision likely extend through the lower half of this AOI, too. The prevalence of bedrock likely minimized the potential for channel incision throughout the upper half of the AOI. Reporting by the LA times suggests that the road surface that once traversed this portion of the AOI was comprised of rocks stacked atop the now exposed bedrock, and flash flood events repeatedly stripped away the loose rock from this reach (Romney, 2006). This suggests that while an incised channel did not result from the combination of flooding and anthropogenic impacts, this portion of the WSRC was nonetheless subjected to rather extreme disturbance events over the course of the study period. Signs of recent grazing by Burros were observed throughout the latter half of the AOI.
Surprise Canyon Narrows Reach

SC Choke 20-01: AOI

<table>
<thead>
<tr>
<th>Transect Field</th>
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</tr>
</thead>
<tbody>
<tr>
<td>15% desert Baccharis, 30% riparian trees, 15% horsetails, 5% standing water, 65% bare ground</td>
<td></td>
</tr>
</tbody>
</table>
**Chris Wicht Reach**

The Chris Wicht Reach AOI is the last reach of Surprise Canyon Creek within the newly established WSRC. This final reach is oriented roughly NE-SW and runs parallel to the present-day Surprise Canyon Road. This AOI begins ~ 50 m upstream of the Chris Wicht parking area at the downgradient edge of the Surprise Canyon Narrows AOI and continues to the terminus of the Surprise Canyon Creek WSRC at the southern boundary of Section 14 Township 021S, Range 044E. This reach of Surprise Canyon Creek is understood to be ephemeral in nature, and the AOI was delineated to cover the active channel and associated floodplain area as the creek flows from Surprise Canyon out onto the associated and rather expansive alluvial fan. Total vegetation cover in the AOI was observed to be rather low (< 15%). Vegetation was predominantly dryland in nature, with Creosote Bush appearing to be the dominant species. Vegetation groups observed within the AOI were broadly consistent with the AOI’s LANDFIRE EVT group classifications of *Creosotebush Desert Scrub* and *Sparse Vegetation*.

There was clear evidence of channel incision through the upper half of this reach, as was the case in the majority of the AOI reaches located upgradient from the Chris Wicht AOI. Field observations suggest that the compacted surface of Surprise Canyon Road likely contributed to the areas of incised channel observed, though unlike upgradient areas, the Surprise Canyon Road through this area is still actively maintained. Evidence of burro grazing was observed throughout the Chris Wicht Reach AOI.
BLM Valley Bottom AOIs

Post Office Spring

![Graph showing NDVI and Potential Water Deficit (PPT-ET0, mm) over the years from 1990 to 2020. The graph includes markers for floods and tamarisk removal begins.]

![Map indicating the location of Post Office Spring AOI with various areas of interest (AOIs) and climate adjusted NDVI trend units per year.]

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Post Office Spring

25 m; South—Facing (positive trend)

50 m; North—Facing (positive trend)

100 m; South—Facing (positive trend)

POS 20-01: AOI

<table>
<thead>
<tr>
<th>Transect</th>
<th>Field</th>
</tr>
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<tbody>
<tr>
<td>POS 20-01</td>
<td>65% riparian trees with low stress/mortality, 15% tamarisk with high stress mortality/signs of prior removal efforts, 5% greasewood with high stress/mortality due to trampling, strong evidence of burro grazing.</td>
</tr>
</tbody>
</table>

Notes
Warm Sulphur Spring

[Graph showing NDVI and Potential Water Deficit (PPT-ET0, mm) values over a period from 1990 to 2020.]

[Map highlighting Warm Sulphur Springs AOI with various areas of interest and climate-adjusted NDVI trend with unitless/year values.]
Warm Sulphur Spring

25 m; East—Facing (slightly negative trend)

75 m; South—Facing (negative and positive trend)

100 m; West—Facing (negative and positive trend)

WSS 21-01: AOI

Transect Photograph Locations
Zonal Statistics Area

- Transect Field
- 65% graminoid cover, adjacent to bulrush/cattail marsh. Evidence of grazing.
0 m; West—Facing (negative trend)

75 m; South—Facing (positive trend)

100 m; East—Facing (positive trend)

WSS 21-02: AOI

<table>
<thead>
<tr>
<th>Transect Field</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>65% graminoid cover, 15% riparian trees. Evidence of grazing.</td>
<td></td>
</tr>
</tbody>
</table>
## Indian Ranch Road

![Graph of NDVI and Potential Water Deficit over time]

- **NDVI**
- **Potential Water Deficit (PPT-ET0, mm)**

![Map of Indian Ranch Road AOI]

**Areas of Interest (AOIs):**
- BLM
- NPS
- Indian Ranch Road AOI

**Climate Adjusted NDVI Trend (unitless/year):**
- High: 0.005
- Low: -0.005
Indian Ranch Road

IR 20-01: AOI

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>30% greasewood, 15% riparian trees, low stress/mortality, 30% bare ground with salt crust</td>
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</tbody>
</table>
Mesquite Bosque AOI

[Graph showing NDVI and Potential Water Deficit for different years]

[Map showing areas of interest and spring locations]

Areas of Interest (AOIs):
- BLM
- NPS
- Mesquite Bosque AOI

Climate Adjusted NDVI Trend (unitless/year):
- High: 0.005
- Low: -0.005
Mesquite Bosque AOI

0 m; East—Facing (negative trend)

25 m; West—Facing (negative trend)

75 m; South—Facing (negative trend)

MB 21-01: AOI

<table>
<thead>
<tr>
<th>Transect</th>
<th>30% riparian trees, high stress/mortality, presence of salt crust and evidence of burro grazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td></td>
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<tr>
<td>Notes</td>
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</table>
25 m; North—Facing (negative trend)

75 m; East—Facing (negative trend)

100 m; South—Facing (negative trend)

MB 21-02: AOI

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<tbody>
<tr>
<td></td>
<td>65% riparian trees, intermediate</td>
<td>water stress/mortality</td>
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</tbody>
</table>