



# ***Baseline Assessment of Groundwater Dependent Vegetation in relation to Climate and Groundwater Levels in select Hydrographic Basins of Nevada: Oasis Valley***

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June 2023

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**Publication No. 41293**



Amargosa River at Parker Ranch, Oasis Valley, NV  
Photo credit: Blake Minor

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## ABSTRACT

Located at the headwaters of the Amargosa River, the Oasis Valley hydrographic area of Nevada is home to multiple endemic species, including the Amargosa toad (*Bufo nelsoni*), Oasis Valley speckled dace (*Rhinichthys osculus* ssp.), as well as several other plant and animal species of conservation concern that are reliant on habitat provided by shallow groundwater. Due to the ecological importance of these groundwater dependent ecosystems (GDEs), including wetlands, riparian areas, and phreatophyte shrublands, the objective of this study is to establish a contemporary baseline for monitoring and assessing the potential impacts of groundwater developments to GDEs in Oasis Valley. In doing so, this study quantifies the current status and historical trends in the condition of groundwater dependent vegetation relative to trends in both climate and groundwater levels using field observations, readily available groundwater level data, gridded meteorological data, and 38 years (1984-2021) of Landsat satellite imagery. The approach follows the methods used in a recent study, where similar assessments were conducted for Pueblo, Continental Lake, Mud Meadow, Dixie, Railroad-North, Steptoe, Goshute, and Independence Valley hydrographic areas.

Delineation of Oasis Valley's GDE area using satellite imagery and other contemporary datasets indicate a 10 percent larger area relative to initial estimates made in 1962 by the U.S. Geological Survey. This discrepancy is likely due to differences in methods used, rather than a meaningful increase in the areal extent of GDE vegetation. Within this contemporary delineation, 21 percent of the area is comprised of introduced species and developed land uses, a larger proportion than most basins previously assessed. Relations between satellite-based vegetation and climate indices indicated stronger relations between climate and vegetation vigor and more positive trends in vegetation vigor in upland areas relative to areas delineated as GDEs. Within GDE areas, mesic and wet-mesic GDE types were characterized by larger magnitude trends and a larger proportion of negative trends (i.e., reduced vegetation vigor) relative to non-mesic GDE vegetation. The spatial patterns of vegetation trends in Oasis Valley are similar to those observed in other basins previously assessed.

Groundwater-right commitments in Oasis Valley total half the basin's perennial yield, but as ground and surface waters are managed as an integrated resource among several basins within the Amargosa system, permitted abstractions total 115.3 percent of the perennial yield for the broader system. Overall, the lack of groundwater data represented the most critical uncertainty in assessing the hydrology of Oasis Valley's GDEs. Of the 39 shallow groundwater monitoring locations considered in this study, only 11 had more than six years of data, and seven (3 falling, 4 rising) of these had significant ( $p < 0.05$ ) trends. The three well measurement locations with declines in water levels were associated with a spring system near the eastern side of Torrance Ranch, where shallow groundwater declines of up to 5.2 ft occurred. The reason for the decline is unclear but may be related to water management infrastructure development that occurred in 2009. Significant groundwater elevation increases were observed at the four wells located near 7J Ranch, where positive trends in vegetation vigor were also observed.

Vegetation and groundwater responses to contemporary restoration activities varied substantially in terms of direction and magnitude. In many cases, insufficient data were available to characterize responses and establish strong linkages between groundwater levels, management activities, and vegetation. Increased demand for groundwater related to renewable energy, mining, and population growth is expected to occur in this region in the near future. Expanded data collection and monitoring activities, especially those that can improve understanding of groundwater flows within the region will be important for assessing impacts of groundwater developments to these ecosystems.

## **ACKNOWLEDGEMENTS**

The authors wish to thank Maria Vasquez for assistance with report production and review, and Mark Hausner, Steve Bacon, Laurel Saito, Michael Clifford, and Levi Kryder for their reviews and suggestions that helped to improve this report. Funding for this work was provided by the Bureau of Land Management and The Nature Conservancy in Nevada under grant agreement number NVFO523.



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## LIST OF ACRONYMS

AFA	Acre-Feet Annually
AOI	Areas of Interest
BLM	Bureau of Land Management
DRI	Desert Research Institute
DTW	Depth to Water
ETM+	Enhanced Thematic Mapper Plus
ETo	Evapotranspiration
EVI	Enhanced Vegetation Index
EVT	Existing Vegetation Type
GDE	Groundwater Dependent Ecosystem
GEE	Google Earth Engine
HA	Hydrographic Area
LaSRC	Landsat Surface Reflectance Code
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NDWR	Water Level Data
NWIS	National Water Information System
OLI	Operational Land Imager
PI	Prediction Interval
PPT	Precipitation
PPT-ETo	Potential Water Deficit
PWD	Precipitation – Potential Evapotranspiration
QA	Quality Assessment
QC	Quality Control
RIB	Rapid Infiltration Basin
sUAS	Small Unmanned Aircraft System
TM	Thematic Mapper
TNC	The Nature Conservancy
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WY	Water Year

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## INTRODUCTION

The Amargosa River, sometimes called the “Crown Jewel of the Mojave Desert”, is a largely ephemeral river whose headwaters flow from a system of groundwater-fed of springs and seeps located in Oasis Valley, Nevada. The Amargosa is distinct from other rivers in North America in that it is predominantly subterranean and terminates in the hottest and driest valley in the northern hemisphere (Death Valley, California) rather than flowing to the Ocean (Figure 1).

Along the river’s 180-mile course, perennial water occurs in places where groundwater is forced to the surface by changes in subsurface permeability and/or topographic relief. The long residence times and slow movement of groundwater allow these features to exist year-round, despite the low frequency of precipitation and surface flows. Shallow groundwater throughout the Amargosa River supports groundwater dependent ecosystems (GDEs), which provide critical habitat for more than 100 species targeted for conservation (TNC, 2022a), including the Amargosa Toad (*Bufo nelson*) and Oasis Valley speckled dace (*Rhinichthys osculus* ssp.), both of which are endemic to Oasis Valley. Ash Meadows National Wildlife Refuge, one of the most extensive areas of perennial water along the Amargosa, is home to at least 24 plants and animals found nowhere else on earth—the greatest concentration of endemic species in the United States (TNC, 2022b).

Due to the ecological importance of this region, large areas of the river corridor have been afforded protection under various jurisdictions, including:

- Wild and Scenic River Act: A roughly 30-mile reach from just north of Shoshone, California, to near Dumont Dunes, California (protected in 1997 and 2009; Figure 1)
- Ash Meadows National Wildlife Refuge: Over 23,000 acres of spring-fed wetlands and alkaline desert dryland GDE communities near the California-Nevada border (U.S. Fish and Wildlife Service, 2022; Figure 1)
- Death Valley National Park: Roughly 76 miles of the river fall within the park, mostly from Dumont Dunes to Badwater Basin (Figure 1)
- Private conservation efforts: The Nature Conservancy owns and manages over 1,600 acres throughout Oasis Valley for conservation (Figure 2), and over 5,000 acres have been protected in California from Shoshone to the Amargosa Canyon

While these protected areas are relatively large, they only cover a small fraction of the river’s total GDE area.

The interaction of surface and groundwater within river systems is an area of active research and a topic of particular interest for the Amargosa River, given the river system’s largely subterranean nature. In 1998, Nevada State Engineer’s Ruling 4669 determined the groundwater and surface water resources in Oasis Valley are closely linked, and therefore should be represented as a single resource (Nevada State Engineer, 1998). Though this ruling only pertains to the Oasis Valley Hydrographic Area (HA 228) rather than the entire Amargosa River drainage, the presence of perennial surface water throughout the Amargosa River corridor suggests the interconnection of groundwater and surface water is widespread. Therefore,

groundwater and surface water diversions may impact perennial waters of the Amargosa River, regardless of diversion type, point of diversion, or place of use. Moreover, the Amargosa River spans both California and Nevada, and are subject to different water regulation policies.

Oasis Valley is the most upgradient area within the Amargosa River drainage where regional groundwater discharges to the surface. Assessing historical variability and trends of vegetation, climate, and hydrologic conditions within GDE areas of Oasis Valley provides important baseline information for management, monitoring, and mitigation of potential impacts to GDEs related to groundwater abstraction. For example, the North Bullfrog Project, a proposed gold mining operation in close vicinity to Oasis Valley has the potential to impact water availability for GDEs in cases where hydrogeologic connections exist. In addition, increases in evaporative demand associated with warming climate have the potential to impact water use and needs of these ecosystems. In addition to this, renewable energy development, and urban growth in Beatty, NV are likely to result in increased demand of groundwater.

While the need for and benefits of historical baseline assessments of GDE conditions are clear, in-situ vegetation, hydrologic, and climate data are limited, making the use of satellite and spatial climate datasets necessary. Management actions such as invasive species control, modified grazing practices, and riparian restoration have influenced GDE conditions, however, there is no information on the extent or magnitude of GDE changes, or baseline conditions prior to such actions. In addition, short- and long-term variations in climate, and natural (e.g., flooding) and anthropogenic disturbances associated with mining, renewable energy development, and other development activities can impact GDE conditions. Characterizing trends and interannual variations in measures of vegetation status, climate, and hydrologic conditions is an important step towards improved monitoring and management of GDEs throughout Oasis Valley.

## **OBJECTIVES**

The primary goal of this study is to develop baseline information that can be used for future monitoring and assessments of GDEs in Oasis Valley. As described in Albano *et al.* (2021), this is accomplished by quantifying the current status and historical trends in the condition of groundwater dependent vegetation relative to trends and variations in climatic conditions and groundwater levels based on field observations, groundwater level data, gridded meteorological data, and 38 years (1984-2021) of Landsat satellite imagery. Specific objectives of the study are to:

- 1) establish baseline conditions of vegetation and groundwater levels to facilitate evaluation of the effects of groundwater developments on water availability and groundwater dependent vegetation,
- 2) characterize the sensitivity and historical range of variations in groundwater dependent vegetation in response to changes in climatic and groundwater conditions,
- 3) characterize historical trends since 1984 in depth to groundwater (DTW), climatic conditions, and groundwater dependent vegetation, and



- 4) develop, document, and make available datasets used for this assessment to facilitate future assessments and monitoring.

A database containing data created and used in this study is provided as a supplement to this report and is available at <https://www.dri.edu/project/groundwater-dependent-ecosystem-assessments/>. The database contains three main categories of data, including a groundwater level summary dataset, a basin-phreatophyte area dataset, and an areas of interest (AOI) dataset. Details are included in the metadata and are further described in [Albano \*et al.\* \(2021\)](#).

## STUDY AREA

Oasis Valley is a 460 mi<sup>2</sup> hydrographic area (HA), as defined by the Nevada State Engineer (Figure 1). It is located roughly 100 miles north-northwest of Las Vegas, Nevada, in the upper part of the Death Valley Regional Groundwater Flow System. The basin contains four general landform types: valley lowlands, piedmont slopes, volcanic plateaus, and mountain blocks. Pahute Mesa, a massive volcanic plateau formed by the eruption of several Cenozoic calderas, covers most of the northern half of Oasis Valley. The basin is bounded by the north-south trending Bullfrog Hills to the west, Quartz and Black Mountains to the north, Timber Mountain and Pahute Mesa to the east, and feeds into the Amargosa Valley to the south (Figure 1). Several prominent faults that cross Oasis Valley are thought to influence the occurrence and movement of groundwater on a regional scale by acting as either conduits or barriers to groundwater flow (Jackson *et al.*, 2021). Faults believed to influence groundwater flow and result in spring discharge include the Hogback, Colson Pond, Fleur De Lis, and Hot Springs faults (Jackson *et al.*, 2021).

The climate of the study area is classified as arid with a dry warm season and wet cool season. Mean annual precipitation ranges from 6 inches per year in the lowlands to 8–13 inches per year in higher elevation areas (Soulé, 2006; Western Regional Climate Center, 2022). Groundwater rights currently recognized by the Nevada Division of Water Resources in Oasis Valley (1,138 AFA, accessed Nov 21, 2022) make up just over half of the basin's perennial yield (2,050 AFA, as estimated by Malmberg and Eakin (1962)), though NDWR now considers appropriations in Oasis Valley as part of the broader Amargosa Flow system (HAs 225-through 230) which has a combined perennial yield of 24,000 AFA and is over-appropriated by 15.3 percent (combined commitments for Amargosa Desert (HA 230), Crater Flat (HA 229), Oasis Valley (HA 228), Rock Valley (HA 226), Mercury Valley (HA 225), and Forty Mile Canyon (HAs 227A and 227B) equals 27,672 AFA, accessed Nov 21, 2022) .

Oasis Valley's groundwater discharge supports numerous GDE habitats and vegetation types that can broadly be divided into dryland (phreatophytic shrubland) and mesic to wet-mesic (meadow, riparian, and wetland) communities. Phreatophytic shrubs, the most prolific GDE vegetation- type in Oasis Valley, cover large areas of valley lowlands. Though rates of groundwater discharge due to evapotranspiration from phreatophyte shrublands are generally low, the large area that they occupy in Oasis Valley results in their collective volume of groundwater evapotranspiration comprising a substantial fraction of the basin's total groundwater discharge. Across the Great Basin and Mojave regions, these communities tend to

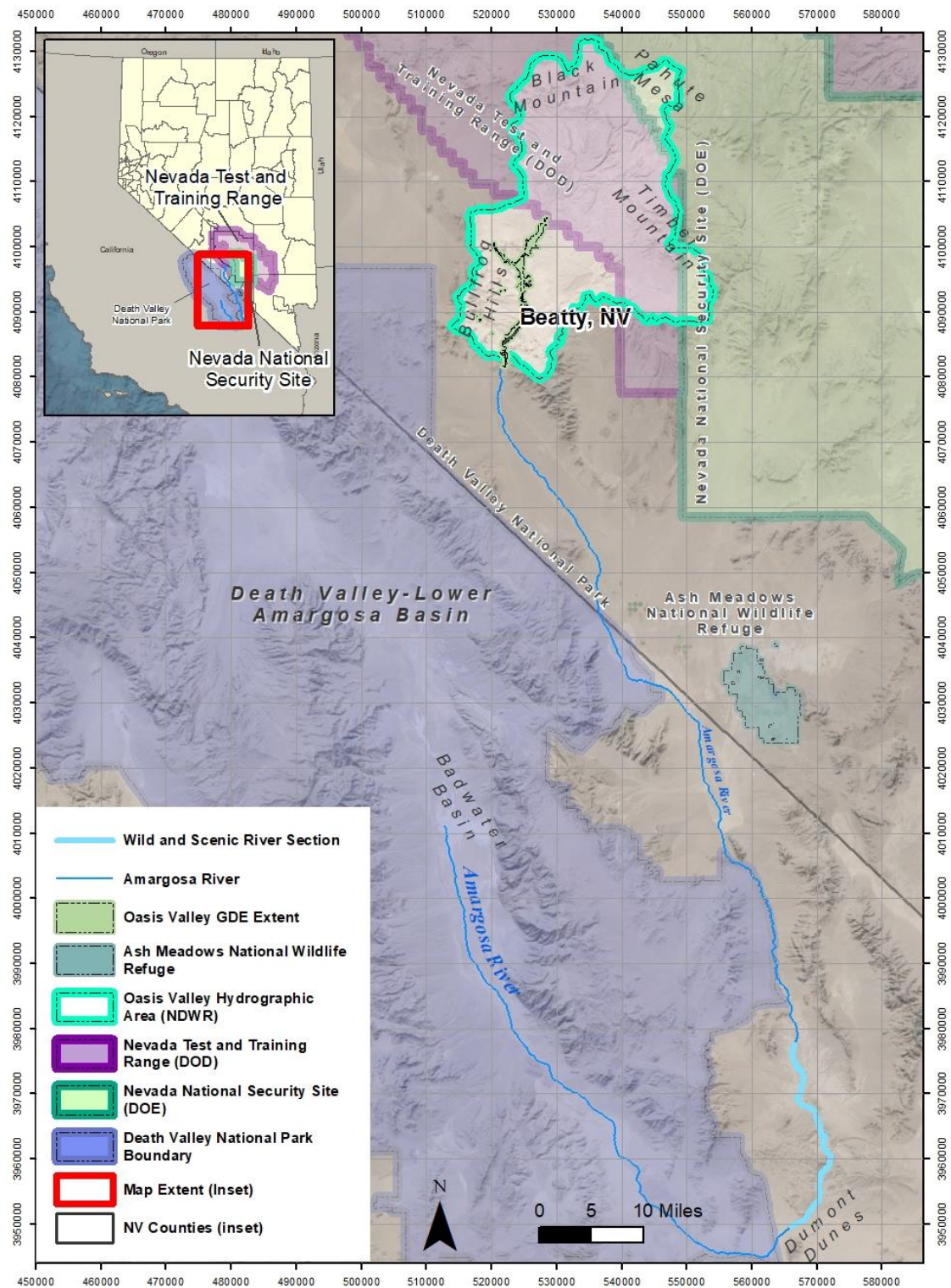


Figure 1. Map showing the general location of the Oasis Valley Hydrographic Area (HA 228) and the basin's potential groundwater discharge area.

occur where depth to water (DTW) is less than 35 feet (ft), though phreatophytic greasewood (*Sarcobatus vermiculatus*) has been found growing in areas where DTW exceeds 60 ft (Robinson, 1958; Garcia *et al.*, 2015). Mesic to wet-mesic GDE communities (meadows, riparian groves, meadows, and wetland communities) primarily occupy areas along stream and river channels and around perennial springs. Within Oasis Valley, depth to groundwater is assumed to be 20 ft or less in riparian groves, from 1 to 10 ft in meadow communities, and near land surface in wetland areas (Reiner *et al.*, 2002).

## METHODS

This section provides an overview of the datasets and analytical approaches used in this study. For a more detailed description of datasets, methods and considerations related to interpretation of results, please see [Albano \*et al.\* \(2021\)](#).

## STUDY AREA

The study area described in this report covers the Oasis Valley HA (HA 228) as defined by the Nevada State Engineer (Figure 1). The study area is identical to the official HA except for inclusion of a GDE area of interest just outside the southern HA boundary, which was included specifically to assess restoration efforts by The Nature Conservancy (TNC) on the portion TNC owns and manages in the Beatty Narrows area. Site specific area of interest (AOI) boundaries were collaboratively delineated with TNC. Selected AOIs targeted locations where restoration efforts are planned or have been carried out, where GDEs are of distinct ecological value, and/or where future groundwater development is believed to have the potential to impact GDEs and the species that rely on these ecosystems for habitat.

## DATASETS

To address the study objectives the following publicly available datasets were compiled. Additional details describing these datasets are provided in Appendix A.

- The daily resolution [gridMET](#) gridded (~2.5 mi/4 km), meteorological dataset (Abatzoglou, 2013) was used for all climate analyses. Key variables analyzed in association with vegetation include grass reference evapotranspiration (ET<sub>o</sub>), precipitation (PPT) and potential water deficit (PPT-ET<sub>o</sub>).
- [Landsat Collection 2, Level-1](#) archive images available through the Google Earth Engine (GEE) cloud computing and environmental monitoring platform (Gorelick *et al.*, 2017).
- Groundwater elevation data from the USGS National Water Information System (NWIS) (<https://waterdata.usgs.gov/nwis/gw>; USGS, 2016), and the NDWR Water Level Data (<http://water.nv.gov/WaterLevelData.aspx>; accessed August 2, 2022) groundwater elevation databases.

## **ANALYTICAL APPROACH**

### **Groundwater Dependent Ecosystem (GDE) Boundary Delineation**

An updated boundary representing the potential area of groundwater discharge (i.e., GDE area; Figure 2) was adapted from Reiner *et al.* (2002) and Heilweil & Brooks (2011). These boundaries were adjusted to reflect contemporary boundaries based on satellite data, groundwater levels, and soils data using methods described in Minor (2019) and Huntington *et al.* (2022). More specifically, the GDE boundary was refined by overlaying historical (Malmberg & Eakin, 1962) and recent (Reiner *et al.*, 2002; Heilweil & Brooks, 2011) boundaries with remote sensing and hydrogeologic datasets. Spring locations, well groundwater elevations, gSSURGO gridded soils data (USDA, 2017), Landsat-derived surface temperature data, 30 m resolution digital elevation model (Gesch *et al.*, 2002), and several additional remote sensing products (long-term NDVI values, NDVI trends, NDVI-climate correlation measures, etc.) were used to constrain the extent of potential GDE areas. Areas of permanent development (e.g., paved roads, permanent buildings, etc.) were removed from the potential GDE boundary using high-resolution aerial imagery from 2010 – 2020. Additional GDE area just outside the southern HA boundary was also included to assess restoration efforts by TNC on the portion they own and manage in the Beatty Narrows area. This refined extent covers an area of 4,239 acres (4,181 of which are in the Oasis Valley HA), placing the present estimate between historical (3,800 acres; Malmberg and Eakin, 1962) and relatively recent USGS (4,465 acres, Heilweil and Brooks, 2011). The resulting GDE boundary spans from low-density dryland GDEs (e.g., greasewood and rabbitbrush) to perennial wetland features (e.g., ponds surrounded by reeds and tules).

### **Vegetation**

#### ***Comparison of Historical and Contemporary Vegetation***

Vegetation within the GDE boundary was assessed by comparing contemporary land cover classifications based on the LANDFIRE vegetation type database (U.S. Department of Interior, 2016) to historical accounts from Malmberg and Eakin (1962). Although these comparisons are very coarse, major changes in the proportions of different vegetation types may be indicative of effects of groundwater pumping or other types of development or disturbance on GDEs that occurred in the last several decades.

#### ***Vegetation Status***

Vegetation status was characterized as a basis for evaluating future change and for interpreting site-specific results in a basin-wide context. Vegetation status was quantified as the 10-year average (2012-2021) annual late summer (median July 15-September 15) Normalized Difference Vegetation Index (NDVI) value for each 30-m Landsat pixel. NDVI is a metric that accurately tracks the chlorophyll content of mesophyll tissue in vegetation (Gitelson & Merzlyak, 1997), and therefore serves as a robust proxy for overall vegetation vigor (Gitelson *et al.*, 2014). Vegetation in the study area is generally water limited (Zomer *et al.*, 2022), and water limitations tend to be greatest during late summer and coincident with the period of greatest evaporative demand. Given these attributes, late-summer NDVI provides a robust and useful metric for assessing spatiotemporal groundwater dependence and vegetation vigor within GDEs



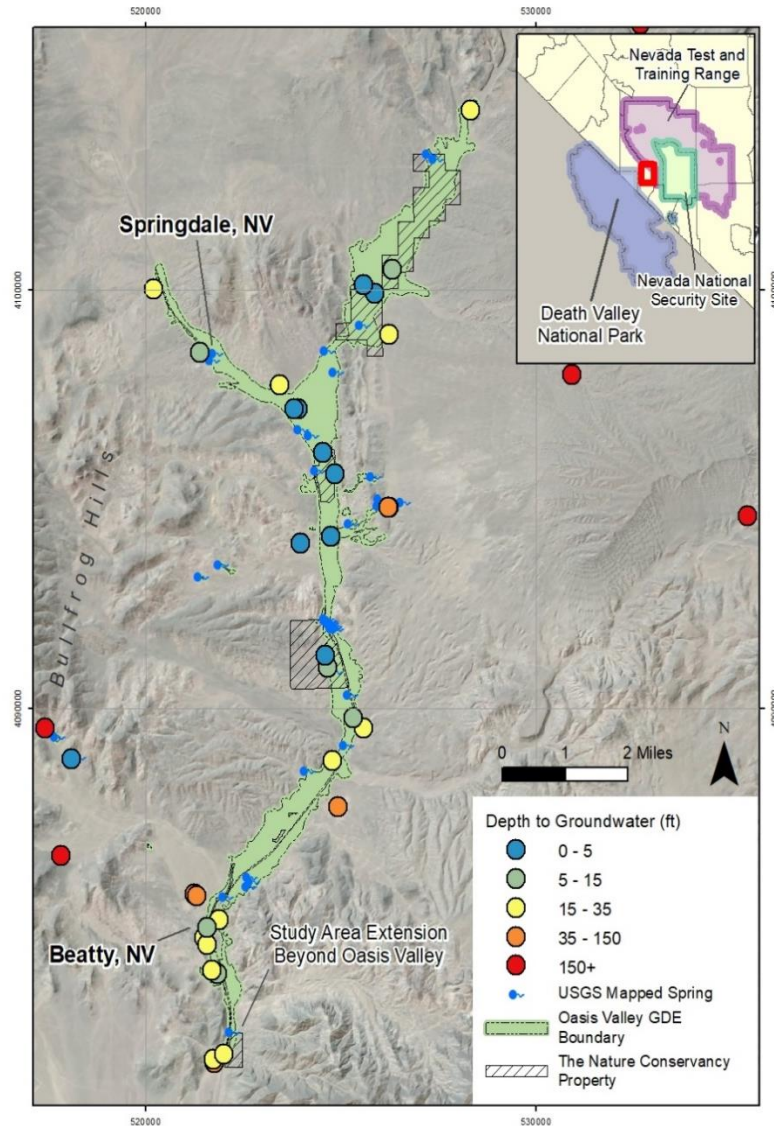


Figure 2. Overview of the GDE area extent, wells with groundwater data (most recent depth to groundwater measurement indicated), springs, and The Nature Conservancy properties.

(Huntington *et al.*, 2016). A 10-year time period was chosen because it reflects the most recent conditions and because we deemed 10-years to be a reasonable amount of time to smooth over large interannual variations in climate that are likely to influence NDVI from year-to-year. Long-term averages of NDVI values provide an indication of water availability, as well as species composition, cover, and condition. See Albano *et al.* (2021) for additional details on the use of NDVI for assessing vegetation status.

### ***Vegetation Sensitivity to Climate***

The sensitivity of changes in vegetation vigor due to interannual variations in climate over the 1984–2021 period was quantified based on the Pearson’s correlation coefficient between annual late summer NDVI and water year potential water deficit (i.e., water year precipitation

minus potential evapotranspiration) for each pixel. Correlations were summarized for pixels within the phreatophyte area that were classified as select focal vegetation types to identify which vegetation types most strongly depend on water sources derived from near-term precipitation. Under static conditions, pixels and vegetation types with larger magnitude correlation coefficients indicate higher sensitivities to (i.e., greater change in response to) interannual variations in potential water deficit. In general, water-limited areas are expected to exhibit higher climate sensitivity (correlation nearer to 1), while more mesic areas with more consistent water availability due to connections with groundwater or surface water will be less sensitive (correlation nearer to 0), but sensitivity also varies according to adaptations and characteristics of component plant species. Sensitivities to climate can also be masked by disturbances (natural or anthropogenic) that cause trends or step-changes in NDVI, as these decouple the natural relationship between interannual climate and vegetation productivity. Thus, sensitivities of a given pixel need to be interpreted in the context of how values compare to other pixels of the same vegetation in similar environmental settings (climate regime, soil type, elevation, aspect), and whether step changes or trends in NDVI are also occurring.

### ***Vegetation Climate-Adjusted Trend***

The purpose for quantifying climate-adjusted trends in vegetation is to characterize historical trends in vegetation vigor while accounting for the influence of interannual variations in precipitation and evaporative demand (i.e., potential water deficit) to identify areas of historical change that are likely attributed to factors other than interannual variations in climate. The climate-adjusted trends metric was calculated using the Adjusted Kendall approach described in Alley (1988) and Section 12.3 in Helsel & Hirsch (2002). Potential water deficit was calculated for each water year (Oct-Sept), and an ordinary least-squares linear regression analysis between potential water deficit and annual late summer (median July 15-September 15) NDVI values over the 1984-2021 time period was conducted for each pixel.

The non-parametric Sen's slope estimator method (Sen, 1968) was then applied to NDVI regression residuals (observed NDVI minus predicted NDVI) to estimate the monotonic trend of residuals 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 minimized. 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. By adjusting for climate, resultant trends more definitively highlight changes that are likely due to anthropogenic or other types of disturbance. This information is useful for identifying areas of vegetation change, targeting field investigations, and developing hypotheses on causal factors of change.

### **Groundwater**

A total of 17,498 groundwater elevation measurements collected from 386 locations (wells or unique screened intervals) in a bounding box surrounding the study area were obtained from NDWR and USGS databases. Locations where the most recent depth to water measurement was greater than 150 ft were omitted from basin-scale groundwater assessments to limit analyses to monitoring points with shallow groundwater, given the focus of this study on GDEs. Of the original 386 groundwater monitoring locations, 39 were retained for analysis.

Groundwater level measurements for the 39 monitoring locations were used to compute the Sen's slope for each well hydrograph covering the period of the Landsat archive (1984-2021). Many sites had multiple groundwater level measurements each year. The last measurement in a given water year was selected to reduce the data in a manner that minimizes the effects of seasonal variability and captures end of growing season conditions, when possible. A minimum of 3 years of observations were required for a given well to be included in the trend analysis. Although 3 years is a minimal sample size, we deemed this appropriate given that it greatly increased the spatial distribution of wells. The statistical significance of the Sen's slope was assessed based on the Mann-Kendall test for monotonic trend (Kendall, 1975; Mann, 1945), modified to account for up to three years of serial autocorrelation in cases where autocorrelation was statistically significant (p-value of less than 0.05) (Hamed & Rao, 1998). Sen's slopes were estimated in Python using the SciPy package (Virtanen *et al.*, 2020), and the modified Mann Kendall trend test was computed using the PyMannKendall (Hussain and Mahmud, 2019) package. We note here that we did not apply a climate adjustment as was done for NDVI given the small sample sizes and lack of consistent groundwater level measurement timing and frequency, leading to spurious statistical relationships with climate data.

We also note that estimated trends in DTW may be affected by inconsistencies in the frequency and timing of groundwater level measurements, as these varied across individual wells during the study period. Wells with a minimum of 3 unique years of groundwater depth observations over 1984 – 2021 ( $n = 25$ ) were included in the trend analysis. Of the 25 qualified wells, 14 had relatively short records consisting of 4 – 6 years of unique measurements between 1996 and 2001, one had 11 years of data between 1999 – 2009 (12 in entire record, one from 1971), and the remaining 10 wells had more than 25 years of observations, all of which occurred between 1996 – 2021. Depth to groundwater measurements shown on figures and/or discussed in the text represent the most recent available for each site, unless explicitly stated otherwise. Results of the groundwater level data analysis were summarized and are included in the database supplement to this report.

### **Site-Specific Analyses for Areas of Interest (AOIs)**

Landsat and climate data summaries, field investigations, and aerial surveys were conducted for discrete areas of interest (AOIs) around Oasis Valley. These AOIs were collaboratively identified with staff from The Nature Conservancy and represent GDE areas that were identified as being valuable, vulnerable to impacts, known to be disturbed, or where past or future restoration efforts are targeted. In total, 9 AOIs ranging from 1.5 to 97 acres were identified and investigated.

For each AOI, spatial averages of annual gridded climate and NDVI were compiled and used to calculate vegetation metrics of status, sensitivity, and climate-adjusted trend based on the same methods described above and described in greater detail in Albano *et al.* (2021). Other selected vegetation index metrics (e.g., Normalized Difference Water Index-NDWI, Gao, 1996; Modified Soil Adjusted Vegetation Index - MSAVI, Qi *et al.*, 1994) were also calculated and are provided in the supplementary database for this report. Annual time series figures of NDVI, climate, and depth to groundwater were also developed to visualize and provide a detailed view

of the interannual variability and long-term change for each AOI. In cases where nearby groundwater levels were available, groundwater levels were summarized, graphed, and attributed with links to original data sources. All readily available groundwater data from wells within 1 mile of AOIs were considered. If sufficient data (i.e., a minimum of 3 annual observations) were available, a groundwater elevation trend assessment was performed.

A field investigation was conducted in May 2022 to ground truth, interpret satellite-based results, and collect vegetation information via vegetation transects and small uncrewed aircraft systems (sUAS) flights. A database was developed documenting field site visits and associated data collection, including field photographs, vegetation assessment transects (relative abundance of GDE categories, degree of mortality observed, signs of disturbance or water stress, etc.), and high-resolution orthomosaic imagery of AOIs (where conditions permitted sUAS flight). Field methods are described in Albano *et al.* (2021).

## **RESULTS AND DISCUSSION**

In this study, historical baseline and trends of vegetation vigor and groundwater levels were assessed in Oasis Valley to develop information and datasets that can be used for future monitoring and assessments of GDEs. The results are intended to be comparable to those presented for eight other hydrographic areas (Albano *et al.*, 2021). Status and trends in vegetation and groundwater levels within GDEs were assessed based on field investigations, groundwater level data, gridded meteorological data, and 38 years (1984-2021) of Landsat satellite imagery. Results presented below include:

- 1) a general overview of status and trends of vegetation and groundwater across the phreatophyte area and entire hydrographic basin;
- 2) site-specific analyses for a subset of AOIs within each basin that were selected for field investigation, including detailed analyses and visualizations of vegetation, climate, and available groundwater timeseries. These data are summarized and interpreted with presentations of maps and photographs from site visits; and
- 3) a bulleted summary of key results based on both basin-wide and site-specific analyses.

Data compiled for this basin, including groundwater well data, the geodatabase containing groundwater site information and statistics, well hydrographs, vegetation trend maps, and site-specific data including shapefiles, photographs, orthomosaics, and vegetation index and climate time series for each AOI can be found within the database prepared for this report.

## **SYNTHESIS OF GDE ANALYSIS RESULTS AT THE BASIN SCALE**

### **Comparison of Historical and Contemporary Vegetation**

The historical description of GDE vegetation for Oasis Valley in the 1962 USGS reconnaissance series report (Malmberg & Eakin 1962) estimates an area of approximately 3,800 acres comprised of a mix of mesic and dryland GDE vegetation types. Unlike most other reconnaissance reports, Malmberg and Eakin (1962) did not provide estimates of the proportions of this area that were covered by different vegetation types. Thus, the ability to discern changes



in vegetation composition based on the 1962 description and LANDFIRE Existing Vegetation Type (EVT) group level classifications is limited. Despite this, the information presented in Table 1 provides a useful benchmark for future assessments. Contemporary GDE areas are dominated by region-specific vegetation classes falling in the [Creosotebush Desert Scrub](#), [Desert Scrub](#), and [Salt Desert Scrub](#) EVT groups, which collectively account for 64 percent of the GDE area. An additional 9 percent of the area is classified as [Sparse Vegetation](#). A notable result from this LANDFIRE-based assessment is the relatively large (20%), combined area of disturbed/developed (11%) and introduced vegetation (9%) groups, which is on par with Steptoe Valley (23% combined area), the hydrographic area with the largest proportions of these classes. (Albano *et al.*, 2021; see Table 2).

Table 1. Type and areal extents of vegetation within Oasis Valley’s Groundwater Dependent Ecosystem area based on historical (Malmberg & Eakin, 1962) and contemporary (LANDFIRE) accounts. The contemporary boundary is based on the refinement described in this study. \*Note that 57 acres of the contemporary GDE is outside the Oasis Valley HA 228 (i.e., in the Amargosa Desert HA 230), thus the contemporary GDE acreage within the Oasis Valley HA 228 is 4182 acres.

Historical			
Vegetation Type		Acres	% GDE Area
Mixture of Saltgrass, Bermuda Grass, Greasewood, and Saltbush; Reeds and Tules in Spring Areas		3,800	100%
Total		3,800	100%
Contemporary			
Vegetation Type		Acres	% GDE Area
Dryland	Big Sagebrush Shrubland and Steppe	12	0.3%
	Chaparral	51	1.2%
	Creosotebush Desert Scrub	1530	36.1%
	Desert Scrub	486	11.5%
	Salt Desert Scrub	685	16.2%
	Sparse Vegetation	365	8.6%
	Other	55	1.3%
Mesic	Western Herbaceous Wetland	83	2%
	Western Riparian Woodland and Shrubland	84	2%
	Freshwater Marsh	9	0.2%
Disturbed/ Developed	Agricultural-Close Grown Crop	13	0.3%
	Agricultural-Pasture and Hayland	18	0.4%
	Developed or Transitional	473	11.2%
	Introduced Vegetation	375	8.8%
Total		4,239*	100%

Historical and contemporary estimates of the areal extent of GDEs in Oasis Valley were 3,800 and 4,182 (4,239 including the Beatty Narrows area in Amargosa Desert HA) acres, respectively, a 10 percent difference. As shown in Figure 3, these differences are due to the inclusion of springs-associated GDEs in the Bullfrog Hills north and northwest of Beatty, NV (e.g., Crystal Spring Complex), and a large GDE area between Stagecoach and the Beatty Narrows area (Figure 3) not being included by Malmberg and Eakin (1962). Though much of the latter area that was likely once GDEs has been developed, GDE vegetation still actively covers nearly 150 acres and depth to water is less than 35 feet within this area (Figure 4). Beyond these example areas, other differences may be the result of either the coarse scale of the historical dataset (e.g., boundary differences south of Colson Pond fault; Figure 3) or due to land development.

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

The LANDFIRE EVT groups shown in Table 1 were used to organize the pixel-wise estimates of NDVI status, climate sensitivity, and trend. It is important to note that LANDFIRE classifications are imperfect and misclassifications are common (McGwire, 2019; Provencher *et al.*, 2009) but this still provided a useful way to identify characteristic ranges of long-term average NDVI values and sensitivities of NDVI to climate variability for different vegetation types and for pinpointing the types of vegetation that are changing the most.

#### ***Vegetation Status***

The most recent 10 years (2012–2021) of median annual late-summer (July 1 – September 15) NDVI values (not climate-adjusted) were averaged for each pixel in the GDE area to represent the current status of vegetation vigor. These pixel-average values were plotted for each of the LANDFIRE groups to characterize the ranges of NDVI values occurring within each group (Figure 5). This provides context for comparing site-specific NDVI for a given vegetation type to other areas of the same vegetation type in the same basin. It also provides a baseline for assessing future change. Pixels with long-term NDVI values that are on the fringes of the distribution may indicate areas of disturbance or change, a transition zone from one vegetation type to another, and/or misclassification by LANDFIRE. Regardless, this information can be useful for targeting field investigation to gain insights into why these anomalous NDVI values have occurred.

Throughout the study area's GDE extent, ranges of vegetation status estimates clearly distinguished dryland vegetation types from more mesic GDEs. Seventy-five percent of pixels within most dryland vegetation groups had 10-year mean late-summer NDVI values below 0.25 (Figure 5) and narrow interquartile ranges of NDVI values, which is consistent with results described for other basins in Albano *et al.* (2021). The exception to this is the Creosote Desert Scrub group, which is characterized as having higher vegetation densities (i.e., 25-50%) relative to other dryland groups. Similarly, seventy-five percent of pixels within mesic vegetation groups have NDVI values above 0.25, with fifty percent of them being greater than 0.3 for most groups. Introduced vegetation types span a large range of NDVI values as this group includes a variety of mesic and dryland species.

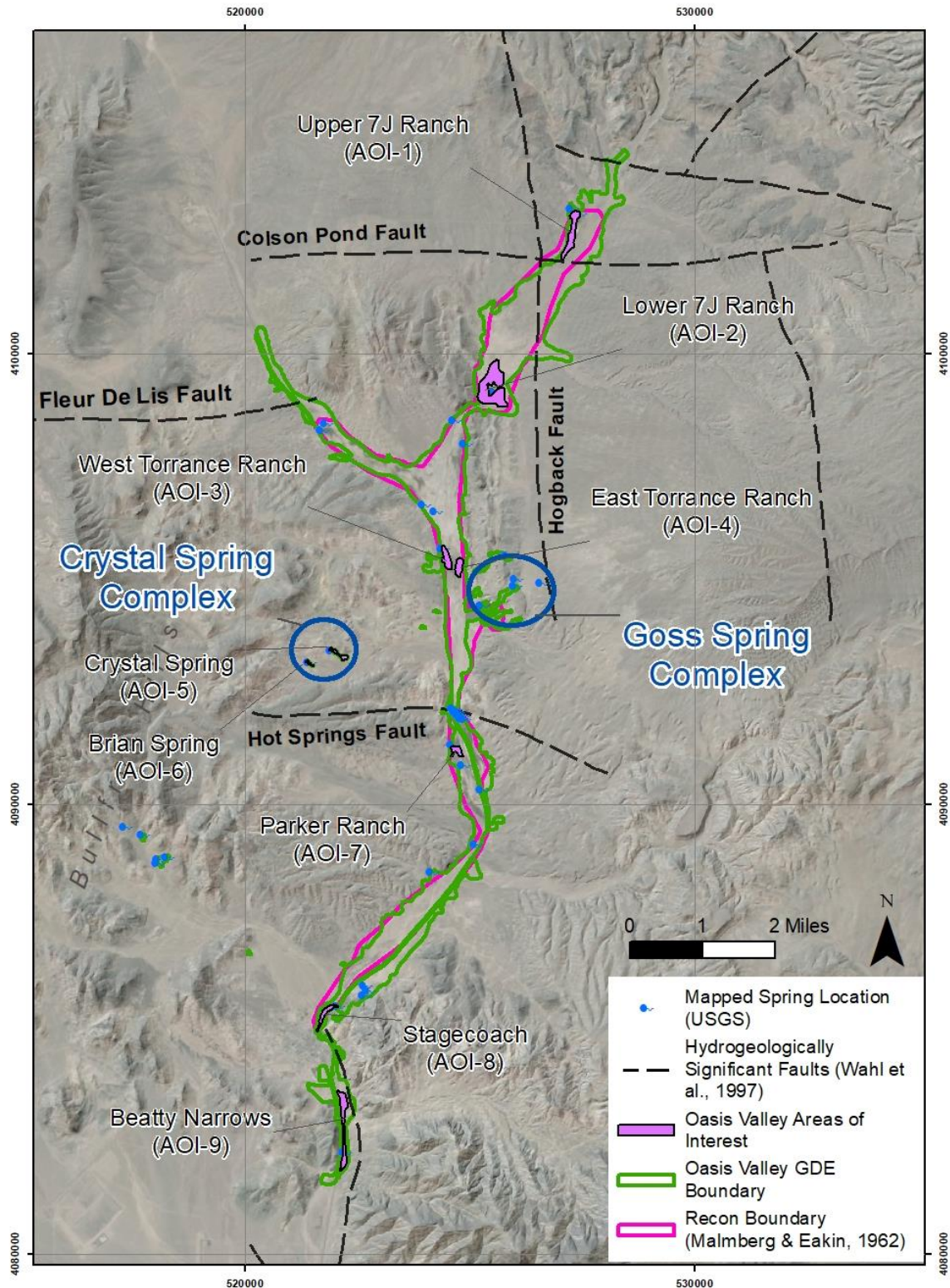


Figure 3. Map showing the locations of nine AOIs where detailed analyses were conducted, groundwater discharge area delineations from this and previous studies, and hydrogeologically significant faults.



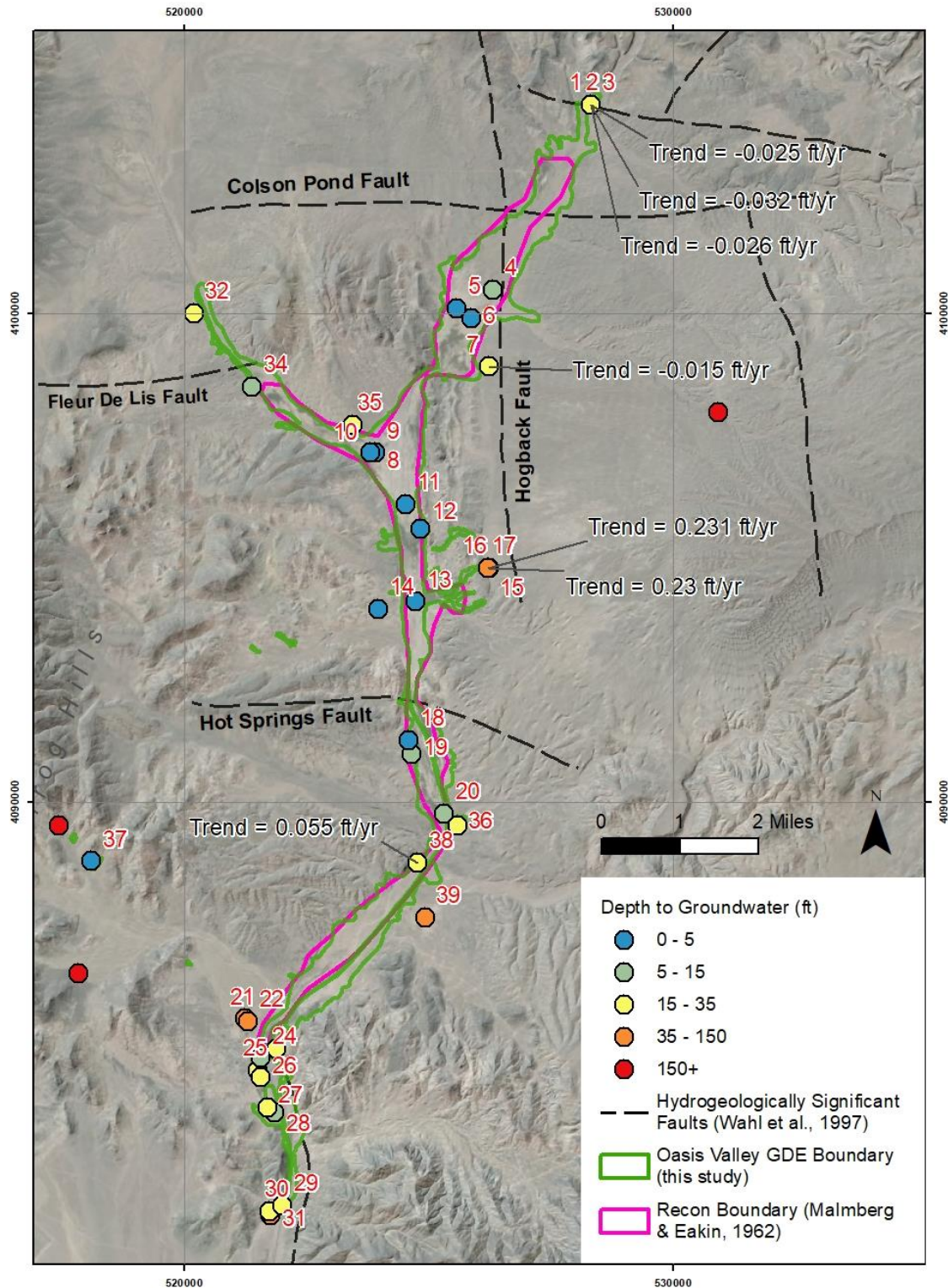


Figure 4. Groundwater discharge area delineations from this and previous studies and spring and well locations for the Oasis Valley Study Area indicating the most recent depth to groundwater and statistically significant trends over the time periods data are available (See Table 2 for more information on period of record and groundwater level statistics).

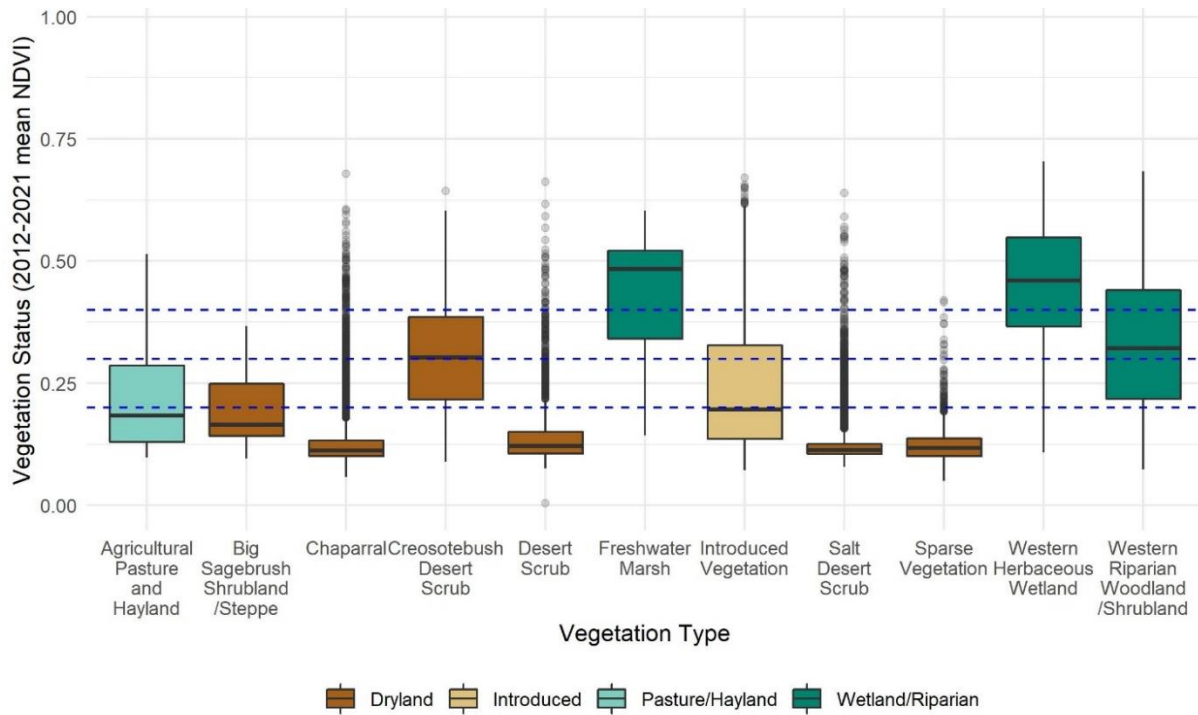


Figure 5. Vegetation status, as indicated by 2012–2021 average ranges of late-summer NDVI, for select natural LANDFIRE vegetation types within GDE boundaries. Horizontal lines are shown for NDVI values = 0.2, 0.3, and 0.4 as references, as these represent the range of NDVI values associated with mesic vegetation types based on past studies in arid and semi-arid regions (McGwire, 2019, Albano *et al.*, 2021). More developed LANDFIRE types including Developed/Transitional and Agricultural -Close Grown Crop are excluded, as is the ‘Other’ category, which includes a wide variety of vegetation types and covers a small area.

### Vegetation Sensitivity to Climate

To evaluate vegetation sensitivity to interannual variations in climate, correlation coefficients between annual potential water deficit ( $PWD = \text{precipitation} - \text{potential evapotranspiration}$ ) and late summer NDVI were calculated. The difference in the NDVI-PWD relationships between GDE and non-GDE areas are readily apparent when mapped (Figure 6) with non-GDE vegetated areas, showing an almost universal statistically significant ( $p < 0.05$ ) response to interannual variability in climate. Within GDE areas, all groups had interquartile ranges of correlations below  $r=0.55$ , and all median values were less than 0.5, with the exception of the Salt Desert Scrub group (Figure 7), which had higher correlations and occurs in the northern portion of the GDE area (Figure 6). Mesic LANDFIRE groups tended to have lower NDVI-PWD correlations than dryland groups, indicating that the vigor of these mesic vegetative communities are less influenced by interannual variations in PWD. Overall, NDVI-PWD correlations tended to be lower than those for the same vegetation types in other basins (see Albano *et al.*, 2021, Figure 3) which could be due to the stronger reliance of vegetation on groundwater subsidies due to shallower groundwater and lower precipitation in this region as compared to other basins assessed. This could also be driven by distinctions in plant phenology



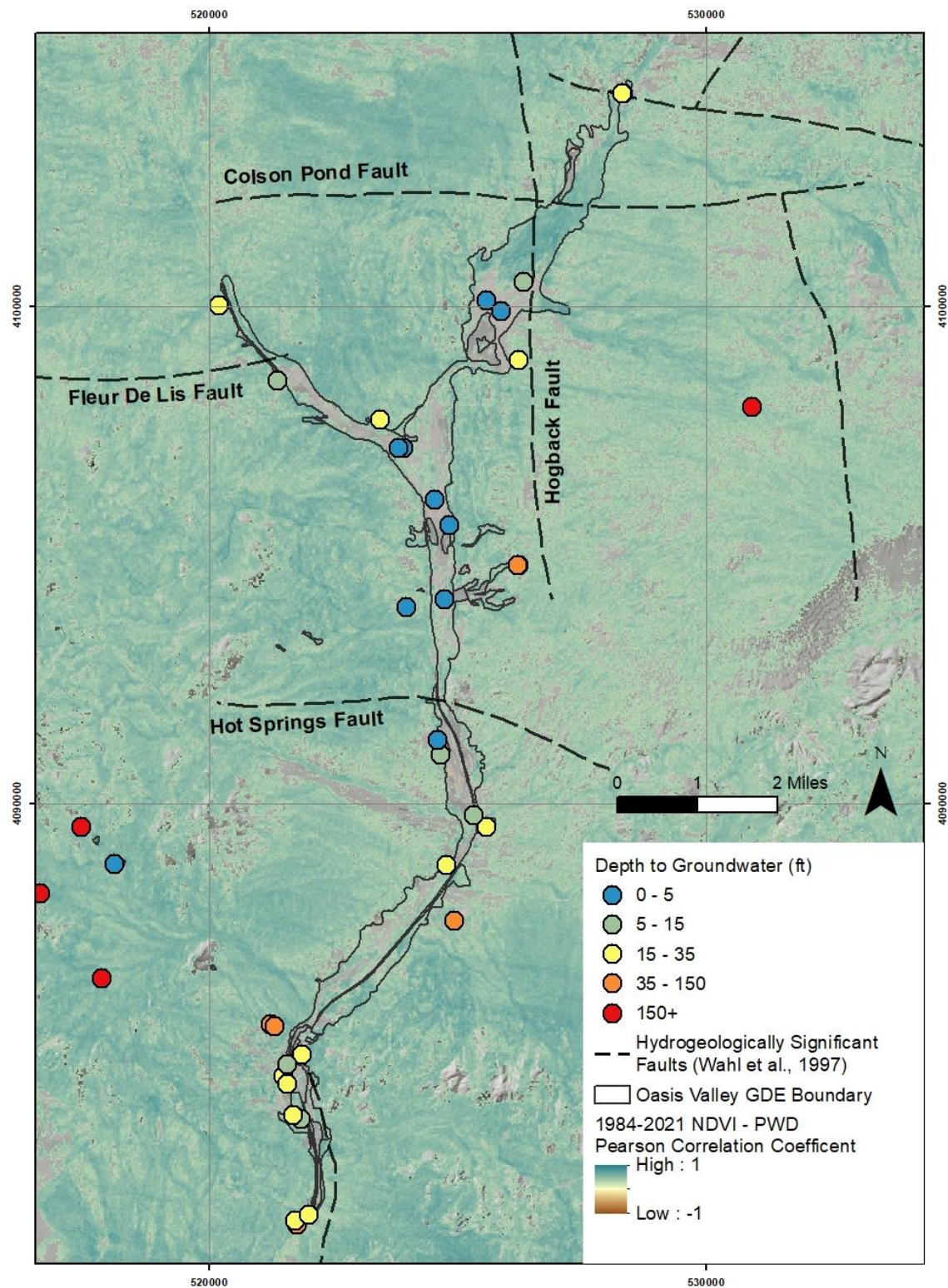


Figure 6. Map showing the distribution of the 1984 - 2021 NDVI-PWD Correlation (Pearson's  $r$ ) throughout the Oasis Valley study area. Non-significant correlations ( $p > 0.05$ ) are transparent.

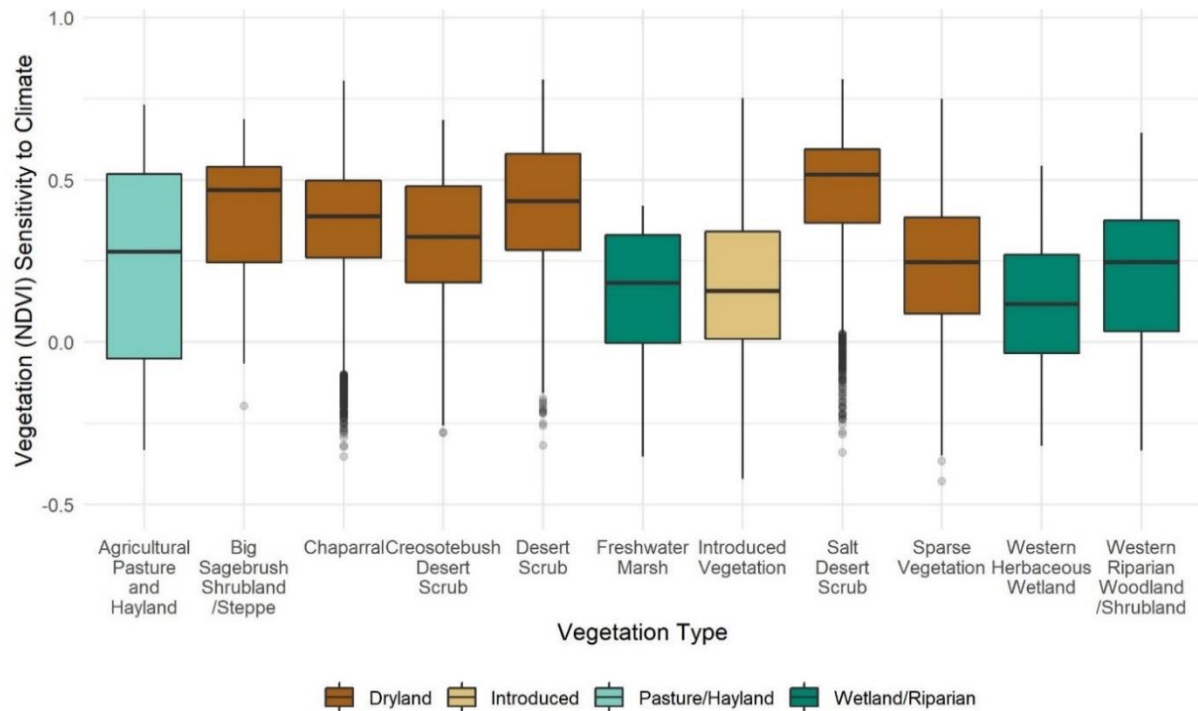


Figure 7. Sensitivity of late-summer NDVI to interannual variations in climatic conditions (measured as the Pearson correlation coefficient between annual median July-Sept NDVI and water year PWD) for select LANDFIRE vegetation types within GDE areas. More developed LANDFIRE types including Developed/Transitional and Agricultural - Close Grown Crop are excluded, as is the 'Other' category, which includes a wide variety of vegetation types and covers a small area.

of the Mojave relative to those that occur in the Great Basin. Many plants in the Mojave are adapted to respond to both winter and monsoonal precipitation and this distinction is not specifically accounted for with the use of annual PWD. Because the timing of riparian NDVI peaks in southern Nevada tended to occur later in the season (July-Sept) relative to upland vegetation types (April-May) (see Albano *et al.*, 2020, Figure S2), the use of annual PWD was used here but additional studies that assess seasonal (e.g., pre-monsoon, April-June) precipitation influences could provide additional insight.

### ***Climate-Adjusted Trends in Vegetation Vigor***

Overall, the distributions of climate-adjusted trends tended to be more positive in upland (i.e., non-GDE) areas, than within the GDE area (Figure 8), meaning that a larger proportion of pixels classified as upland vegetation types have increasing (positive trend) vegetation vigor than is the case for pixels within the GDE area. That said, the largest magnitude trends (slopes greater and lesser than 0.0025 and -0.0025 for positive and negative trends, respectively) tended to occur in mesic vegetation types (Figure 9) and GDE areas (Figure 10).

One potential reason for differences between GDE and upland areas is that the former often occur at the lowest elevations in the watershed or basin and are therefore more likely be impacted by the direct and indirect effects of anthropogenic disturbances, such as land use change, groundwater pumping, and surface water diversion and capture, in aggregate. These

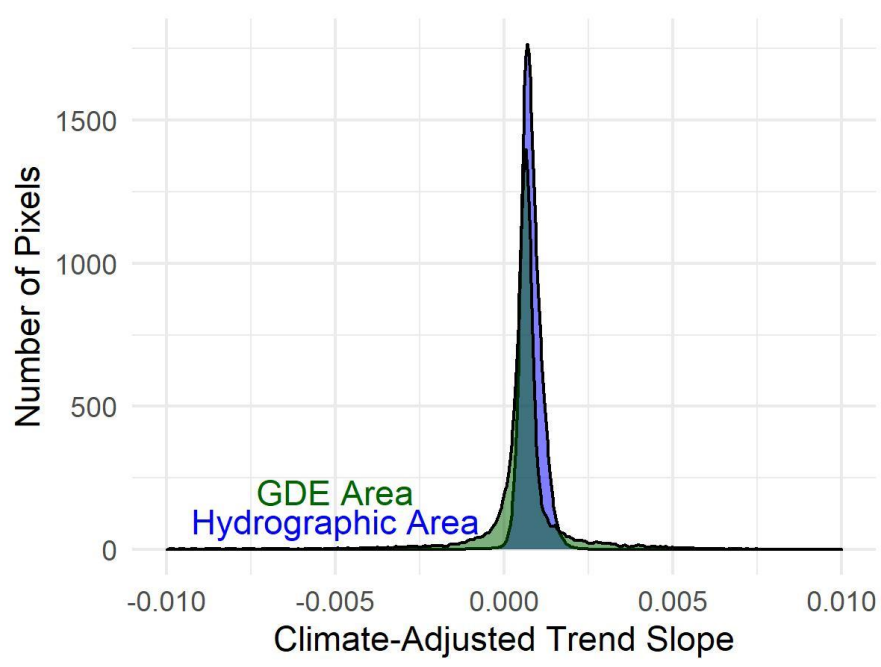


Figure 8. Distribution of climate-adjusted trends in late-summer NDVI for pixels within non-GDE areas vs. those in the GDE areas for the Oasis Valley Hydrographic Area (i.e., excluding Beatty Narrows).

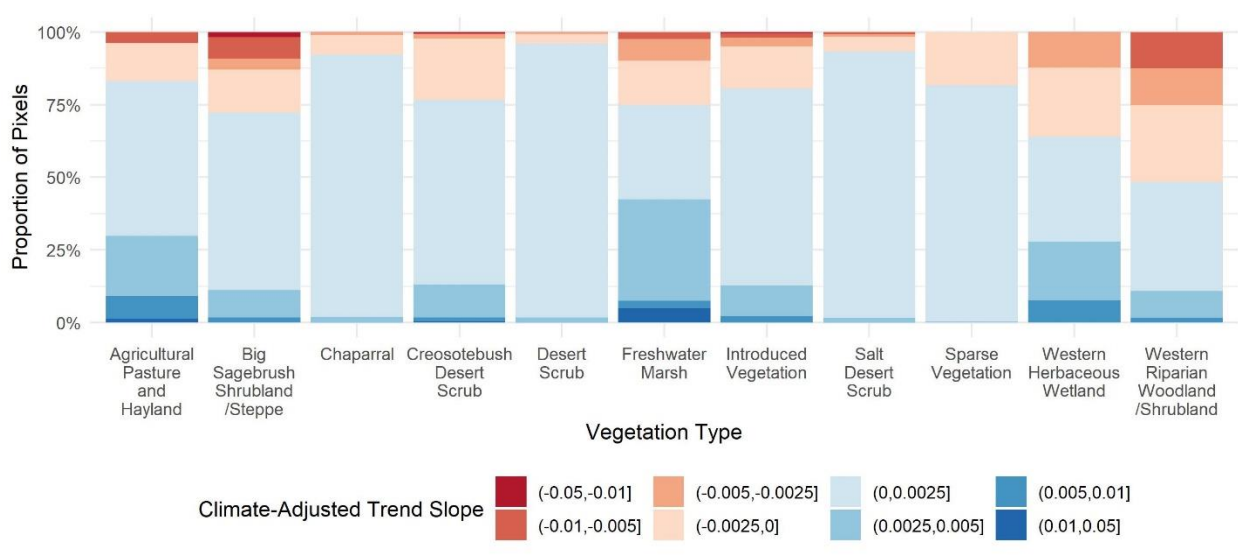


Figure 9. GDE Area Climate-adjusted 1984 – 2021 trend slope magnitude and direction by LANDFIRE group for vegetation types within GDE boundaries. Note that positive trends dominate most classes, and a greater proportion of moderate-large magnitude trends are seen in mesic groups.



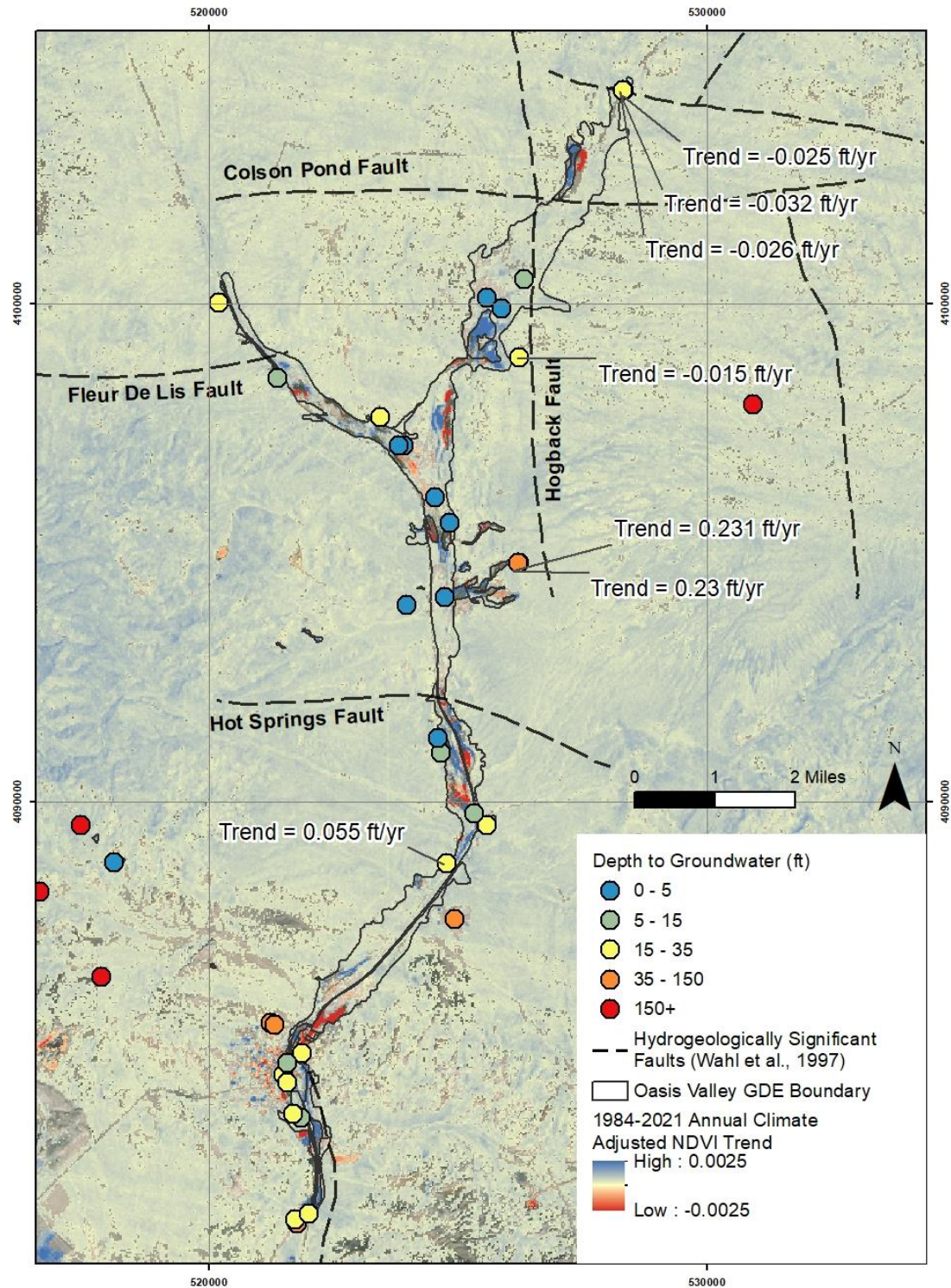


Figure 10. Map showing the distribution of the 1984-2021 late summer climate-adjusted NDVI trend slope (Sen's estimate of slope) throughout the Oasis Valley study area. Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map (note that some wells overlap).

disturbances are particularly prevalent where water is closest to the ground surface, as is the case in areas of mesic vegetation. Another potential reason for more positive slopes in non-GDE areas may be the greening of higher elevation vegetation where water is less limiting as part of the global greening phenomenon driven by increased concentration of carbon dioxide in the atmosphere (Lu *et al.*, 2016; Zhu *et al.*, 2016). This pattern of more positive trends in upland vegetation relative to that observed in phreatophyte boundaries was also observed in all other basins assessed by Albano *et al.* (2021). In terms of the large proportion of negatively trending Riparian Woodland and Shrubland vegetation (Figure 9), TNC partners suggest that these changes are likely a combination of tamarisk removal, water diversion, or changes in irrigation in the Colson Ponds area of the 7J Ranch and Revert Springs.

### **Groundwater Status, Trends, and Relation to GDEs**

For the 39 well locations used in this study, maximum recorded DTW from wells within the GDE boundary ranged between 0 – 25 feet, with an average maximum depth of 10 feet. The IDs, dataset temporal information, DTW values, and trend information of all 39 of the qualified groundwater monitoring locations are summarized in Table 2 (see Figure 4 for corresponding map locations). Of this subset, 25 locations had the minimum selection criteria of 3 years of unique observations required for trend assessment.

Overall, most (17 of 25) wells exhibited rising water levels (decreases in DTW), though in most cases changes were not statistically significant. Seven wells, all of which had at least 25 years of data, had statistically significant trends. Four of the seven had rising water levels, where DTW decreased between  $0.032 - 0.015 \text{ ft yr}^{-1}$  and amounted to total water elevation increases of  $0.53 - 0.74 \text{ ft}$  over the period of record. These were located in the 7J Ranch area (Well IDs 1,2,3, and 7; Table 2). The other three exhibited declines in water levels, where DTW increased between  $0.055 - 0.23 \text{ ft yr}^{-1}$  between 1997 and 2022, and amounted to total decreases in water elevations of  $0.29 - 5.2 \text{ ft}$ . These are near the Torrance Ranch East AOI (Well IDs 15-17; Table 2). Unknowns related to the timing and extent of the spring diversion and disturbance history of GDEs in the area obscure any potential indication that abstraction may be affecting downgradient GDEs. Conclusions regarding groundwater development-related impacts to GDEs throughout Oasis Valley are difficult to make given the spatially and temporally limited groundwater monitoring data.

### **SITE-SPECIFIC RESULTS FOR AREAS OF INTEREST (AOIs)**

More detailed assessments of climate, vegetation, and groundwater relations were conducted for 9 AOIs located across the Oasis Valley study area (Figure 3). The AOIs assessed here were identified in collaboration with TNC and were selected to represent areas of recent or future restoration, critical habitat for sensitive species, spring features exposed to potential impacts from planned mining operations, and areas of ecological importance. Field investigations and aerial sUAS surveys (where permitted) were conducted to ground truth changes observed in the satellite record in May 2022. These field activities resulted in the collection of detailed vegetation transect data and high-resolution aerial images that can be used as a baseline for future assessments and monitoring. A summary of satellite and climate statistics for each AOI is included in Table 3, and observations of disturbance based on field investigation are included in Table 4.

Table 2. Statistics for shallow groundwater wells within the Oasis Valley study area (See Figure 4 for locations of each well ID). Wells associated with each AOI are within 1 mile of the AOI. Depth to groundwater values are reported as feet below ground surface (bgs). Positive trends indicate increasing depth to groundwater (i.e., lower groundwater levels). Red or blue shading indicates statistically significant positive or negative trends, respectively, with darker shading indicating steeper slopes. Trend test p-values are based on the Mann-Kendall test modified to account for up to 3-years of serial autocorrelation for locations with at least 3 water years (WYs) of data during 1984 – 2021. Minimum, maximum, and mean DTW values considered the entire span of the groundwater record.

ID	USGS / NDWR Site Name	Groundwater Record			Elevation (ft amsl)		Depth to Groundwater (ft bgs)			Depth to Groundwater Trend	
		No. WYs	Start Year	End Year	Land Surface	Mean Groundwater	Min.	Max.	Mean	Slope (ft yr <sup>-1</sup> )	p- value
AOI-1 7J Ranch Upper											
1	<a href="#">228 S10 E47 11ADAD1 ER-OV-01</a>	25	1997	2021	4007.3	3992.7	17.4	18.4	17.9	-0.032	0.00
2	<a href="#">228 S10 E47 11ADAD2 ER-OV-06a</a>	25	1997	2021	4007.5	3995.7	14.5	20.4	15	-0.025	0.00
3	<a href="#">228 S10 E47 11ADAD3 ER-OV-06a2</a>	25	1997	2021	4007	3991.8	17.9	24.2	18.5	-0.026	0.00
AOI-2 7J Ranch Lower											
4	<a href="#">228 S10 E47 22DBD 1 OVU-Dune Well</a>	4	1998	2001	3883	3879.4	6.1	7.5	6.8	0.093	0.31
5	<a href="#">228 S10 E47 22CCD 1 OVU-Middle ET Well</a>	3	1999	2001	3856	3856.4	0.9	4.6	2.8	Insufficient Data	
6	<a href="#">228 S10 E47 27BAA 1 OVU-Lower ET Well</a>	4	1998	2001	3861	3859.3	2.7	6.2	4.8	-0.297	0.09
7	<a href="#">228 S10 E47 27BCD1 ER-OV-02</a>	25	1997	2021	3880.3	3855.1	28	29	28.3	-0.015	0.00
AOI-3 Torrance Ranch West											
8	<a href="#">228 S10 E47 33CCA 1 Springdale ET Deep Well</a>	6	1996	2001	3714.2	3718.1	-2.3	0.8	-0.8	-0.063	0.71
9	<a href="#">228 S10 E47 33CCA 2 Springdale ET Shallow Well</a>	6	1996	2001	3714.2	3716.4	-0.3	2.8	0.9	-0.04	1.00
10	<a href="#">228 S10 E47 33CCB 1 Springdale Lower Well</a>	6	1996	2001	3710	3709.5	-0.1	8.1	3.6	-0.443	0.26
AOI-3 Torrance Ranch West and AOI-4 Torrance Ranch East											
11	<a href="#">228 S11 E47 04ACC 1 OVM ET Well</a>	5	1997	2001	3690.7	3691.1	0.2	4.4	2.7	-0.063	0.81
12	<a href="#">228 S11 E47 04D 1 NC-GWE-OV-01</a>	5	2011	2015	3684.9	3687.1	-4	0	-2.1	-0.565	0.22
13	<a href="#">228 S11 E47 09DBD 1 Boiling Pot Rd Well</a>	5	1997	2001	3620	3621.1	0.4	3.3	2	0.014	0.81
14	<a href="#">228 S11 E47 09CBD 1 Pioneer Road Seep Well</a>	5	1997	2001	3650	3652.1	-0.3	2.6	1	0.32	0.46

Table 2. Statistics for shallow groundwater wells within the Oasis Valley study area (See Figure 4 for locations of each well ID). Wells associated with each AOI are within 1 mile of the AOI. Depth to groundwater values are reported as feet below ground surface (bgs). Positive trends indicate increasing depth to groundwater (i.e., lower groundwater levels). Red or blue shading indicates statistically significant positive or negative trends, respectively, with darker shading indicating steeper slopes. Trend test p-values are based on the Mann-Kendall test modified to account for up to 3-years of serial autocorrelation for locations with at least 3 water years (WYs) of data during 1984 – 2021. Minimum, maximum, and mean DTW values considered the entire span of the groundwater record (continued).

ID	USGS / NDWR Site Name	Groundwater Record			Elevation (ft amsl)		Depth to Groundwater (ft bgs)			Depth to Groundwater Trend	
		No. WYs	Start Year	End Year	Land Surface	Mean Groundwater	Min.	Max.	Mean	Slope (ft yr <sup>-1</sup> )	p- value
AOI-4 Torrance Ranch East											
15	<a href="#">228 S11 E47 10ACAB1 ER-OV-03a</a>	25	1997	2021	3841.3	3785	56.5	61.7	59.4	0.23	0.00
16	<a href="#">228 S11 E47 10ACAB2 ER-OV-03a2</a>	25	1997	2021	3840.7	3683.7	159.4	160.9	160.1	0.03	0.00
17	<a href="#">228 S11 E47 10ACAB3 ER-OV-03a3</a>	25	1997	2021	3840.7	3784.6	56.3	61.6	59.2	0.23	0.00
AOI-5 Crystal Spring											
No wells within 1 mile											
AOI-6 Brian Spring											
No wells within 1 mile											
AOI-7 Parker Ranch											
18	<a href="#">228 S11 E47 21ACC 1 P Ranch Well</a>	1	1996	1996	3590	3592.9	0.1	0.1	0.1	Insufficient Data	
19	<a href="#">228 S11 E47 21DBAC1 NC-GWE-OV-02</a>	5	2011	2015	3545.3	3534.8	9.3	12	10.5	-0.251	0.31
20	<a href="#">228 S11 E47 27BCB 1 Ute Springs Drainage Well</a>	5	1997	2001	3490	3490.5	-0.1	5.9	2.6	0.13	0.81
AOI-8 Stagecoach											
21	<a href="#">228 S12 E47 06DC 1 Beatty Water Test Hole</a>	1	1963	1963	3365	3288	80	80	80	Insufficient Data	
22	<a href="#">228 S12 E47 06DCC 1 Beatty Well No. 1</a>	1	1962	1962	3365	3273	95	95	95	Insufficient Data	
AOI-8 Stagecoach and AOI 9 Beatty Narrows											
23	<a href="#">228 S12 E47 07ADAC1</a>	1	2018	2018	3294	3275.7	18.1	18.7	18.3	Insufficient Data	
24	<a href="#">228 S12 E47 07ACD 1 Central Beatty Well</a>	3	1966	1998	3300	3290.2	10.6	14.8	12.8	-0.056	1.00



Table 2. Statistics for shallow groundwater wells within the Oasis Valley study area (See Figure 4 for locations of each well ID). Wells associated with each AOI are within 1 mile of the AOI. Depth to groundwater values are reported as feet below ground surface (bgs). Positive trends indicate increasing depth to groundwater (i.e., lower groundwater levels). Red or blue shading indicates statistically significant positive or negative trends, respectively, with darker shading indicating steeper slopes. Trend test p-values are based on the Mann-Kendall test modified to account for up to 3-years of serial autocorrelation for locations with at least 3 water years (WYs) of data during 1984 – 2021. Minimum, maximum, and mean DTW values considered the entire span of the groundwater record (continued).

ID	USGS / NDWR Site Name	Groundwater Record			Elevation (ft amsl)		Depth to Groundwater (ft bgs)			Depth to Groundwater Trend	
		No. WYs	Start Year	End Year	Land Surface	Mean Groundwater	Min.	Max.	Mean	Slope (ft yr <sup>-1</sup> )	p-value
25	<a href="#">228 S12 E47 07DBA 1 Beatty Well No. 2</a>	1	1963	1963	3300	3283	20	20	20	Insufficient Data	
26	<a href="#">228 S12 E47 07DBD 1 Beatty Well No. 3</a>	1	1965	1965	3290	3277	16	16	16	Insufficient Data	
27	<a href="#">228 S12 E47 18AAB 1 BGC-1 Well</a>	1	1999	1999	3270	3257	15.9	15.9	15.9	Insufficient Data	
28	<a href="#">228 S12 E47 18AAC 1 BGC-2 Well</a>	2	1999	2000	3261	3252.6	10	12.6	11.3	Insufficient Data	
<b>AOI-9 Beatty Narrows</b>											
29	<a href="#">230 S12 E47 19ADA 1 Narrows South Well 2</a>	12	1971	2009	3180	3164.3	15.6	20	18.6	-0.023	0.09
30	<a href="#">230 S12 E47 19ADCB1 Narrows South Well 1</a>	2	1971	1987	3180	3164.1	17.6	20	18.8	Insufficient Data	
31	<a href="#">230 S12 E47 19ADC 1 Narrows South Well 3</a>	2	2020	2021	3180	3138.8	41	41.4	41.2	Insufficient Data	
<b>Additional well sites &gt; 1 mile from AOIs</b>											
32	<a href="#">228 S10 E46 24DDDC1 ER-OV-05</a>	25	1997	2021	3934.7	3905.9	31.7	32.2	31.9	-0.001	0.75
33	<a href="#">228 S08 E49 03 23 UE-20f (6976-7174 ft)</a>	1	1964	1964	6116.3	6078.6	-4.7	112.8	41.7	Insufficient Data	
34	<a href="#">228 S10 E47 30DCC 1 Springdale Windmill Well</a>	4	1941	2000	3870	3858.8	13.6	17	14.3	-0.04	0.46
35	<a href="#">228 S10 E47 32ADC 1 Springdale Upper Well</a>	26	1996	2021	3775	3754	23.1	24.7	24.1	-0.003	0.22
36	<a href="#">228 S11 E47 27BCDD1 ER-OV-04a</a>	25	1997	2021	3488.3	3467.5	23	24.6	23.9	-0.003	0.61
37	<a href="#">228 S11 E46 26DCC 2 Lower Indian Springs Well</a>	5	1996	2001	4030	4031.5	0.2	3	1.7	-0.61	0.26
38	<a href="#">228 S11 E47 28DCD 1 Beatty Wash Terrace Well</a>	26	1996	2021	3450	3433.1	17	22.3	19.9	<b>0.055</b>	<b>0.00</b>
39	<a href="#">228 S11 E47 33DAC 1 Perlite Canyon Ranch Well</a>	3	1988	1997	3510	3410.4	100.8	106	102.6	-0.58	0.30

Table 3. Zonal statistics for nine Oasis Valley AOIs. Minimum, maximum, and mean NDVI values are from the annual late summer median NDVI time series. NDVI sensitivity to climate is the Pearson correlation coefficient between NDVI and annual PWD. Climate-adjusted NDVI trend is the Sen's slope estimate of NDVI residuals (1984 – 2021), accounting for the influence of annual water deficit. Climate trend is the Sen's slope of water year PWD (1984 – 2021). Blue or red shading indicate statistically significant positive or negative trends or correlation, respectively. No shading indicates trend or correlation was not statistically significant based on a threshold p-value of 0.05. Trend test p-values are based on the modified Mann-Kendall test.

AOI		1984-2021 Annual Median July-Sept. NDVI (unitless)			NDVI Sensitivity to Climate	Climate Adjusted NDVI Trend	Climate (PWD) Trend
ID	Name	Min.	Mean	Max.	Pearson's <i>r</i>	(yr <sup>-1</sup> )	(in/yr)
AOI-1	7J Ranch Upper	0.20	0.27	0.37	-0.05	0.004	-0.15
AOI-2	7J Ranch Lower	0.27	0.35	0.44	0.03	0.003	-0.14
AOI-3	Torrance Ranch West	0.35	0.40	0.50	0.25	-0.001	-0.14
AOI-4	Torrance Ranch East	0.29	0.36	0.50	0.19	-0.001	-0.14
AOI-5	Crystal Spring	0.17	0.21	0.25	0.24	0.002	-0.14
AOI-6	Brian Spring	0.10	0.13	0.16	0.11	0.001	-0.14
AOI-7	Parker Ranch	0.32	0.47	0.59	0.37	-0.002	-0.14
AOI-8	Stagecoach Reach	0.15	0.24	0.31	-0.03	0.003	-0.10
AOI-9	Beatty Narrows	0.18	0.25	0.31	-0.04	0.003	-0.10

Table 4. Summary of observed impacts based on field observations from May 2022 and 38-year trends in Normalized Difference Vegetation Index (NDVI) and potential water deficit (PWD; see Table 3). Sites are ordered from north to south. Note that groundwater trends are reported in terms of elevation rather than depth in this table only to facilitate consistent directional conventions in comparisons of trends across multiple variables. Green or red shading indicate statistically significant at  $p < 0.05$  positive or negative trends, respectively. In the case of groundwater elevation trends, lighter shading indicates only a portion of wells had significant trends, while darker shading indicates trend was significant for all wells in the vicinity of the AOI.

AOI	Observed Impacts				Time Series Data		
Name	Diverted Water	Channel Erosion / Incision	Invasive Plants	Grazing	NDVI Trend	Groundwater Elevation Trend	PWD Trend
AOI-1 7J Ranch Upper	X		X	X (Livestock)	Increase	Increase	Decrease
AOI-2 7J Ranch Lower	X	X		X (Livestock)	Increase	No trend/ Increase	Decrease
AOI-3 Torrance Ranch West	Recently restored, all impacts previously applied				No trend	No trend	Decrease
AOI-4 Torrance Ranch East	X	X	X	X (Livestock)	No trend	No trend/ Decrease	Decrease
AOI-5 Crystal Spring	X		X		Increase	No Data	Decrease
AOI-6 Brian Spring	X		X	X (Livestock + Burro)	Increase	No Data	Decrease
AOI-7 Parker Ranch	X		X		No trend	No trend	Decrease
AOI-8 Stagecoach	X	X	X		Increase	No trend	Decrease
AOI-9 Beatty Narrows	X	X	X	X (Livestock + Burro)	Increase	No trend	Decrease

## AOI-1—Upper 7J Ranch

### *Site description*

The Upper 7J Ranch AOI is located at the headwaters of the Amargosa River and encompasses Suzie Kimball Spring which is the source of discharge for the highest elevation perennial flow within the Amargosa River flow system. The AOI is oriented roughly N-S and covers constructed ponds as well as an area of GDE vegetation extending roughly 0.6 mi downgradient. As with other locations around the basin, the 7J Ranch property has a long legacy of anthropogenic involvement and impact. Dating back to circa 1910, spring discharge was diverted into an unlined impoundment (pond) constructed of native fill (Boisrame *et al.*, 2021). A water right application associated with this effort indicates the spring's annual discharge was approximately 1,090 acre-feet annually (AFA) before its ponding. Two measurements by the USGS in 1962 and 1967 put the post-pond construction discharge at 80 and 160 AFA, respectively.

Field observations revealed clear evidence of anthropogenic disturbances in the forms of water diversion, grazing, and the presence of invasive species. Following the Ranch's acquisition by TNC in 2019 grazing practices were modified and invasive species removed to promote the sustainability of GDEs. During the May 2022 site visit, surface water flow was observed in the area immediately downgradient of the pond, and along two braided swales. This area supports obligate wetland species, while dryland GDE shrubs like rabbitbrush and greasewood occur near the AOI's downgradient and lateral boundaries. Dense graminoids cover the majority of the AOI's extent, which was drawn to intentionally avoid a dense stand of mature Fremont Cottonwood trees, thus focusing on the wet meadow area, though several scattered cottonwoods exist within the AOI boundary. Overall vegetative cover along transects varied from relatively low (< 30%) in dryland shrub areas to very dense (> 95%) in graminoid-dominated areas. The vegetation observed along transects was relatively consistent with LANDFIRE classifications of *Freshwater Marsh* and *Western Riparian Woodland and Shrubland*. See Appendix B for photographs and aerial imagery.

### *Groundwater*

Upper 7J Ranch is located just under a mile downgradient of three groundwater monitoring points close enough to the AOI to warrant consideration (Table 2). All three wells had adequate data for trend analysis (3 + years) and were found to have significant trends ( $p < 0.05$ ). Groundwater elevations in all three wells were found to be rising (DTW decreasing) at a rate of  $0.025 - 0.32 \text{ ft yr}^{-1}$  between 1997 and 2022 (Figure 11). Hydraulic head values indicate an upwards gradient suggesting groundwater discharge in this area may originate from a deep source. Groundwater elevations rose by a total of  $0.5 - 0.7 \text{ ft}$  between 1997 and 2022. The reason for these changes in groundwater levels is uncertain but merits additional study.

### *Vegetation*

NDVI values for Upper 7J Ranch AOI were generally between  $0.2 - 0.4$  (Figure 12), consistent with expected values for mesic vegetation types. The early portion of the NDVI timeseries is characterized by a visually apparent relationship with interannual PWD, but by about 2003 these variables no longer closely covaried and the NDVI-PWD correlation over the



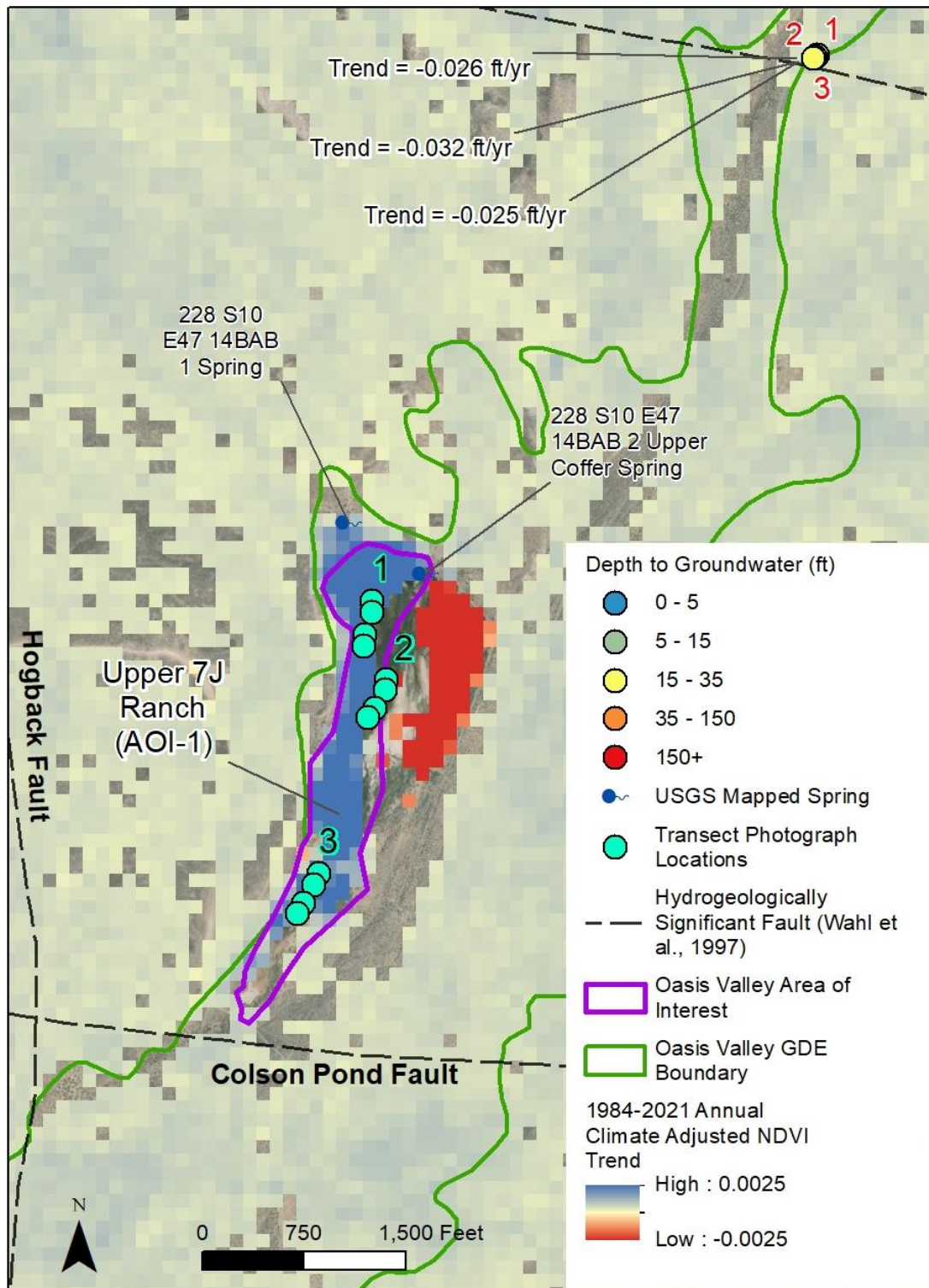


Figure 11. Map showing climate-adjusted NDVI trend for Upper 7J Ranch AOI (AOI-1). AOI and well ID's (red numbers) correspond to data in Table 2. Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map (note that some wells overlap).

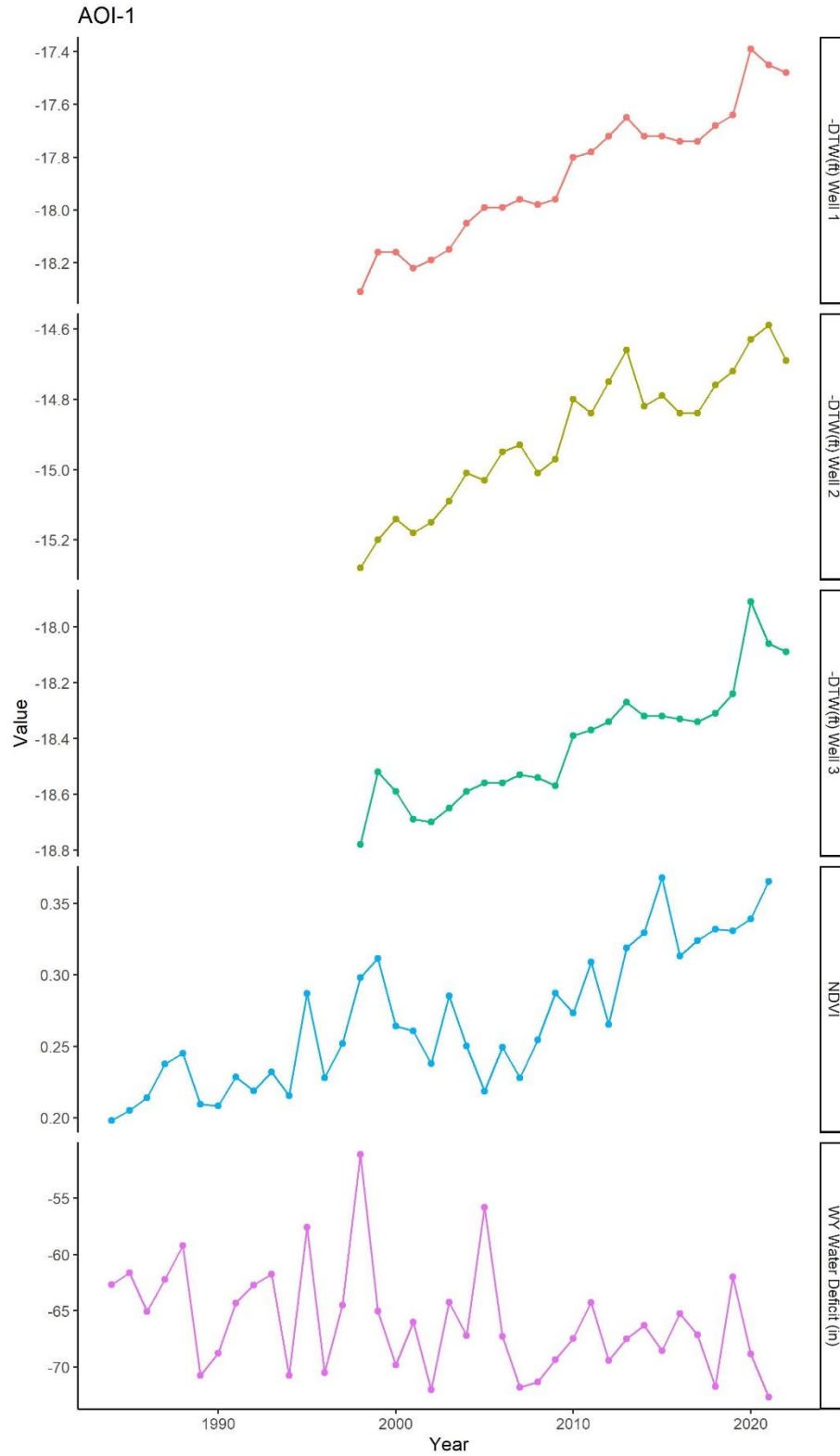


Figure 12. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD), and groundwater levels for wells within 1 mile of the Upper 7J Ranch AOI (AOI-1).

period of study was not significant (Table 3). NDVI values exhibit a positive trend starting in about 2005 (Figure 12). Groundwater levels are observed to be somewhat variable during the 1997-2003 period, then consistently start rising (see links in Table 2), which could explain observed changes in sensitivity and greening of vegetation, as groundwater becomes more accessible to plants. Figure 13 provides 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD. Because NDVI-PWD relations are essentially unrelated and NDVI is trending positively (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable but the historical range (Table 3) may still be useful for identifying the occurrence of anomalous NDVI values relative to the historical record.

## AOI-2—Lower 7J Ranch

### Site description

The Lower 7J Ranch AOI (AOI-2) is located roughly 2 mi downgradient of AOI-1 towards the downgradient end of the 7J Ranch property. Unlike Upper 7J, which is centered around a single spring with high discharge, the Lower 7J Ranch AOI covers a GDE derived from a broader area of diffuse seepage supported by shallow groundwater. This area of shallow groundwater is believed to be associated with the regionally significant Hogback fault. The Hogback Fault acts as a barrier to cross-fault flow in the Lower 7J Ranch area because offset from the fault's motion has resulted in the abrupt thinning of the highly conductive welded tuff aquifer. The welded tuff aquifer is a regionally significant pathway for groundwater moving from areas of recharge around Pahute Mesa towards discharge areas in Oasis Valley (Jackson *et al.*, 2021).

Lower 7J Ranch AOI (Figure 14) is roughly triangular, with a bedrock high excluded from the middle. At approximately 0.6 mi in the N-S direction and about 0.5 mi wide at its largest width, the 97-acre AOI-2 is more than double the size of the next largest AOI in this

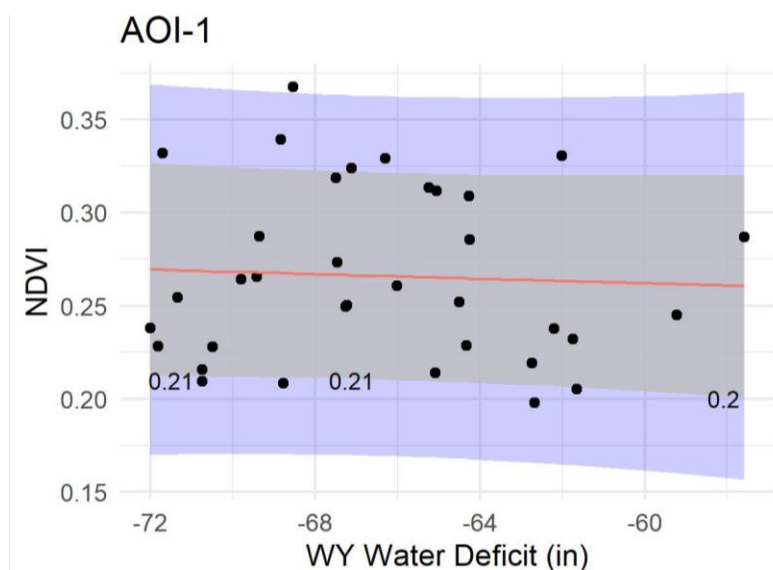


Figure 13. Linear regression relationships between annual PWD and NDVI for Upper 7J Ranch AOI (AOI-1). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.



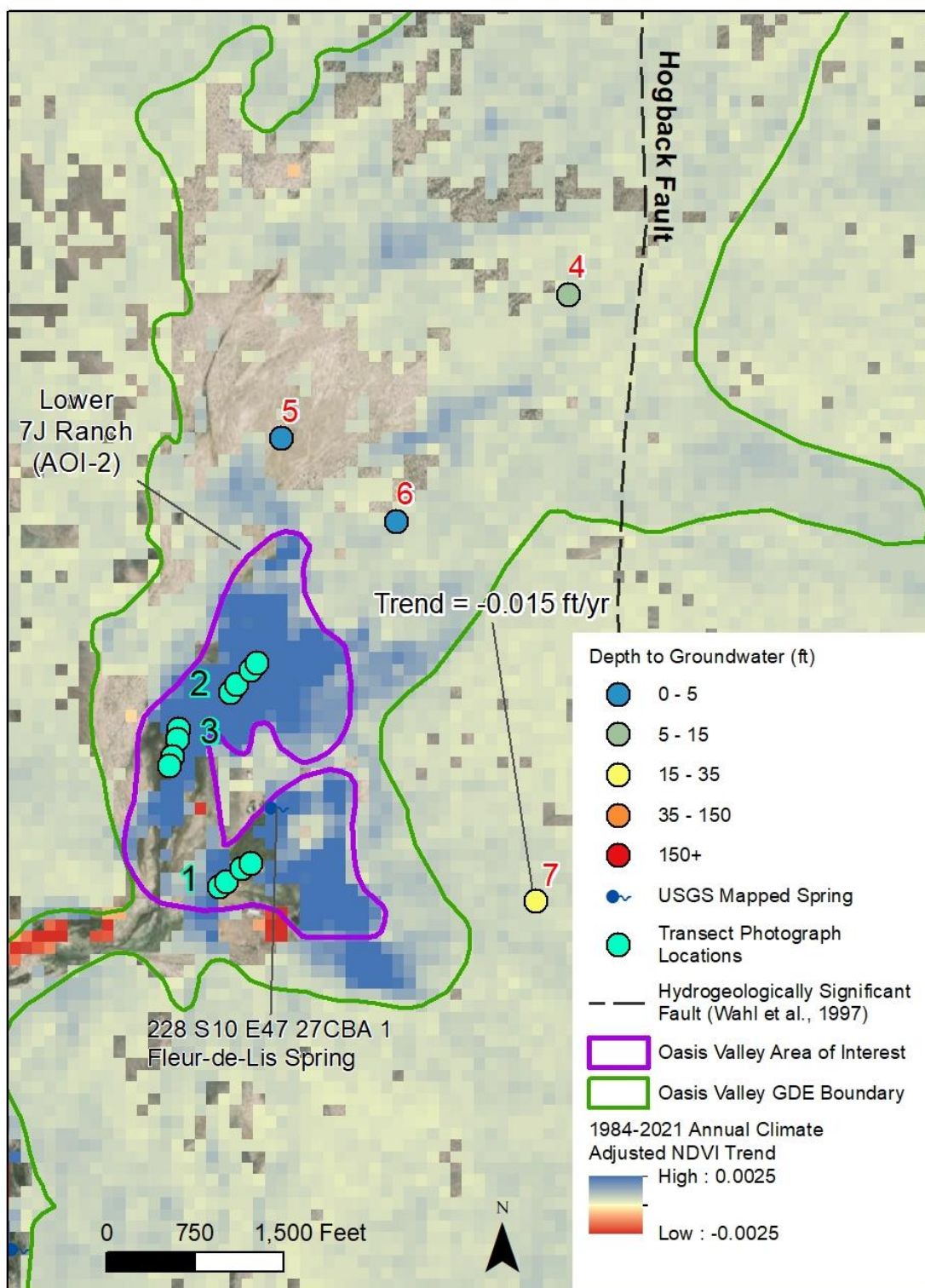


Figure 14. Map showing climate-adjusted NDVI trend for Lower 7J Ranch AOI (AOI-2). AOI and well ID's (red numbers) correspond to data in Table 2 Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map (note that some wells overlap).

study. Though most of the groundwater discharge appears to occur in the form of diffuse seepage and evapotranspiration, several springs with discrete discharge points were observed throughout the AOI during the May 2022 field visit. Diffuse and shallow surface water was observed over significant portions of the AOI, particularly within the north and western sections. Saturated areas were observed to be characterized by very slow but nonzero overland flow velocity, an observation that reflects the diffuse but perennial groundwater discharge throughout AOI-2. The AOI supports a large area of mesic to wet-mesic GDE vegetation classified as Western Herbaceous Wetland. Other dominant vegetation classes include *Introduced Annual Grassland* and Creosotebush Desert Scrub. See appendix B for site photographs and aerial imagery.

### ***Groundwater***

Four wells were identified close enough to AOI-2 to warrant consideration, of these, three had adequate data for trend assessment. Only ER-OV-02 (located roughly ¼ mile to the east-southeast of AOI-2) was found to have a significant ( $p < 0.05$ ) trend (Table 2; Figure 15) and this was the only well with a record beyond 2001. Groundwater levels in this well were found to be increasing (decreasing DTW) at a rate of  $0.015 \text{ ft yr}^{-1}$  between 1997 and 2022 resulting in a total of 0.6 ft of groundwater recovery. DTW values at all four wells are relatively shallow (mean DTW of 2.8-28.3 ft), consistent with expectations given the wet meadow GDE system observed throughout most of the AOI. The reason for the observed trend is unknown.

### ***Vegetation***

NDVI values for Lower 7J Ranch (AOI-2) are between 0.25 – 0.44 (Table 3). Similar to Upper 7J Ranch, the NDVI timeseries shows correspondence with interannual changes in PWD, but starting in the 2000s, an upward trend in NDVI (Figure 15) decouples the PWD-NDVI relationship, resulting in a non-significant correlation overall (Table 3). Given the close timing of changes in both vegetation and groundwater levels in well [ER\\_OV-02](#) (see Table 2) to that observed in Upper 7J ranch, it is plausible that rising groundwater levels may explain positive trends in vegetation in Lower 7J Ranch as well, given overall drying climate (Table 3), which potentially could cause reduced vegetation vigor. Figure 16 provides 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD. Because NDVI-PWD are essentially unrelated ( $r$  close to 0; Table 3) and NDVI is trending positively (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable but the historical range (Table 3) may still be useful for identifying the occurrence of anomalous NDVI values relative to the historical record.

## **AOI-3—West Torrance Ranch**

### ***Site description***

West Torrance Ranch AOI (AOI-3; Figure 17) is located just west of the Amargosa River's channel roughly 2.1 mi downgradient of the Lower 7J Ranch AOI. AOI-3 is a roughly N-S oriented elongated oval area situated between the Amargosa River and U.S. Route 95. This location has been protected from most forms of anthropogenic disturbance since its purchase and restoration by TNC in 1999. Located on the first property TNC purchased in Oasis Valley, this location was selected as an AOI because of the extensive restoration work carried out to improve

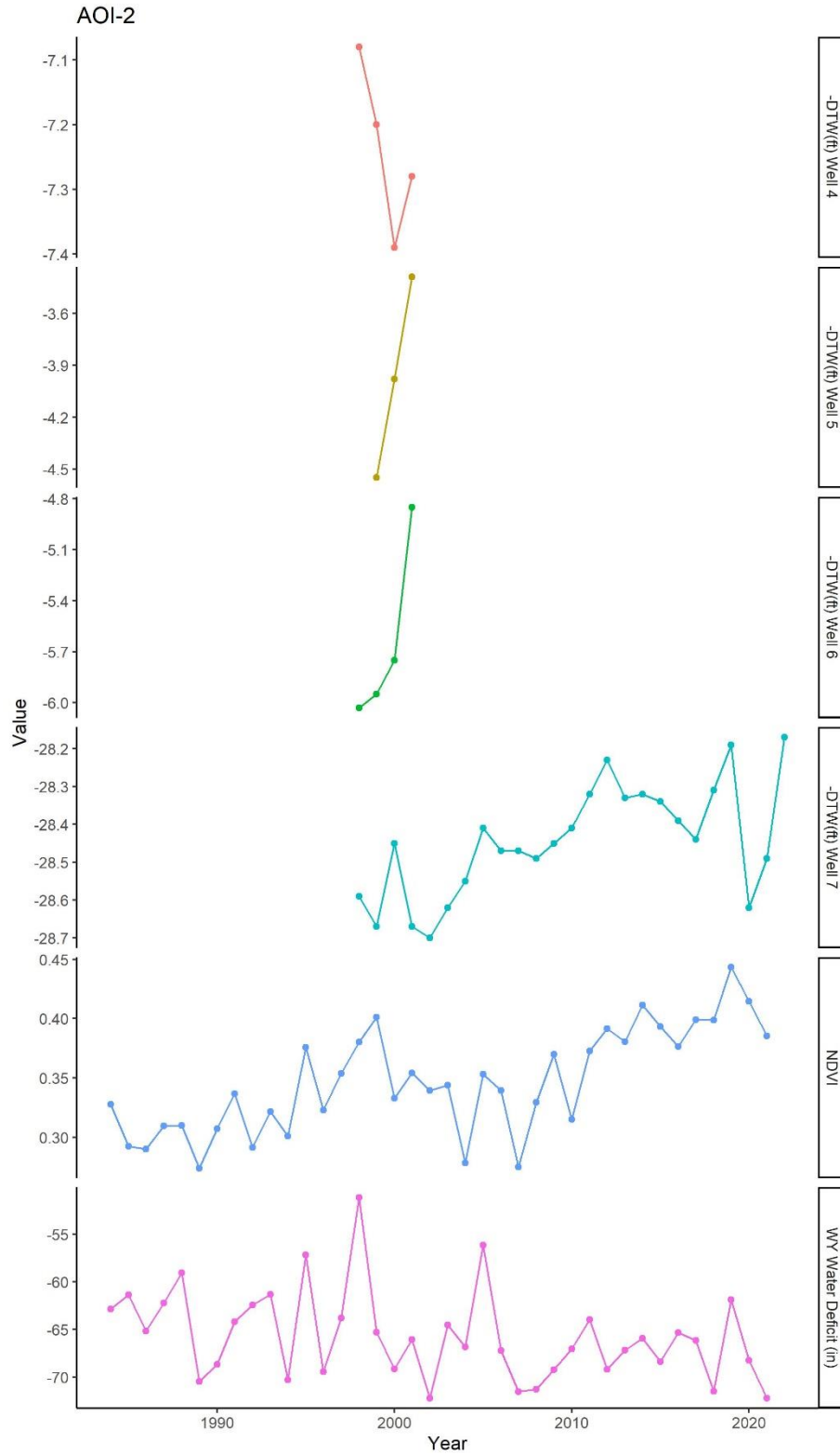


Figure 15. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD), and groundwater levels for wells within 1 mile of the Lower 7J Ranch AOI (AOI-2).

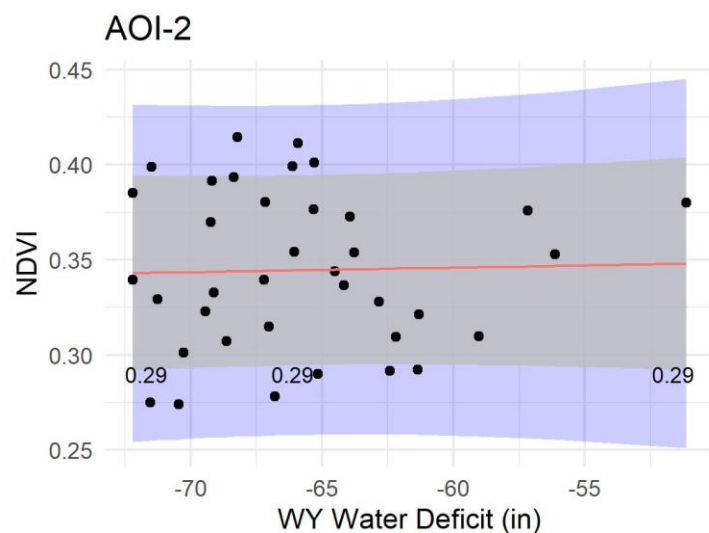


Figure 16. Linear regression relationships between annual PWD and NDVI for Lower 7J Ranch AOI (AOI-2). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.

the function and resilience of GDE vegetation within the AOI. Restoration efforts included a prescribed burn during the winter of 2007/2008, removing invasive species, fencing to exclude cattle and burro grazing, installation of a boardwalk, and significant restoration of natural topography to restore hydrologic function and critical habitat. In 2020 and 2021 over 10,000 riparian trees were planted to increase the riparian habitat, and NDVI values are expected to increase as leaf area increases with vegetation growth.

Surface and shallow groundwater appear to support a richly mesic area of riparian and wetland vegetation from Torrance Spring at the upgradient end of the AOI on down to the southeastern edge of the AOI where the AOI's channel continues to the Amargosa River proper. Vegetation in the AOI was observed to be relatively evenly split between dryland GDE shrubs (rabbitbrush and greasewood), mesic graminoids (saltgrass and other graminoids), and riparian trees and shrubs (Fremont cottonwoods, several willow species). Significant crown mortality was observed in large mature cottonwoods close to areas of standing water through the middle of AOI-3, possibly from anoxic root conditions from a rebounding water table following restoration. No signs of active disturbance from grazing, water diversion, invasive plants, or any responses other than overt anthropogenic cause of impacts were observed. Management information shared by The Nature Conservancy indicates that impacts resulting from each of the above potential disturbance causes did occur in the years preceding restoration efforts. The restoration and subsequent protection of this AOI provide an opportunity to assess how respond to interventions aimed at restoring their natural form and function following a decades long history of anthropogenic disturbance. See Appendix B for site photographs and aerial imagery.



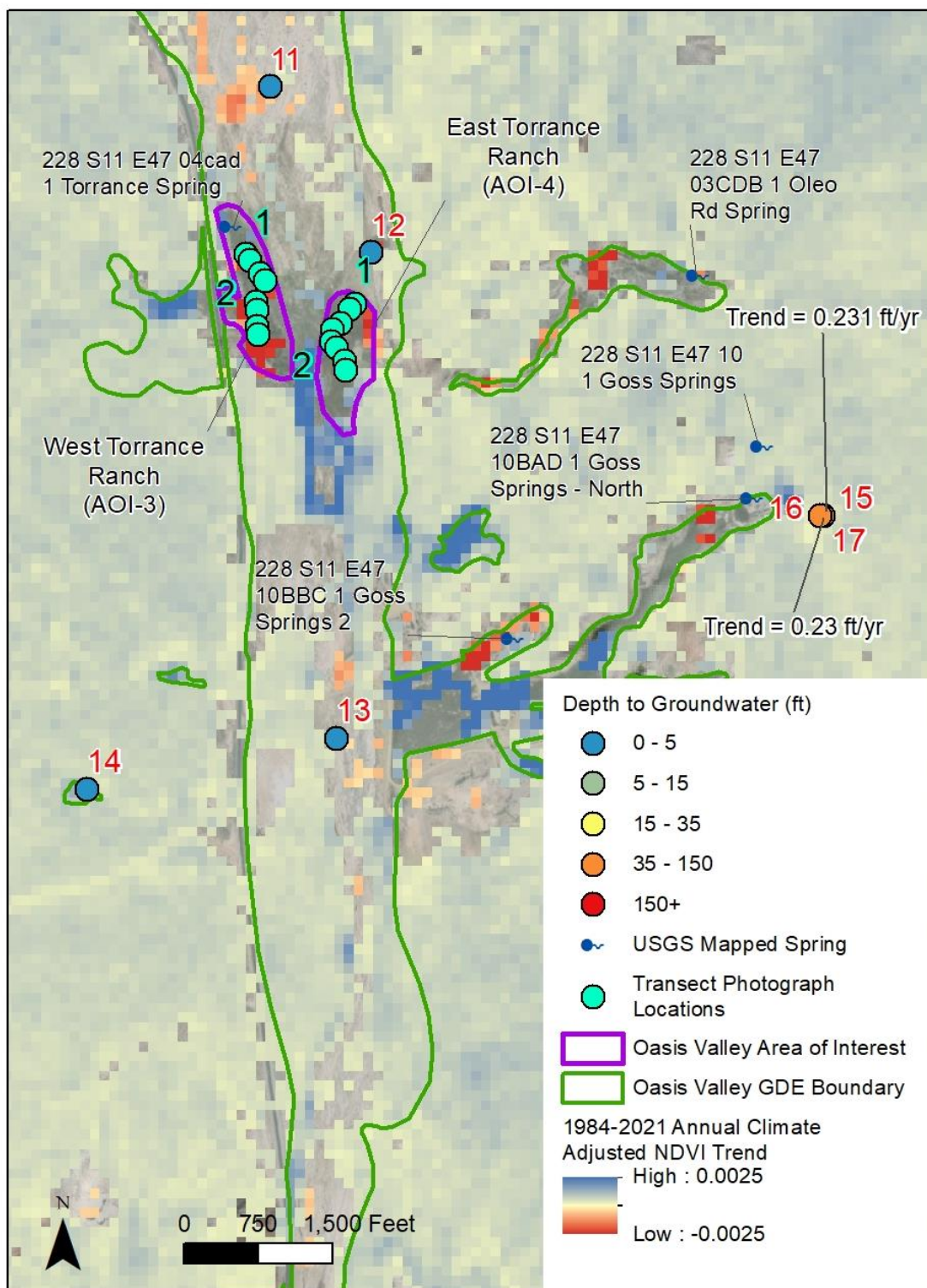


Figure 17. Map showing climate-adjusted NDVI trend for West Torrance Ranch AOI (AOI-3) and East Torrance Ranch AOI (AOI-4). AOI and well ID's (red numbers) correspond to data in Table 2. Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map (note that some wells overlap).



## ***Groundwater***

Seven shallow groundwater monitoring wells were identified within 1 mile of West Torrance Ranch (Table 2) but none of these had more than 5 years of groundwater elevation data and data for all but one well were limited to the 1996-2001 time period. Though all locations had sufficient data to allow for the calculation of statistics, no significant trends in DTW were identified. DTW values at all wells were less than 5 ft, consistent with the wet meadow GDE vegetation observed in the AOI.

## ***Vegetation***

NDVI values for the AOI varied between 0.35 – 0.50 through the 38-year record (Figure 18), consistent with values expected for mesic vegetation. NDVI does not appear to strongly covary with same-year PWD (Figure 18) and was not significantly correlated at the  $p < 0.05$  level., though there may be lagged relationships that were not assessed in this study. Although the NDVI trend was also non-significant, declining NDVI values during the 1995 – 2007 time period may indicate the impetus for the 2007-2008 restoration activities that included the prescribed burn and exclusion of livestock and burros. From 2007-2010, NDVI increases, then stabilizes starting in 2012. Figure 19 provides 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD. Because NDVI-PWD relations are weak (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable (though a slight positive relationship can be observed in Figure 19), but the historical range (Table 3) and prediction intervals may still be useful for identifying the occurrence of anomalous NDVI values relative to the historical record.

## **AOI-4—East Torrance Ranch**

### ***Site description***

The East Torrance Ranch AOI (AOI-4; Figure 17) is a roughly N-S oriented area of GDE vegetation associated with a spring located just east of the Amargosa River. This 14-acre AOI is situated about 350 ft east of the West Torrance Ranch AOI (AOI-3). Despite their proximity, AOI-4 differs considerably from AOI-3 in terms of vegetation composition, disturbance regime, and most importantly, land management approach. Though habitat restoration projects were completed in both AOIs, these efforts had distinctly differing approaches.

AOI-4 is centered around an unnamed spring associated with the Goss spring complex (Figure 3). This spring system has been subjected to repeated restoration efforts aimed at restoring historically degraded Amargosa toad habitat. Between 2001 and 2009 at least 3 different attempts were made to excavate the springhead and install a French drain-like system to provide water to a small network of channels and ponds. None of these efforts were successful in the long term, and while the pond network functioned for a short period after each iteration, ultimately each attempt was foiled by a gradual drop in discharge due to clogging via siltation. By circa 2016 the clogged system apparently built enough pressure to result in artesian discharge directly from the engineered spring system's manifold overflow. Field observations indicated spring discharge was still occurring in May 2022.

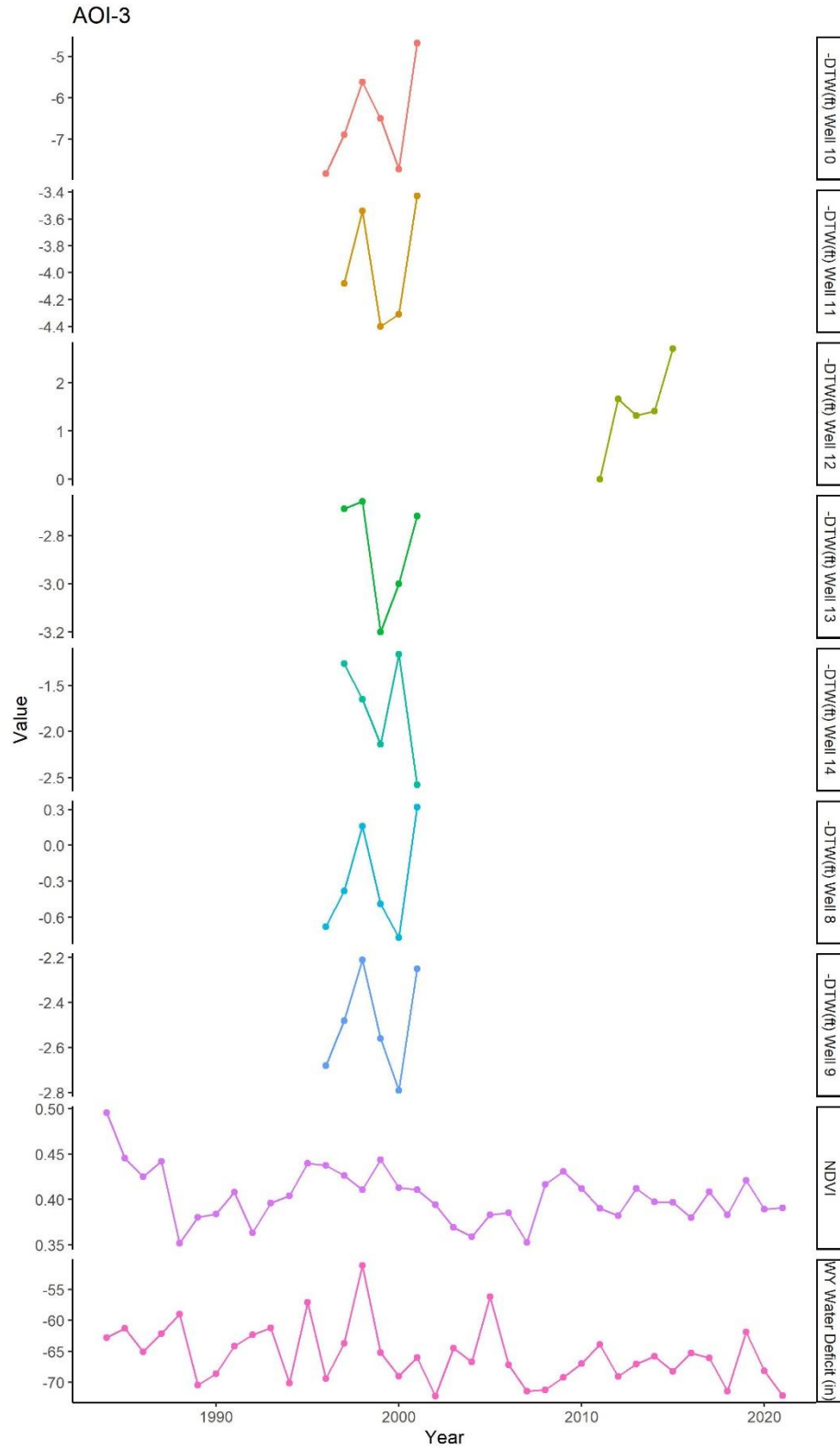


Figure 18. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD), and groundwater levels for wells within 1 mile of the West Torrance Ranch AOI (AOI-3).

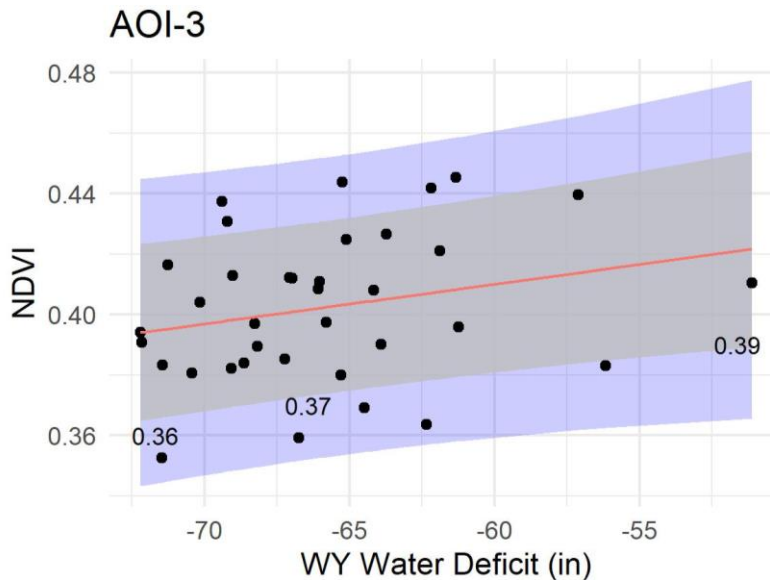


Figure 19. Linear regression relationships between annual PWD and NDVI for the West Torrance Ranch AOI (AOI-3). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.

At the time of the field visit, there was no surface water flowing through the Amargosa River adjacent to the AOI, suggesting the adjacent reach is intermittent or ephemeral. Despite the lack of river flow, several areas of standing and slowly flowing water fed by diverted spring discharge were observed that supports perennial wet mesic vegetation. Total vegetative cover throughout the AOI was observed to vary from moderately low (< 30%) to quite dense (> 75%), with spatially segregated low- and high-coverage areas associated with dryland (phreatophyte greasewood and rabbitbrush) shrub species and wet-mesic graminoids (a heterogeneous mixture of saltgrass and other graminoids mixed with abundant stream orchids, *Epipactis gigantea*). Clear evidence of anthropogenic disturbances including hydrogeologic impacts from restoration attempts, extensive grazing, and numerous invasive species were observed throughout the AOI. Just east of the AOI compacted road surfaces and remnant sections of raised and compacted railroad grade appeared to result in several localized areas of active head cut. Dominant LANDFIRE groups within the AOI include Western Herbaceous Wetland, Creosotebush Scrubland, Desert Scrubland, and Western Riparian Woodland and Shrubland. Photographs and aerial imagery from the field visit are included in Appendix B.

### **Groundwater**

As with AOI-3, a total of 7 unique groundwater monitoring locations were identified within 1 mile of East Torrance Ranch (AOI-4). Of these, 4 locations overlap with the sites identified in proximity to AOI-3, none of which were found to have statistically significant trends in groundwater elevation. The three sites unique to AOI-4, however, were characterized by significant ( $p < 0.05$ ) declining trends in groundwater elevation (increasing depth to water). Groundwater elevation was declining at rates between  $-0.23 - -0.026 \text{ ft yr}^{-1}$  between 1997 and 2022 resulting in between 0.5 – 5.2 ft of total groundwater drawdown. The three monitoring

points are associated with a triple completion nested monitoring well located roughly a mile to the west-southwest of AOI-4. Interestingly, a distinct and rapid drop in head was observed in the two shallow well completions right around the time of the last (circa 2009) restoration attempt. This drop suggests restoration-related springhead excavation may have resulted in a temporary, unintentional, and small magnitude dewatering of the volcanic tuff aquifer by effectively providing an artificially lower elevation drain for the local system. These lowered groundwater levels have the potential to affect downgradient spring discharges within the alluvium, while deeper groundwater flows, guided by the Hogback Fault, likely discharge at Goss Springs (Jackson *et al.*, 2021).

### ***Vegetation***

NDVI values for East Torrance Ranch AOI were generally between 0.3 – 0.4, before jumping to 0.5 over the past four years (Figure 20). The NDVI timeseries is not significantly correlated with interannual PWD (Table 3), and does not appear to strongly covary with same-year PWD (Figure 20), though there may be lagged relationships that were not assessed in this study. This AOI's moderately high NDVI and non-significant correlation with PWD are consistent with the mixed but uniformly groundwater dependent vegetation types observed within the AOI. Figure 21 provides 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD. Because NDVI-PWD relations are weak (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable (though a slight positive relationship can be observed in Figure 21), but the historical range (Table 3) for time periods within the historical record and the prediction intervals may still be useful for identifying the occurrence of anomalous NDVI values. In doing so, time periods should be selected taking into consideration the effects of changes in water management that have clearly influenced NDVI values.

Although the long-term NDVI trend for the AOI is not statistically significant (Table 3), the NDVI time series plot for AOI-4 (Figure 20) shows a slight overall decline in NDVI values for most of the timeseries before experiencing a distinct large magnitude increase from 2016 – 2021. Field observations suggest the recent increase in NDVI results from groundwater discharged from the engineered spring manifold's overflow drain. This circa 2016 change in discharge point and rate appears have led to a redistribution of GDE vegetation within the AOI that drove observed NDVI values, despite a lack of recovery of groundwater levels (Table 2, Figure 20).

## **AOI-5—Crystal Spring AOI**

### ***Site description***

The Crystal Spring AOI (Figure 22) differs from the preceding AOIs in a number of ways, the most notable being its location away from Oasis Valley's floor and near an area of recharge to the regional flow system. Unlike other GDE areas discussed, the Crystal Spring Complex and the GDE area it supports is situated atop volcanoclastic bedrock and may be disconnected from the regional groundwater flow system due to its perched location (HydroGeoLogica inc, 2021).

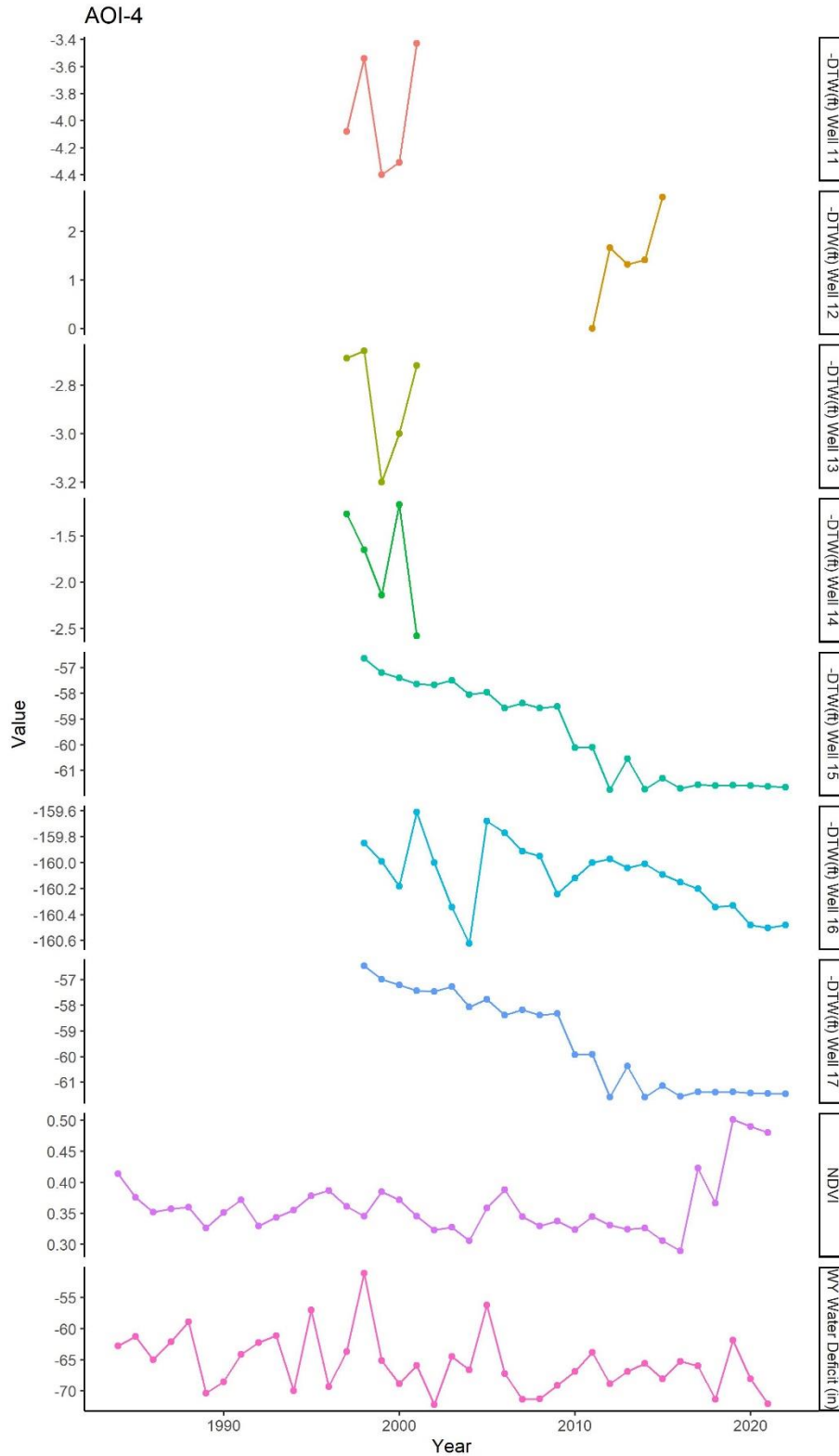


Figure 20. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD), and groundwater levels for wells within 1 mile of the East Torrance Ranch AOI (AOI-4).

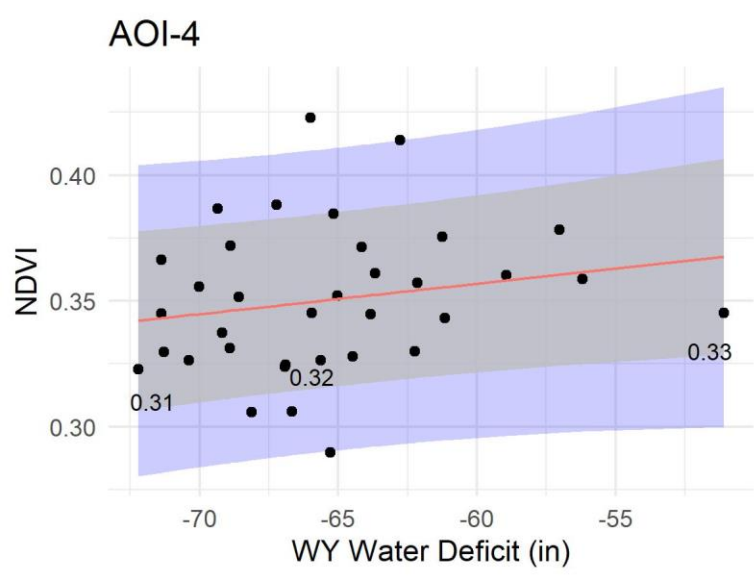


Figure 21. Linear regression relationships between annual PWD and NDVI for the East Torrance Ranch AOI (AOI-4). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.

AOI-5 covers a relatively narrow (~50 m) stretch of GDE vegetation immediately surrounding and extending approximately 1,650 ft downgradient of Crystal Spring. Field observations of well-established ponds, overland flow downgradient of the spring, and mesic vegetation throughout the core of the GDE area suggest that surface and shallow groundwater from the spring support a richly mesic area of riparian and wetland vegetation from the discharge point on down to a cluster of mature riparian trees surrounding a dwelling located near the end of the AOI. Accounts from TNC staff familiar with the AOI indicate Crystal Spring discharges perennially.

Vegetation in Crystal Spring AOI was observed to grade from wet-mesic graminoid-dominated near the spring, channel, and ponds, to a mixture of mesic graminoids and dryland GDE shrubs co-dominated by wildrye and rabbitbrush. Mature riparian trees were also clustered around the springhead and surrounding the dwelling at the downgradient end of the AOI. Consideration was given to precluding the latter group from the AOI boundary over concerns of whether water other than groundwater abstracted from the spring may have been used to irrigate the trees. Ultimately, the trees around the dwelling were included as TNC staff verified only spring-derived groundwater had been used. Total vegetative cover was quite high (< 90%) through the narrow mesic corridor. Clear evidence of impacts from anthropogenic disturbances including water abstraction, surface water diversion, and invasive species were observed throughout the AOI. No signs of recent grazing were observed. Water abstraction-related impacts are ongoing as Crystal Spring continues to be used as a domestic water supply at the time of writing.

LANDFIRE EVT groups within the AOI include Creosotebush Desert Scrub, Desert Scrub, and Chaparral. The vegetation types within these groups are broadly applicable to the dryland GDE portions of the AOI, but none of these groups reflect the wet-mesic vegetation



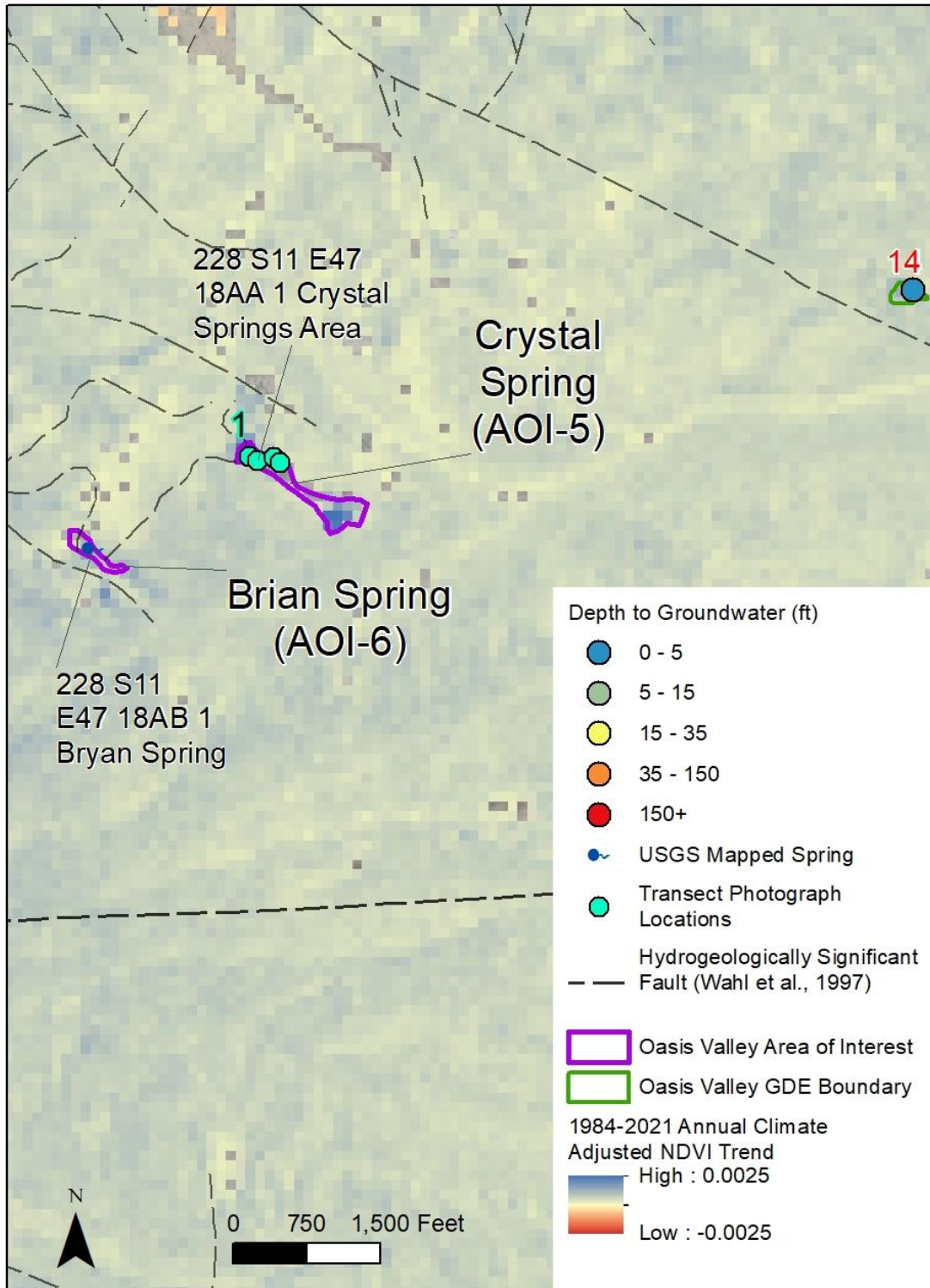


Figure 22. Map showing climate-adjusted NDVI trend for Crystal Spring AOI (AOI-5) and Brian Spring AOI (AOI -6). AOI and well ID's (red numbers) correspond to data in Table 2. Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map (note that some wells overlap).

observed near the springhead, channel, and ponds. This mixed performance by LANDFIRE is unsurprising given the small spatial scale of the AOI and the coarse resolution of the LANDFIRE EVT dataset. The narrow width of the AOI's wet-mesic corridor combined with the gradual transition from mesic to dryland GDE shrub species likely render this AOI a particularly difficult location for a coarse dataset like LANDFIRE EVT to accurately classify. Photographs and aerial imagery from the field visit are included in Appendix B.

### ***Groundwater***

No wells with an adequate quantity of publicly available water level data were identified in close enough proximity to AOI-5 to be of relevance. As such, no water level trend analysis was performed for this or Brian Spring AOIs. A large-scale mining operation, the North Bullfrog Project, is proposed for Bullfrog Hills, which is in the vicinity (approximately 4 miles) of the Crystal Springs complex. Groundwater levels at the proposed Yellowjacket pit lake site are approximately 3976 ft in elevation and exhibit a slight downward gradient toward the southeast (HydroGeoLogica inc., 2021). The Crystal Springs Complex is located to the southeast of the site, and discharges at 3903 ft elevation. Mine pit dewatering is expected to lower groundwater elevations to 3609 ft in the 5<sup>th</sup> year (HydroGeoLogica inc., 2021). If springs throughout the Crystal Spring complex are hydrologically connected to the mine site, dewatering has the potential to affect springflows. The potential for this impact merits further study and continued and expanded monitoring in this area is recommended.

### ***Vegetation***

NDVI values for Crystal Spring AOI were generally between 0.17 – 0.25 throughout the 38-year record (Table 3). These lower values largely reflect the signal of surrounding upland vegetation that is captured within the 30-m Landsat pixels, given the small size of the AOI. PWD and NDVI timeseries appear to show interannual correspondence (Figure 23), but are not significantly correlated (Table 3). A significant, positive NDVI trend is also observed (Table 3), which qualitatively appears to have started in the 2004-2007 time period (Figure 23) and likely explains the lack of significance in the NDVI-PWD correlation as the trend decouples that relationship. A livestock exclosure surrounding the spring was observed during the field visit; if this was added after the AOI was previously subjected to grazing, the removal of that persistent disturbance could explain the gradual NDVI recovery, but that scenario represents only one of many possibilities.

Figure 24 provides 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD, which provides context for interpreting future monitoring observations of NDVI. For example, future values that fall outside the 75th percentile prediction interval for a given PWD may indicate undesirable change and the need for further investigation of possible causal factors. Because NDVI-PWD relations are weak and NDVI is trending positively (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable (though a slight positive relationship can be observed in Figure 24), but the historical range (Table 3) and prediction intervals can be useful for identifying the occurrence of anomalous NDVI values relative to the historical record.

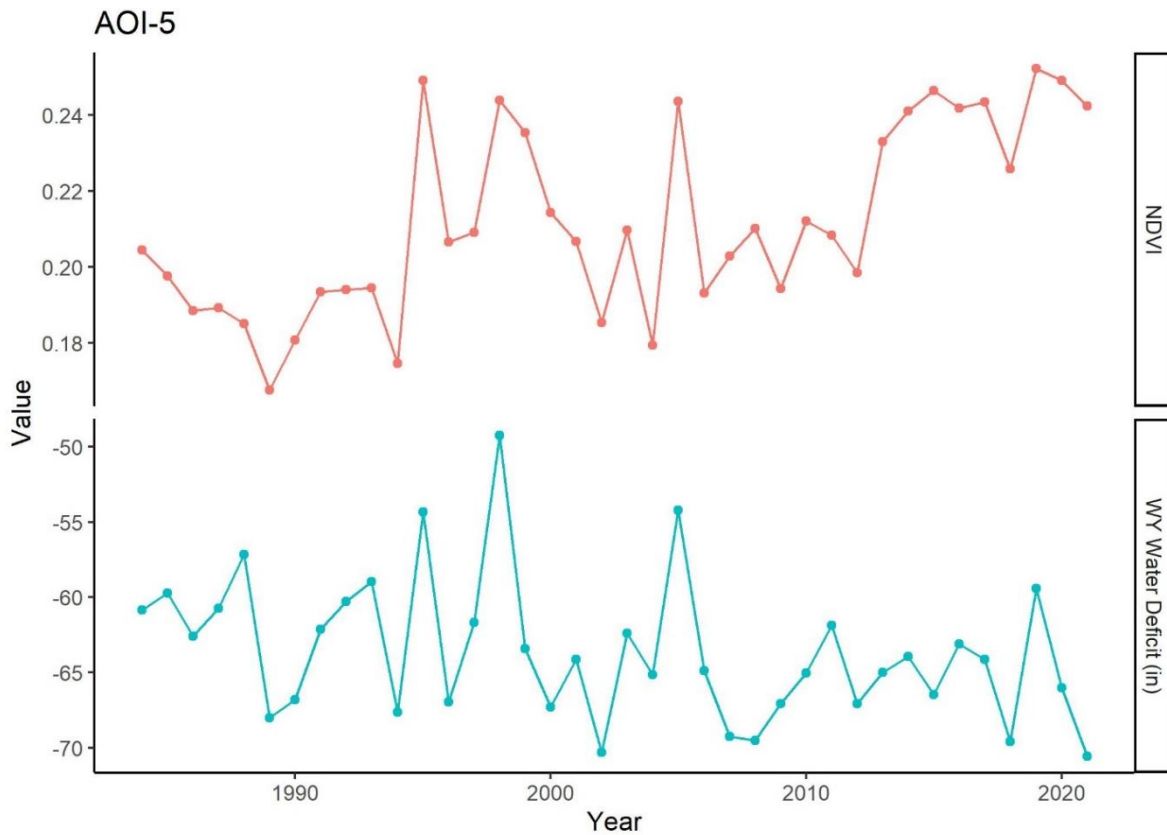


Figure 23. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD) for the Crystal Spring AOI (AOI-5).

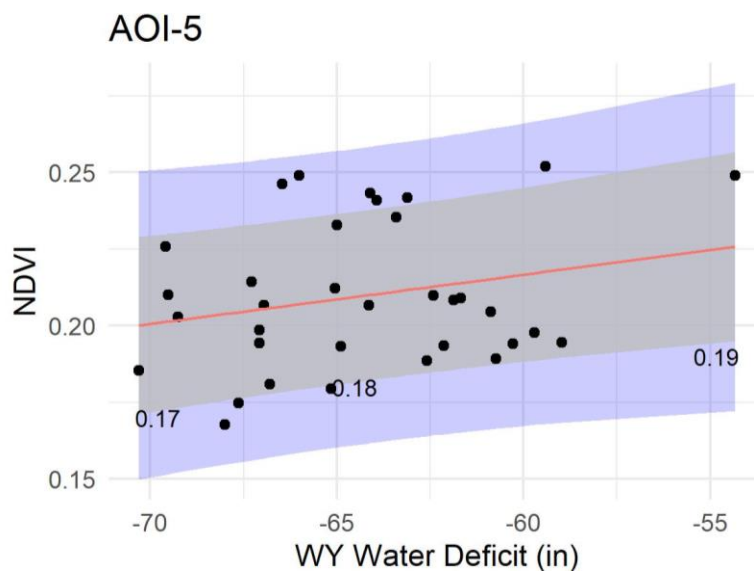


Figure 24. Linear regression relationships between annual PWD and NDVI for the Crystal Spring AOI (AOI-5). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.

## **AOI-6—Brian Spring (Crystal Spring Complex)**

### ***Site description***

The Brian Spring AOI (AOI-6; Figure 22) is located within the same spring cluster as, and less than 0.25 mi SW of, Crystal Spring (AOI-5). At approximately 1.5 acres and 3,950 ft amsl, Brian Spring is the smallest and highest elevation AOI within the study area. The roughly 100 ft wide by 700 ft long Brian Spring AOI covers a narrow corridor of mesic and dryland GDE vegetation associated with one of several springs in the Crystal Springs complex. Field observations of overland flow downgradient of the spring and limited areas of wet-mesic vegetation along the spring's channel suggest that Brian Spring flows perennially, and information from The Nature Conservancy confirms this. Information from TNC also suggests Amargosa toad habitat restoration likely occurred at Brian Spring some time in around 2000 – 2004, though this was not verified. This information and field observations suggest Brian Spring was likely subjected to springhead excavation, and the installation of a “rock cell”, French drain, and grazing exclusion fence, much like AOI-4. The present diversion to a livestock watering trough outside of the fenced area is believed to have been installed to facilitate livestock water access while excluding livestock from the restored toad habitat.

Vegetation in Brian Spring AOI graded from mesic graminoids nearest the spring and channel to dryland shrubs towards the AOI's boundaries, with a handful of small riparian trees intermixed. Total vegetative cover was quite high (< 90%) in the very narrow (5 – 10 ft wide) area of mesic vegetation and drastically lower even 10 feet away. Clear evidence of impacts from anthropogenic disturbances including restoration impacts, surface water diversion, and invasive species were observed throughout the AOI. Impacts from burro grazing were also evident despite the apparently intact exclusion fence. The French drain diversion and watering trough seen during the May 2022 field visit indicate anthropogenic impacts are ongoing.

LANDFIRE EVT groups within AOI-6 include Desert Scrub and Creosote bush Desert Scrub. This is consistent with vegetation observed in the dryland GDE areas of the AOI, but LANDFIRE appears to have missed the narrow strip of mesic vegetation along the channel. As with Crystal Spring, the narrow width of the wet-mesic corridor likely renders this AOI a particularly difficult location for a coarse dataset like LANDFIRE EVT to accurately classify. Photographs and aerial imagery from the field visit are included in Appendix B.

### ***Groundwater***

No wells with readily available groundwater elevation data were in close proximity to this AOI but one existing hydrogeologic assessment (HydroGeoLogica Inc 2021) suggests the groundwater beneath the Bullfrog Hills is generally moving toward, and found at the elevations near, springs in the Crystal Springs complex. As discussed in the AOI-5 section, dewatering associated with proposed mining operations in the Bullfrog Hills has the potential to affect this spring.

### ***Vegetation***

NDVI values for the Brian Spring AOI were between 0.1 – 0.16 over the entire period of record (Figure 25, Table 3). These lower values largely reflect the signal of surrounding upland vegetation that is captured within the 30-m Landsat pixels, given the small size of the AOI.

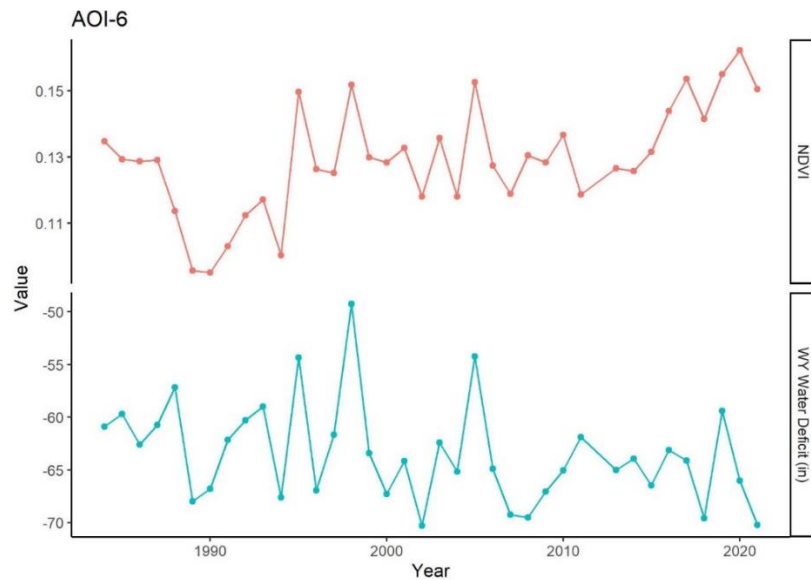


Figure 25. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD) for the Brian Spring AOI (AOI-6).

Figure 25 illustrates that while NDVI appears to respond to highs in the water year PWD time series, the overall relationship between the two variables is not statistically significant, potentially due to the significant positive trend in vegetation (Table 3). As with Crystal Spring, a perimeter fence to exclude grazing was observed during the field visit. Unlike AOI-5, however, signs of ongoing grazing were apparent throughout the AOI, suggesting the elimination of grazing impacts are not driving the observed trend. Figure 26 shows 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD, which provides context for interpreting future monitoring observations of NDVI. For example, future values that fall outside the 75th percentile prediction interval for a given PWD may indicate undesirable change and the need for further investigation of possible causal factors. Because NDVI-PWD relations are weak and NDVI is trending positively (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable (though a slight positive relationship can be observed in Figure 26), but the historical range (Table 3) and prediction intervals can be useful for identifying the occurrence of anomalous NDVI values relative to the historical record.

## AOI-7—Parker Ranch

### *Site description*

Parker Ranch AOI (Figure 27) is a roughly 10-acre spring fed GDE area located along the Amargosa River's western bank roughly 5.5 mi upgradient of Beatty, NV. Evidence of anthropogenic disturbances in the forms of water diversion, grazing, past habitat restoration efforts, and the presence of invasive species were observed on the May 2022 site visit. Restoration efforts on Parker Ranch centered around the construction of several ponds in February of 2003 to restore open water and aquatic habitat. What had previously been a single large anthropogenically made fishing pond was reconstructed into a series of smaller ponds with

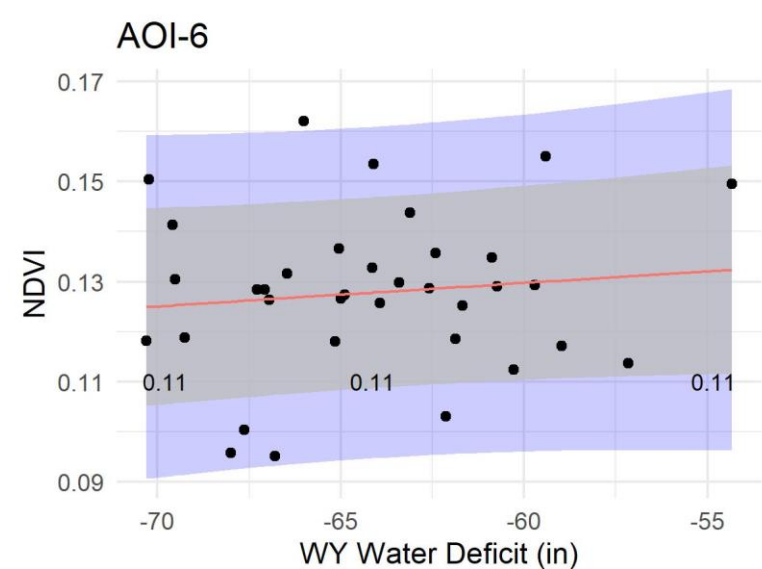


Figure 26. Linear regression relationships between annual PWD and NDVI for the Brian Spring AOI (AOI-6). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.

a network of engineered channels and swales extending downgradient towards the Amargosa River. Additional restoration work was conducted by TNC in subsequent years, but the timing and details are unknown. In the end, this project was not successful and only one of the smaller ponds holds water, which is minimal.

Surface water was observed in May 2022 in one of the ponds and was also flowing through a north-south oriented swale located downgradient and southeast of the ponds. The area surrounding the spring, ponds, and swale supported mesic to wet-mesic GDE vegetation. Mesic graminoids and riparian trees dominated the majority of the AOI, with dryland GDE shrubs relegated to small islands associated with local topographic highs. Total vegetative cover along vegetation transects was rather high (>75%) through most of the AOI, though areas of dryland shrub were much lower (< 20%). Vegetation observed within the Parker Ranch AOI was relatively consistent with LANDFIRE classifications of Western *Herbaceous Wetland*, *Western Riparian Woodland and Shrubland*, and *Introduced Vegetation* groups. Photographs and aerial imagery from the field visit are included in Appendix B.

### **Groundwater**

Three wells with publicly available groundwater data were identified within 1 mi of AOI-7. Two of these three locations had adequate data for statistical analysis and trend assessment, though no significant trends were identified in either 4-year record. DTW values are consistently less than 12 ft and show seasonal variability, with shallow DTW during winter and deeper DTW during the summer (Figure 28), likely reflecting patterns of precipitation and evapotranspiration by the riparian tree GDE vegetation observed within the AOI, but covariance between climate and DTW could not be determined given the short water levels data record.



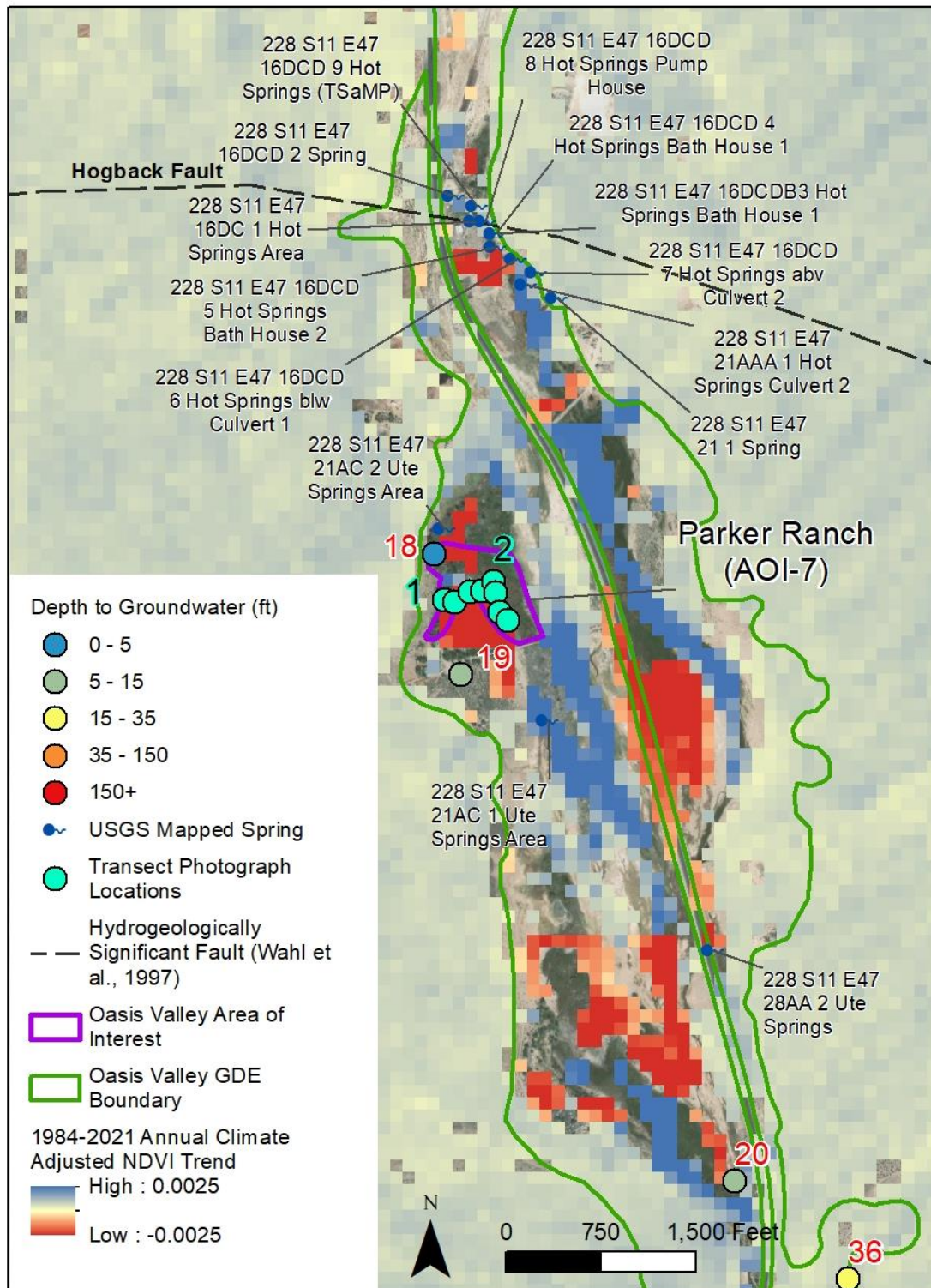


Figure 27. Map showing climate-adjusted NDVI trend for Parker Ranch (AOI-7). AOI and well ID's (red numbers) correspond to data in Table 2. Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map (note that some wells overlap).

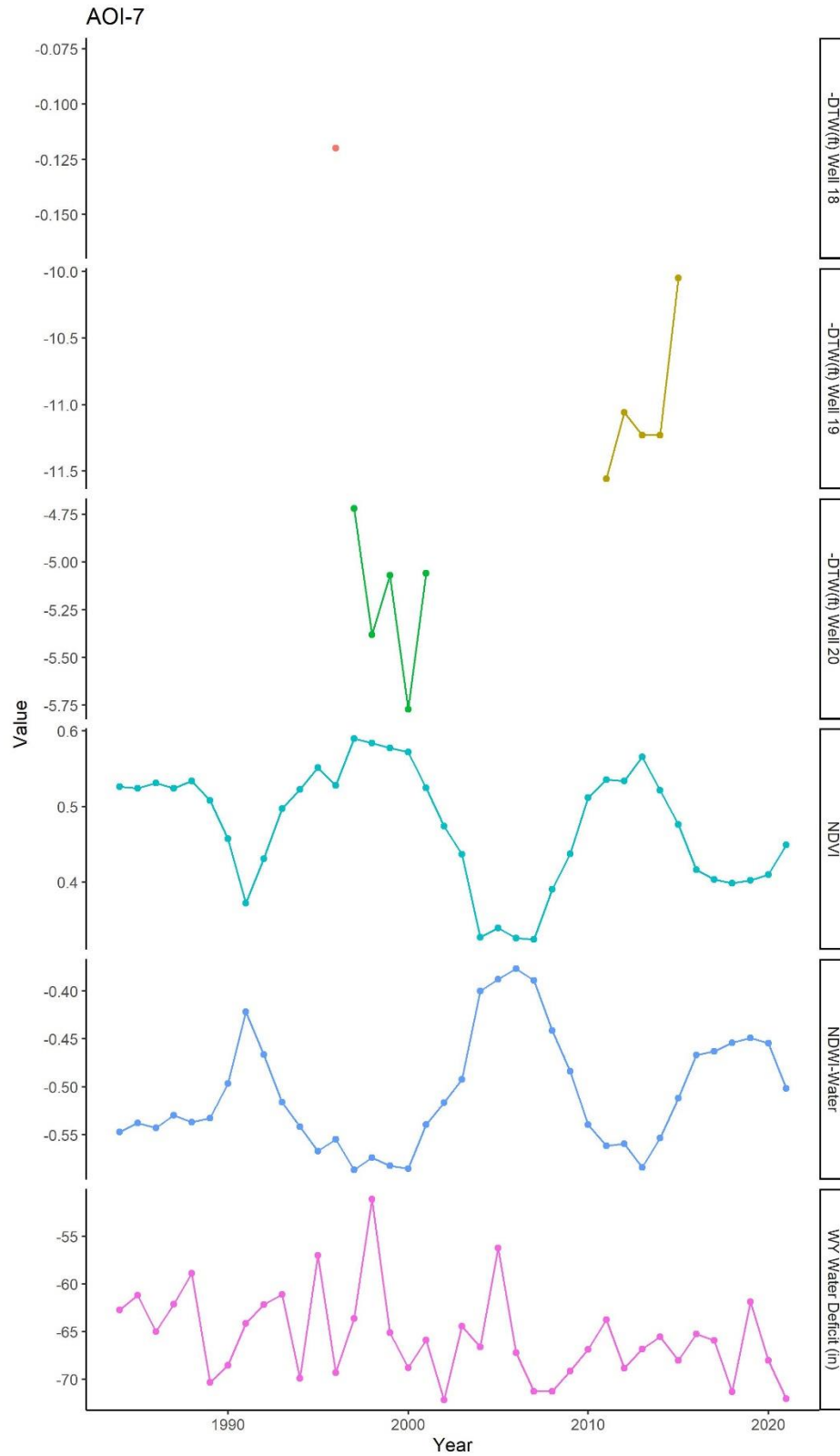


Figure 28. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD), and groundwater levels for wells within 1 mile of the Parker Ranch AOI (AOI-7).

## Vegetation

NDVI values for the Parker Ranch AOI were the most variable of any AOI (Figure 28), exhibiting slowly (~10 year) varying values between 0.3 – 0.6, which correspond with variability in surface water extent, as indicated by low values of NDVI corresponding with higher values of an NDWI metric that is used to identify the presence of water (McFeeters 2006). Thus, fluctuations in NDVI are most likely driven by changes in surface water associated with restoration and water diversion. Despite the obvious negative relationship between NDVI and the presence of surface water, as indicated by NDWI, NDVI still exhibited a statistically significant correlation with PWD (Table 3). Linear regression relationships between NDVI and PWD and the resulting prediction intervals are shown in Figure 29. The 75<sup>th</sup> percentile PIs indicate spatially averaged NDVI values in a very dry year are expected to be greater than 0.35 for the AOI. For a very wet year NDVI is expected to be greater than 0.47 (Figure 29). Although the data used for this analysis passed all outlier tests, results should still be interpreted with caution given the large management-driven variations in NDVI and given that NDVI is reduced by presence of open water.

### AOI-8—Stagecoach

#### Site description

The Stagecoach AOI (AOI-8; Figure 30) is centered around a northeast to southwest flowing reach of the Amargosa River located immediately upgradient of Beatty, NV. This 13-acre AOI encompasses a recently restored area of riparian GDE vegetation surrounded by houses, hotels, and other developed areas. In 2012, sections of raised berms were removed to restore the natural channel and flood plain. Several subsequent efforts to plant native vegetation and remove invasive species have occurred since the initial 2012 work. AOI-8 provides an opportunity to assess how restoration efforts influenced GDE vegetation in the targeted area.

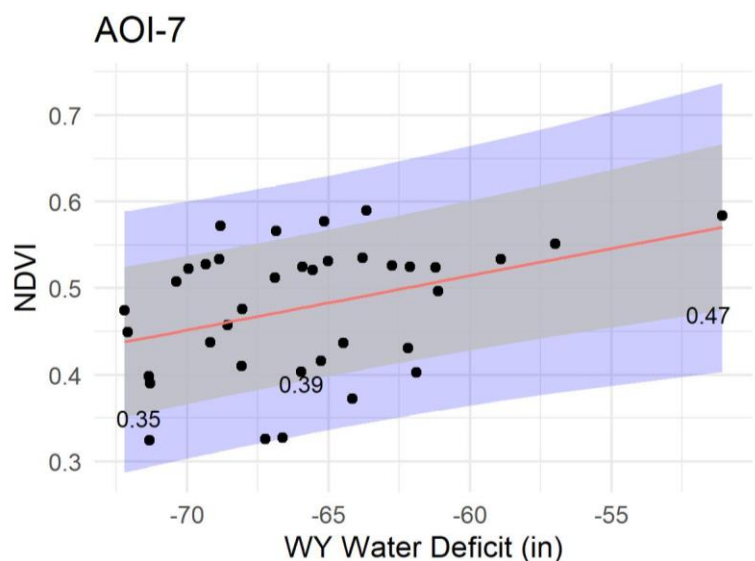


Figure 29. Linear regression relationships between annual PWD and NDVI for Parker Ranch AOI (AOI-7). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.



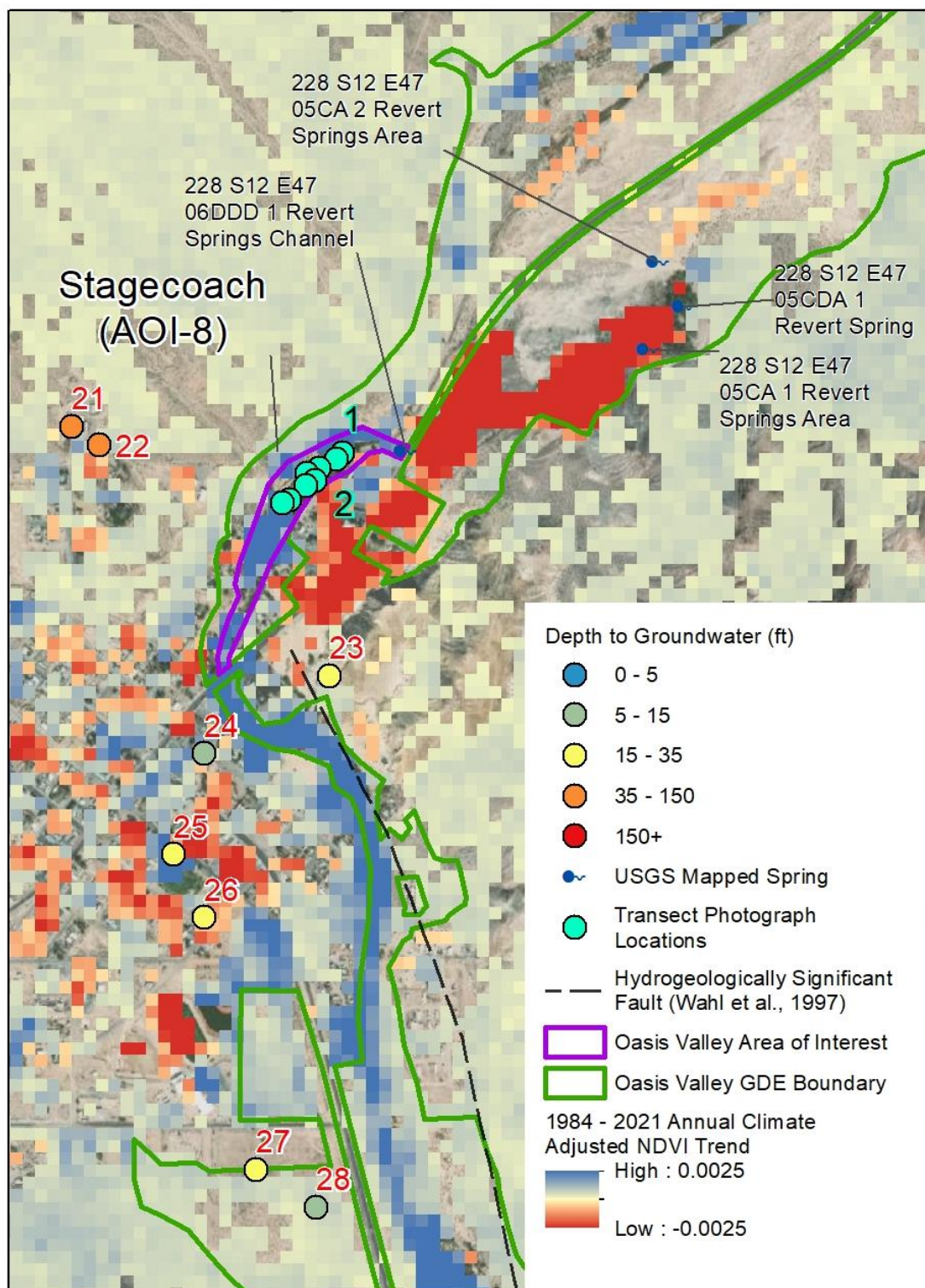


Figure 30. Map showing climate-adjusted NDVI trend for Stagecoach (AOI-8). AOI and well ID's (red numbers) correspond to data in Table 2. Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map (note that some wells overlap).

Surface water was observed flowing through the Amargosa River within the AOI during the May 2022 field visit. Observations of wet-mesic GDE vegetation throughout the AOI suggested year-round water availability, an inference supported by reports from TNC staff of perennial flow through this reach of the Amargosa River. Total vegetative cover along transects was observed to vary from sparse (< 10%) to quite dense (> 75%). High and low coverage areas were largely topographically driven, with wet-mesic riparian trees and dense graminoids throughout topographic lows and predominantly barren ground on raised flood plains, respectively. Dense willows, large cottonwoods and abundant graminoids were the dominant species observed. The majority of the area is classified by LANDFIRE as Developed-Low Intensity, likely due to its proximity to urban infrastructure, but the AOI itself is composed of natural vegetation. Evidence of surface water diversion, water abstraction, grazing, and invasive species was observed throughout the AOI during the May 2022 field visit. Recently cut *Tamarix* trunks, freshly planted native riparian trees and signs of compaction from channel morphology restoration were all apparent. Other signs of anthropogenic disturbance included trash and refuse, signs of groundwater abstraction, and small areas of head cut. Photographs and aerial imagery from the field visit are included in Appendix B.

### ***Groundwater***

A total of 8 wells were identified within 1 mi of AOI-8. Of these, only a single location (Well 24) had more than one year of groundwater elevation data (Table 2), and even that modest record of 3 years did not provide enough temporal span to allow for trend assessment. Though no significant trends were identified in any of the groundwater records near AOI-8, DTW values in the only well with a contemporary (2018; Figure 31) observation was 18 ft, consistent with the riparian tree GDE vegetation observed within the AOI, while older observations made in the 1960s and late 1990s were also in the 10-20 ft range. Only four wells with observations overlapping Landsat data are shown in Figure 31, and because each of these had only one or two observations occurring within the same water year, no relation between vegetation and groundwater levels could be inferred but perennial overland flow in the AOI further indicates groundwater is shallow and relatively stable.

### ***Vegetation***

NDVI values for Stagecoach AOI were generally between 0.15 – 0.30 (Figure 31) and are not significantly correlated with PWD. The Stagecoach AOI exhibits an increase in NDVI over the 1990s followed by a period of relatively consistent NDVI values until a short-lived decline around 2012, when restoration occurred, followed by a substantial increase in NDVI beginning in about 2015 (Figure 31). Overall the positive NDVI trend is statistically significant. Figure 32 provides 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD. Because NDVI-PWD are essentially unrelated ( $r$  close to 0; Table 3) and NDVI is trending positively (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable, but the historical range (Table 3) may still be useful for identifying the occurrence of anomalous NDVI values relative to the historical record.

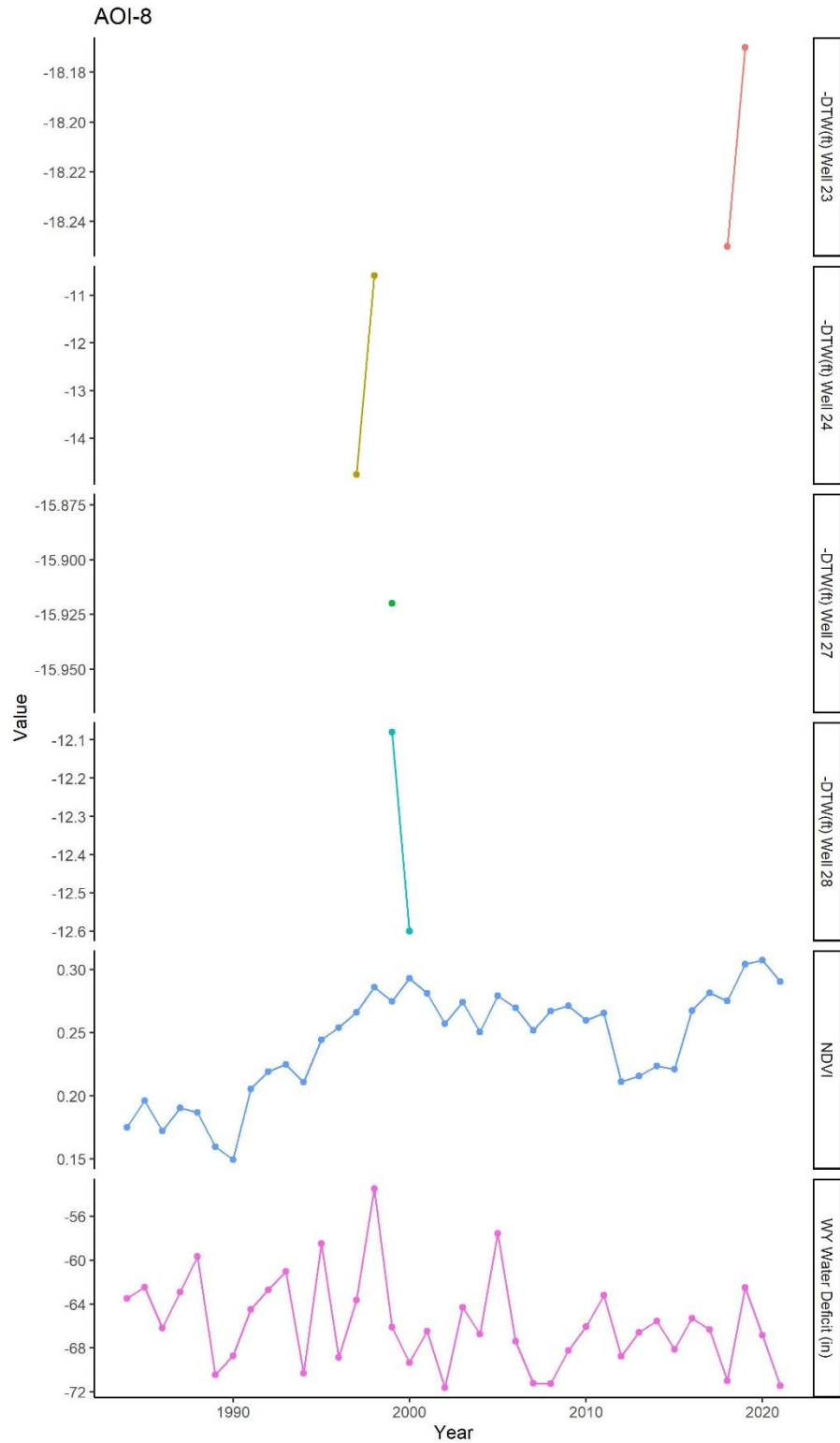


Figure 31. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD), and groundwater levels for wells within 1 mile of the Stagecoach AOI (AOI-8).



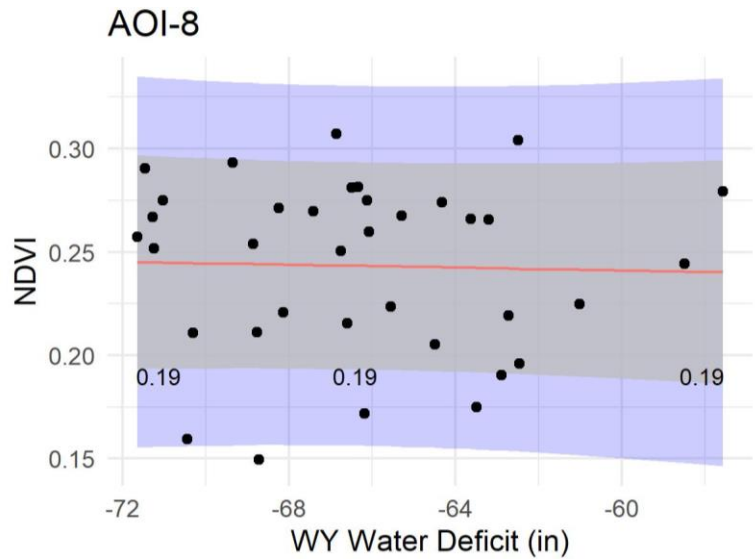


Figure 32. Linear regression relationships between annual PWD and NDVI for the Stagecoach AOI (AOI-8). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (Pis) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.

## AOI-9—Beatty Narrows

### *Site description*

The Beatty Narrows AOI (AOI-9; Figure 33) is located along the Amargosa River just downgradient and south of Beatty, NV. AOI-9 is a long and narrow (< 150 ft at its narrowest) north-south oriented area of GDE vegetation running parallel to both the Amargosa River and U.S. Route 95. The 38-acre AOI-9, the second largest in this study, spans a perennial reach of the Amargosa River critical to efforts to protect and enhance habitat for the endemic Amargosa toad. The northern three quarters of the Beatty Narrows AOI is located on BLM land, but the southern quarter was purchased by The Nature Conservancy. This location was selected as an AOI because of its importance to the Amargosa toad and because it is home to the only stand of screwbean mesquite in the Oasis Valley. In addition, extensive restoration work has been carried out within the TNC owned portion of the AOI to improve the function and resilience of GDE vegetation within. Of particular concern is the mesquite stand, which is believed to be the northernmost in the species entire range. Restoration efforts started in 2018 and ongoing as of 2022 include the removal of invasive tamarisk, planting of native cottonwood and willows, the restoration of natural topography to reengage legacy channels and floodplains, and partial exclusion of grazing.

Field observations of surface flows and wet-mesic obligate GDE vegetation throughout the majority of the AOI suggest the reach of the Amargosa associated with AOI-9 flows perennially, an inference corroborated by TNC staff. Vegetation in the AOI was observed to be relatively evenly split between dryland GDE shrubs (rabbitbrush, greasewood) along the raised floodplains, and a mixture of wet-mesic graminoids and riparian trees (screwbean mesquite, several willow species mixed with graminoids) along the channel bottom. Total vegetative cover

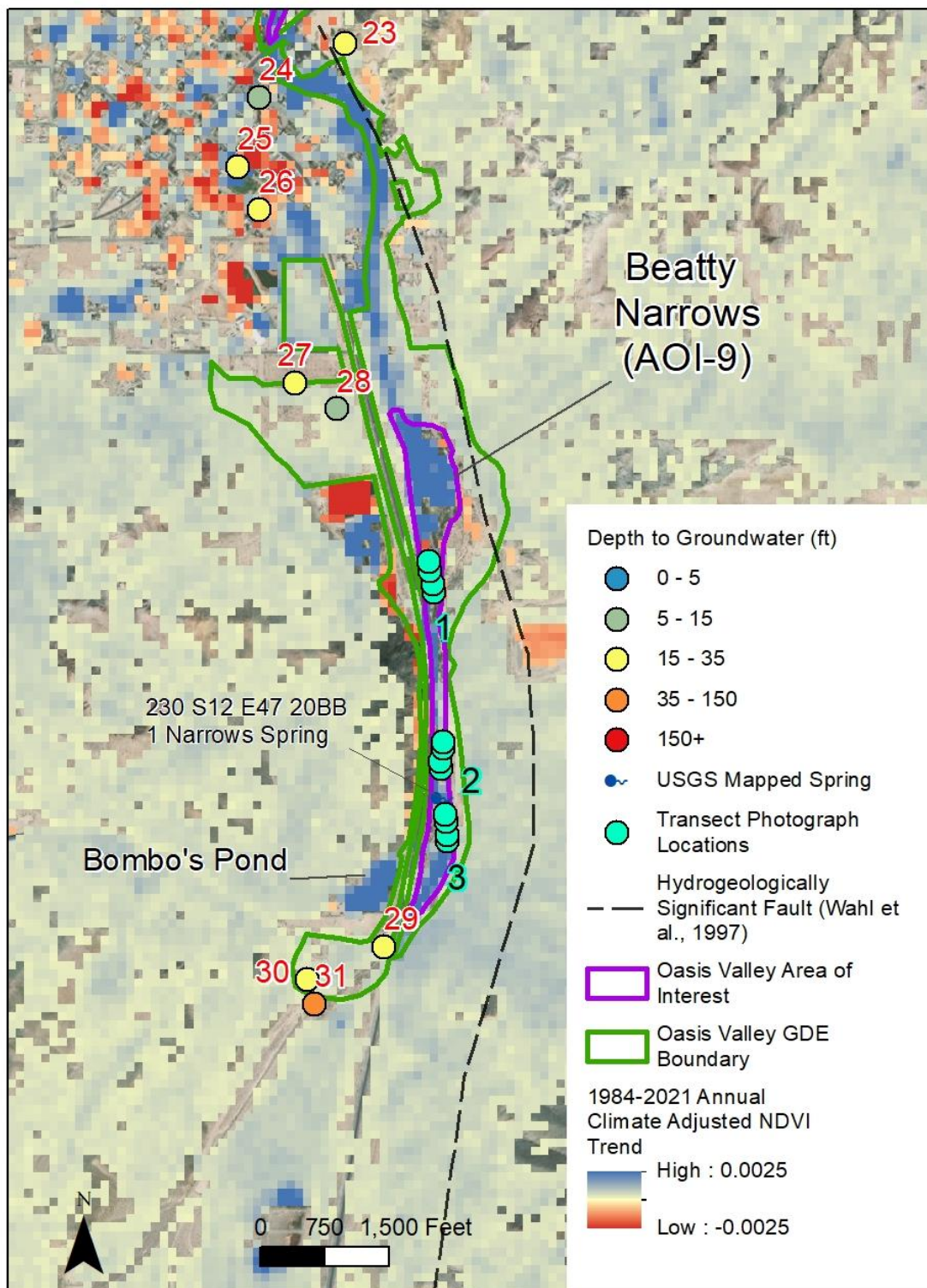


Figure 33. Map showing climate-adjusted NDVI trend for Beatty Narrows (AOI-9). AOI and well ID's (red numbers) correspond to data in Table 2. Additional labels for statistically significant well trends ( $p < 0.05$  modified Mann-Kendall test) are shown on the map, if they occur (note that some wells overlap).

was moderate (< 50%) throughout each of the varying vegetation types observed in the southern portion of the AOI. Total cover was somewhat higher (50 – 65%) in the northern end of the AOI. Photographs and aerial imagery from the field visit are included in Appendix B.

Beyond lingering signs of restoration-related perturbation, no signs of disturbance from grazing, water diversion, or any other anthropogenic cause, were observed in the southern portion of the AOI, though heavy summer grazing occurs outside the fenced areas. Despite repeated efforts to remove invasive tamarisk, however, individuals were observed within the entire AOI. Signs of disturbance were more apparent in the northern (BLM) portion of the AOI and included recent signs of grazing. Management information shared by The Nature Conservancy indicates a long history of anthropogenic impacts resulting from each of the potential disturbance causes mentioned above occurred over the years preceding restoration efforts. Additionally, public records indicate effluent from the Beatty's water treatment plant is discharged to rapid infiltration basins (RIBs) to recharge groundwater, which could also influence vegetation due to nutrient loading. Bombo's Pond, a small anthropogenic groundwater fed pond located to the southwest of AOI-9, resulted from the excavation of a gravel pit for highway construction. The hydrologic influence of both features is not well characterized but could be significant given the location and direct groundwater connection of each.

### ***Groundwater***

With 9 wells located within 1 mi of AOI-9, Beatty Narrows was the AOI with greatest number of proximal groundwater monitoring locations. As was the case with AOI-8, most of these monitoring locations had only one to two years of groundwater elevation data (Table 2, Figure 34). One well (29) had sufficient data to calculate a trend, which was negative (with borderline statistical significance of  $p=0.09$ ). DTW values were consistent with the riparian tree GDE vegetation observed within the AOI, with most ranging between 10-40 ft DTW. A man-made pond just to the AOI's southwest likely resulted in temporary dewatering near the AOI, but unfortunately none of the available groundwater records captured the critical 1988 – 2008 period. Beatty's water treatment plant infiltrates treated effluent upgradient of AOI-9. This likely influences the occurrence and movement of groundwater within the AOI, though there are insufficient data to characterize this at present.

### ***Vegetation***

NDVI values for the AOI were between 0.18– 0.30 over most of the 38-year record, though values have risen as high as 0.31 in recent years (Figure 34). Despite showing some qualitative connection in AOI-9's NDVI time series, the NDVI-PWD correlation was not statistically significant (Table 3), which may, in part, be due to the significant positive trend in NDVI despite the climate drying trend indicated by PWD. Figure 35 provides 75<sup>th</sup> and 95<sup>th</sup> prediction intervals based on linear regression between NDVI and PWD. Because NDVI-PWD are essentially unrelated ( $r$  close to 0; Table 3) and NDVI is trending positively (Table 3), the use of annual climate to estimate expected NDVI is likely to be unreliable, but the historical range (Table 3) may still be useful for identifying the occurrence of anomalous NDVI values relative to the historical record.

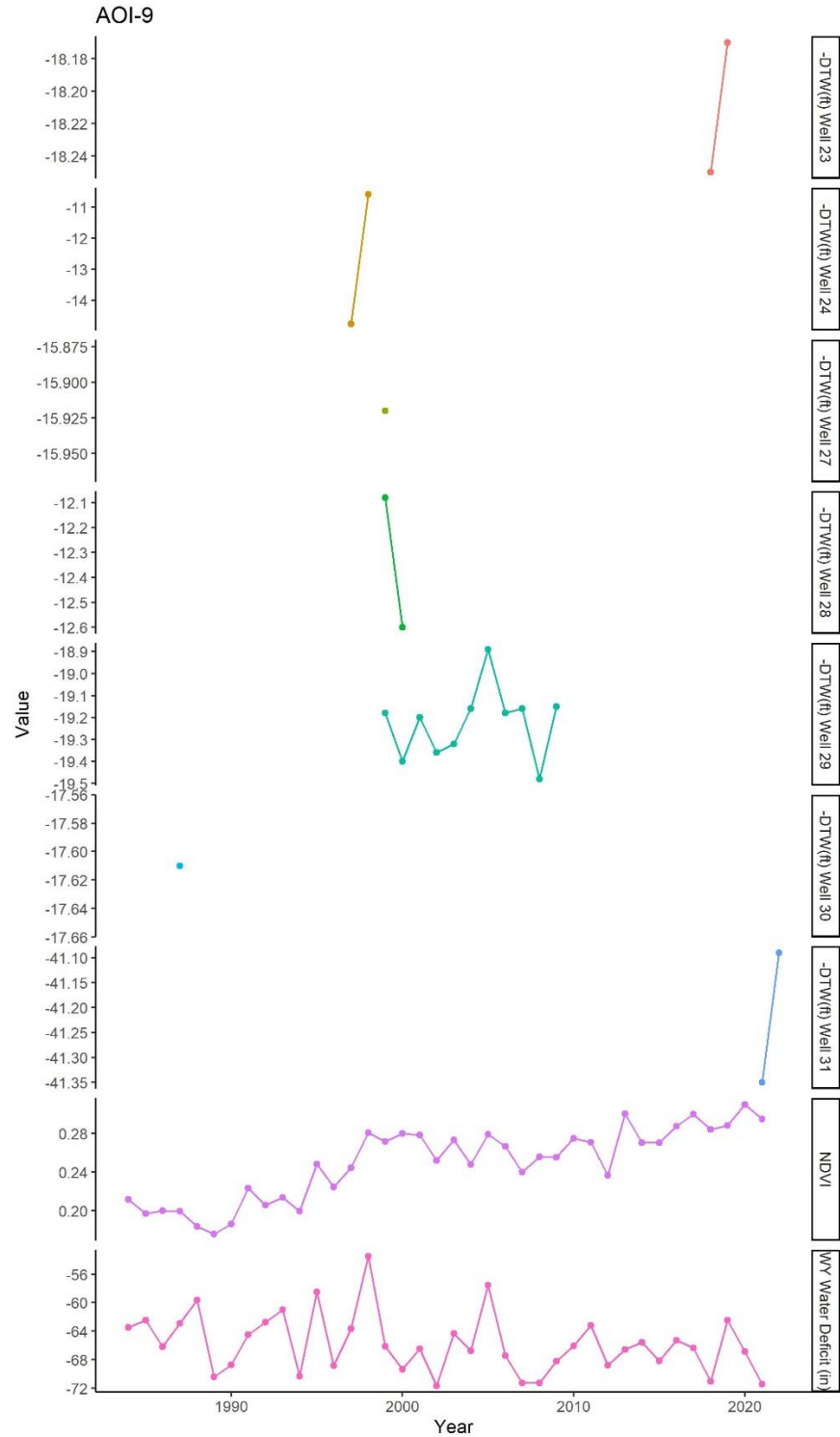


Figure 34. Timeseries of spatially averaged late-summer NDVI and annual (WY) water deficit (PWD), and groundwater levels for wells within 1 mile of the Beatty Narrows AOI (AOI-9).

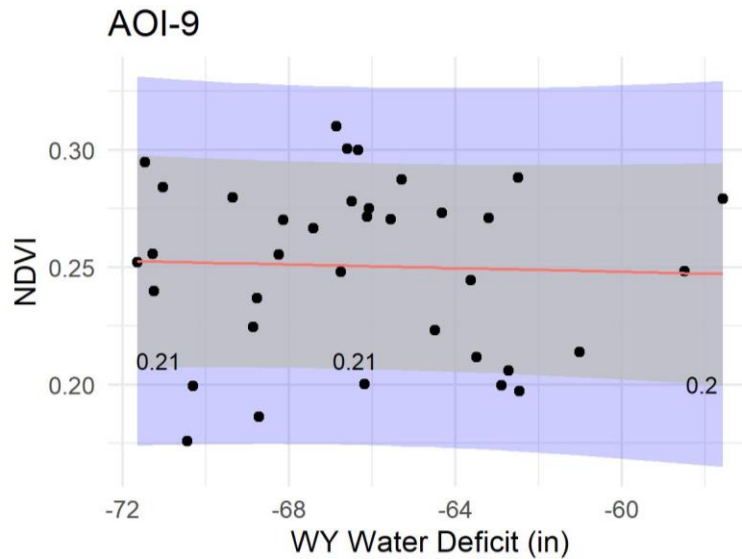


Figure 35. Linear regression relationships between annual PWD and NDVI for the Beatty Narrows AOI (AOI-9). 75<sup>th</sup> and 95<sup>th</sup> percentile prediction intervals (PIs) are shown with gray and blue shading, respectively. Numbers indicate lower bound of 75<sup>th</sup> PI NDVI value for highest, median, and lowest water deficit.

AOI-9's positive and statistically significant NDVI slope may result in part from the post-restoration recovery of GDE vegetation, though additional details regarding the timing and extent of restoration efforts are needed to fully assess this. Another possible explanation for the observed trend centers around the manmade Bombo's pond just southwest of AOI-9. Aerial imagery and remote sensing data indicate Bombo's pond was completely dry until roughly 1994, and full by circa 1998. The rise in NDVI values from 1988 – 1998 may relate to groundwater recovery following dewatering during the gravel pits excavation, groundwater recharge from Beatty's water treatment effluent, or possibly the cessation of mining operations, which also occurred at this time. Presently, there are insufficient hydrologic data available to assess these possible causal factors.

## SUMMARY OF SITE-SPECIFIC RESULTS

- Increases in NDVI in the two 7J Ranch AOIs (AOIs 1 and 2) coincide with increases in groundwater levels that initiated in 2005, suggesting that rising groundwater levels may be promoting GDE health in these areas. This is corroborated by visually apparent decreases in interannual correspondence between NDVI and PWD as groundwater levels increased. The reason for rising groundwater levels is unclear and merits further investigation.
- Prescribed fire treatments and exclusion of livestock and burros in the West Torrance Ranch AOI (AOI-3) in 2007-2008 are followed by a multi-year increase in NDVI values that are indicative of vegetation vigor increases. Long-term effects of the restoration on vegetation vigor are difficult to discern based on patterns of NDVI as the range and variability of values pre- and post-restoration do not differ considerably. Available

groundwater measurements indicate very shallow (< 5 ft) groundwater. This, coupled with the lack of correspondence between NDVI and climate indicate strong groundwater dependence of vegetation. The lack of long-term timeseries of groundwater data limit the ability to discern relations between NDVI and groundwater in greater detail.

- NDVI within the East Torrance Ranch AOI (AOI-4) exhibits slight declines over the period of record until 2016, when a rapid increase occurred, coincident with changes in water management infrastructure. Nearby groundwater levels exhibited a large decline in 2009. This coincided with restoration-related springhead excavation, which may have effectively resulted in local drainage of the system. Observed declines in groundwater levels have the potential to affect downgradient spring discharges, including those at Goss Spring and further investigation of this is warranted. Notably, groundwater levels remained consistently deeper from 2009 onward and thus the 2016 increase in NDVI is likely more strongly related to water distribution (i.e, reductions in surface water) from the changes in water management infrastructure than groundwater depth.
- NDVI within the Crystal and Brian Springs AOIs (AOIs 5-6) show increasing trends, despite greater water deficits (PWD; i.e., climate drying) resulting in a non-significant statistical relationship between NDVI and PWD. Both of these AOIs contain only a very narrow strip of mesic vegetation that is not well-captured by Landsat, and are also misclassified by LANDFIRE as non-mesic, as larger areas of surrounding dryland GDE and upland vegetation dominate the NDVI signal. Although no groundwater wells are located in close vicinity to these sites, groundwater levels in the Bullfrog Hills, where a large gold mine operation is being proposed, are close in elevation to the spring discharge points and are thought to be upgradient and within 4 miles of the spring complex. Thus, mining activities in this region, which are still in the planning phase, have the potential to impact these sites through dewatering activities and if they do occur, monitoring of water levels, spring flow, and fine-scale assessments of vegetation will be important data to collect going forward.
- Large and slowly varying changes in NDVI occur throughout the period of record at Parker Ranch AOI (AOI 7), one of which is coincident with the construction of several ponds in February of 2003 to restore open water and aquatic habitat. A large decrease in NDVI occurred at this time, likely due to the increase in surface water (which has low NDVI) and was sustained until about 2007. After that, a large increase and partial decrease in NDVI occurred, which may have also been coincident with changes in surface water extents due to restoration activities by TNC. Currently, NDVI is relatively low compared to values pre-restoration. Limited groundwater data indicate shallow groundwater (<12 ft DTW) that varies seasonally in conjunction with cool season precipitation and warm season evapotranspiration, suggesting groundwater dependence of mesic vegetation types in this AOI.
- NDVI in the Stagecoach AOI (AOI 8) exhibits an increasing trend, with evidence of NDVI decline and recovery during the 2012-2015 time period, coincident with restoration activities. Very limited groundwater data are available for this site, albeit the



few measurements that exist, along with the proximity to a perennial reach of the Amargosa River indicate relatively stable shallow groundwater conditions. Lack of significant relationships between interannual PWD and NDVI is likely driven by substantial groundwater subsidies and the influence of restoration activities, which potentially mask this relationship over the time period analyzed.

- NDVI in the Beatty Narrows AOI (AOI 9) exhibits a consistent increase over time, but lack of consistent long-term groundwater levels precludes the ability to establish relations to groundwater. Lack of significant relationships between interannual PWD and NDVI is likely driven by substantial groundwater subsidies and the positive trend in NDVI, which potentially masks this relationship over the time period analyzed. No clear relation between TNC restoration activities that began in 2018 and NDVI is evident at this time. The existence of rapid infiltration basins from the Beatty wastewater treatment plant nearby, the excavation of a gravel pit during highway construction that now forms a groundwater fed pond, and cessation of mining activities all have the potential to alter the hydrology of this area but any effects on vegetation, if they exist, appear to be gradual rather than episodic.

## CONCLUSIONS

The objective of this study is to establish a baseline for monitoring and assessing the potential impacts of groundwater developments on GDEs in Oasis Valley, using an approach and data that are consistent with assessments conducted in eight other basins (Albano *et al.*, 2021). Key findings are as follows:

- The extent of the GDE area in this and other (e.g., Heilweil and Brooks 2011) studies suggest that the initial reconnaissance survey (Malmberg and Eakin, 1962) underestimated the GDE extent, as it excluded several springs complexes. For this reason, it is difficult to determine how the extent and composition of the GDE area has changed over time. However, existing land cover classification data indicates 21 percent of the GDE area is covered by introduced vegetation and developed land cover types, a larger proportion than most other basins assessed in Albano *et al.* (2021), suggesting substantial modifications have occurred.
- Analysis of relationships between interannual climate variability and Landsat satellite-derived vegetation metrics showed similar patterns to those seen in other basins in Nevada (Albano *et al.*, 2021), where stronger relations are observed between climate and upland vegetation than GDE vegetation. One distinction is that, on average, GDE vegetation in Oasis Valley was less sensitive to climate relative to other basins, which could be due to the relatively shallow groundwater levels (measured groundwater levels are typically < 25 ft throughout the GDE area) that provide a consistent water resource despite varying climate. This pattern was also observed in most AOIs, as interannual climate variability never explained more than 14 percent of the variation in NDVI. Sensitivities may also be lower due to differences in the timing of green-up and

senescence between Mojave and Great Basin vegetation species but more investigation is needed to determine whether this is the case.

- Analysis of trends in vegetation metrics over 35 years showed similar results to other basins in Nevada, whereby more consistently positive (greening) trends are observed in upland areas, and more variable trends are seen within mesic vegetation types in the GDE area, where management impacts and hydrologic alterations are more concentrated.
- Permitted groundwater rights are greater than the current estimated perennial yield. Lack of consistent and long-term shallow groundwater data was the most limiting factor in this study. Both increasing and decreasing water level trends were observed in localized areas, in cases where multi-year data were available, but the reasons behind changing groundwater levels could not be determined. In the case of declining groundwater levels at East Torrance Ranch starting in 2009, water management and restoration activities may have contributed to these declines, but further investigation is needed to confirm.
- Groundwater level data records were sufficient to assess links between groundwater levels and vegetation at two sites, 7J Ranch and East Torrance Ranch. At 7J Ranch, positive trends in vegetation vigor corresponded with rising groundwater levels. At East Torrance Ranch, groundwater levels declined, but changes in vegetation corresponded more with management of surface waters than with depth to groundwater. Given interrelations between surface and groundwater, indirect linkages likely exist.
- Substantial human impacts were documented at all GDE sites that were visited in the field, but trends in vegetation over time varied from negative to neutral to positive. Restoration activities including prescribed fire, water diversions for habitat construction, and revegetation occurred at several sites, including 7J Ranch, Beatty Narrows, Torrance Ranch, and Parker Ranch. Coincident changes in vegetation associated with management activities were most apparent at East Torrance Ranch, where changes in water management in 2016 may have resulted in rapid vegetation greening. At Parker Ranch, slow varying changes in vegetation indices indicate changes in surface water extents associated with habitat restoration activities such as pond construction around 2003 and subsequent management interventions.
- The North Bullfrog Mine project is located in the vicinity of Crystal and Brian Springs and hydraulic head elevations at the mine site are within tens of feet of the spring discharge elevations. Further study is needed to better determine hydraulic connections between these locations to understand how these sites may be impacted by lowering of groundwater levels that would occur with mine development. This should include groundwater monitoring locations between the mine and the springs so that impacts of pumping can be observed prior to the cone of depression reaching the springs. In addition, on-site monitoring of the spring locations at regular intervals should be incorporated into the monitoring plan, as the spring sites are too small to adequately monitor using freely available satellite imagery.

## RECOMMENDATIONS

The data and analyses presented in this report and included in the accompanying database provide a baseline for future assessment and monitoring at both basin and site-specific scales.

- Future studies should focus on expanding groundwater and springs monitoring, as the lack of availability of these data was the primary limiting factor in this study and this information is needed to understand hydraulic connections that determine groundwater withdrawal impacts.
- Monitoring strategies identified in Albano *et al.* (2021) are recommended, including continued collection of high-resolution imagery from sUAS platforms to complement the Landsat archive, especially for locations with small GDE footprints, such as Crystal and Brian Springs. The development of web-based tools for automated analyses of satellite-based monitoring data, and the employment of advanced statistical methods to robustly quantify the roles of climate and management factors in changes to vegetation vigor are also recommended.
- In addition, the compilation and documentation of details on the timing, locations, and nature of land and water management actions across the region would be useful for future assessments as this information is needed to interpret observed changes in vegetation vigor, which could increase or decrease in the short term, depending on the degree of disturbance or vegetation changes caused by the management action. Ultimately, remotely sensed vegetation vigor is expected to increase following restoration activities in the long term, but the presence of water can interrupt this signal so ground-based information is essential.

In summary, analyses of the responses of groundwater dependent vegetation in relation to documented variations and trends in climatic conditions and groundwater levels is critical to understanding factors responsible for past changes in, and the current condition of, GDEs, the development of effective and efficient monitoring schemes for their protection and anticipating impacts from groundwater development and changes in climatic conditions. Results and recommendations from this study will enhance the current understanding of groundwater-vegetation-climate relations in space and time.

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## **APPENDIX A – ADDITIONAL DETAILS ON DATASETS USED**

### **1) Gridded Climate Data**

Daily resolution gridMET gridded (~2.5 miles/4 kilometers) meteorological data (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 referred to as potential evapotranspiration in this report. For vegetation and site-specific analyses, potential water deficit (calculated as precipitation minus potential evapotranspiration) was aggregated by northern hemisphere water year (i.e., October 1 to September 30) on a pixel-wise basis so each grid cell could be 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 images 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 Google Earth Engine (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 1984 and 2012
- Enhanced Thematic Mapper Plus (ETM+) scenes obtained between 1999 to 2012
- Operational Land Imager (OLI) scenes obtained between 2013 – 2021

Scenes of at-surface reflectance collected by 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 *et al.*, 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 (Schmidt *et al.*, 2013; Vermote *et al.*, 2018).

The Great Basin and Mojave Desert Ecoregions are generally areas where plant vigor and ET are highly water limited (Zomer *et al.*, 2022). The Landsat archive dataset was narrowed to scenes acquired between Julian days 182 and 258 (July 1st - September 15th, non-leap year) for any given year. This mid to late summer period is optimal for assessing the relationship between vegetation vigor and the interannual availability of groundwater in this region since soil moisture is typically at a minimum during this time (Huntington *et al.*, 2016) and riparian vegetation tends to be most sensitive to climate at this time (Albano *et al.* 2020, Figure S2). The late summer period commonly consists of sporadic monsoonal precipitation combined with abundant solar energy, which influences a strong contrast in the phenotypic expressions of phreatophytic and other GDE vegetation types when compared to xerophyte communities 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 interference were automatically flagged as using the “PIXEL\_QA” quality assessment (QA) band. The QA band is generated during Landsat Collection 2 scene processing, and all pixels identified as potentially impacted were removed from consideration. The enhanced vegetation index (EVI), NDWI, albedo, and Landsat-derived surface temperature products were also calculated using the Landsat archive. These remote sensing products were used alongside visual inspection of true and false color images to assist in quality assurance and quality control (QA/QC) of the Landsat dataset.

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

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} \quad [1]$$

Where NIR is the near infrared at-surface reflectance (band 4 Landsat TM and ETM+, band 5 Landsat OLI) and RED is the red at-surface reflectance (band 3, Landsat TM and ETM+, band 4 Landsat OLI).

NDVI (and NDWI) images were statistically analyzed to generate a single image per year, representative of that year of GDE vegetation vigor for the mid to late summer target period. To accomplish this, each year’s collection of NDVI images was reduced into a single image comprised of each pixel-year combination’s median NDVI value.

### 3) Groundwater Elevations Data

Readily available groundwater level data for the study area was obtained from the USGS National Water Information System database (USGS, 2016) and NDWR Water Level Data (accessed August 2, 2022) groundwater elevation databases. Water elevations above mean sea level are based on the NAVD88 vertical datum, and all well elevations were obtained from the original data source. All available groundwater measurements were acquired and subjected to a simple QA process to eliminate spurious measurements. Data from individual wells vary greatly

in terms of temporal span, measurement interval, seasonal timing, and consistency of measurements. It is important to note that none of the well records considered had regular measurements over the entire 1984 – 2021 focal period of this report, though several records with more than 25 years of consecutive measurement (1 or more per year) were found. The groundwater level data compiled may not include all groundwater data for the Oasis Valley area, as additional measurements may exist that are not part of the publicly available USGS and NDWR databases.

## **APPENDIX B – SELECTED SITE PHOTOS AND SUAS IMAGERY**

The following pages contain supplementary information for each area of interest (AOI) discussed in the report. Each page includes 1) representative photos (corresponding to locations of blue dots in AOI map figures) with direction of NDVI trend (positive = increased vegetation vigor; negative = decreased) indicated in overlaying text, 2) small unmanned aircraft system (sUAS)-based visible (upper right) and infrared-derived NDVI (lower right) imagery (where available), 3) boundaries of groundwater dependent ecosystem AOIs for which zonal statistics were calculated, 4) LANDFIRE classifications of dominant vegetation within the AOIs, and 5) field notes describing transect vegetation for each site. In some cases, sUAS imagery was not collected due to proximity to the Nevada National Security Site and permission was not granted to fly.

## *Oasis Valley — Upper 7J Ranch (AOI-1)*



Dominant Landfire Group(s)	Freshwater Marsh, Western Riparian Woodland and Shrubland, Introduced Riparian Vegetation
Transect Field Notes	Transect dominated by mesic graminoids with sparse riparian trees; extensive salt crust; and recent grazing activity.

### AOI-1: Transect 1



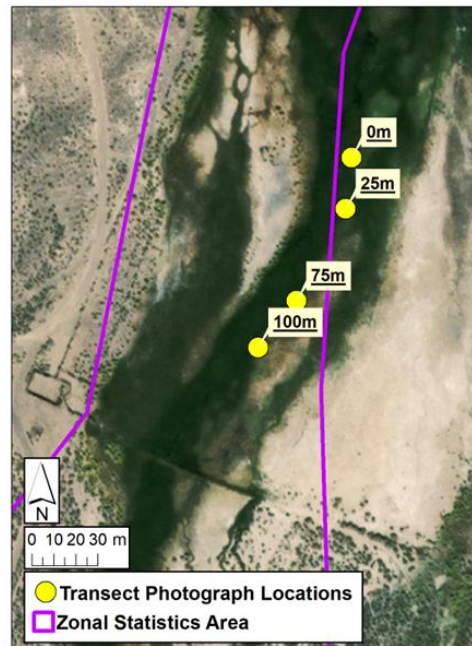


## *Oasis Valley — Upper 7J Ranch (AOI-1)*



Dominant Landfire Group(s)	Freshwater Marsh, Western Riparian Woodland and Shrubland,
Transect Field Notes	Transect dominated by very dense (95% total cover) mesic graminoids; some salt crust (5%); signs of recent grazing activity

AOI-1: Transect 2

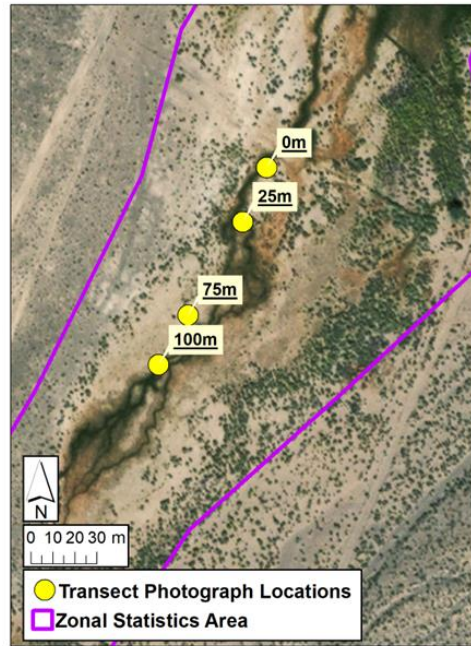


## *Oasis Valley — Upper 7J Ranch (AOI-1)*



Dominant Landfire Group(s)	Western Riparian Woodland and Shrubland, Introduced Riparian Vegetation, Salt Desert Scrub, Freshwater Marsh
Transect Field Notes	Dense (65% total cover) graminoids; some greasewood (15%) and rabbitbrush (5%); salt crust (15%); recent grazing activity; standing water indicates ~0 ft DTW

AOI-1: Transect 3



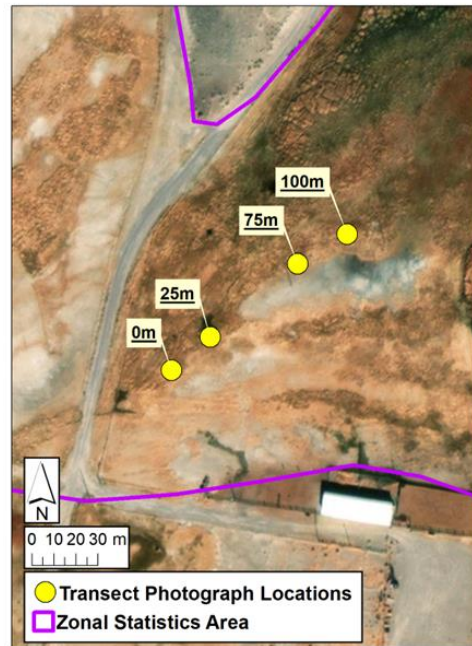


## Oasis Valley — Lower 7J Ranch (AOI-2)



Dominant Landfire Group(s)	Introduced Annual Grassland, Introduced Perennial Grassland and Forbland
Transect Field Notes	Dense graminoids (65% cover class); some salt crust (15%); signs of recent grazing activity

AOI-2: Transect 1

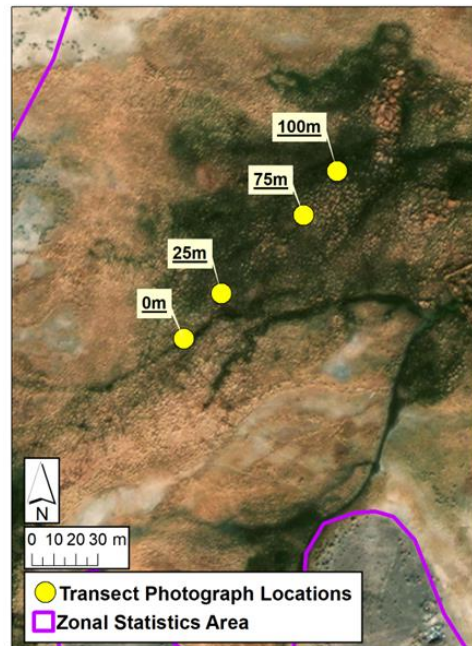


## *Oasis Valley — Lower 7J Ranch (AOI-2)*



Dominant Landfire Group(s)	Western Herbaceous Wetland
Transect Field Notes	Very dense graminoids (95% cover class); some salt crust (5%) and standing water (5%); sings of recent grazing activity and past disturbance; ~0 ft DTW (standing water)

AOI-2: Transect 2



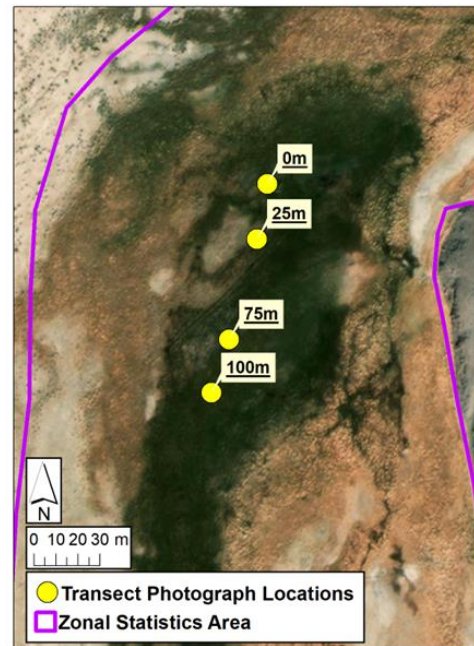


## *Oasis Valley — Lower 7J Ranch (AOI-2)*



Dominant Landfire Group(s)	Introduced Annual Grassland, Western Herbaceous Wetland
Transect Field Notes	Very dense graminoids (95% cover class); some salt crust (5%) and standing water (5%); recent grazing activity and past disturbance; ~0 ft DTW (standing water)

AOI-2: Transect 3



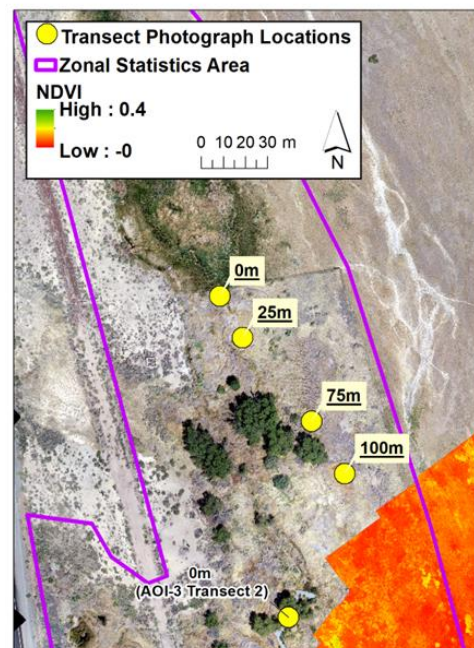
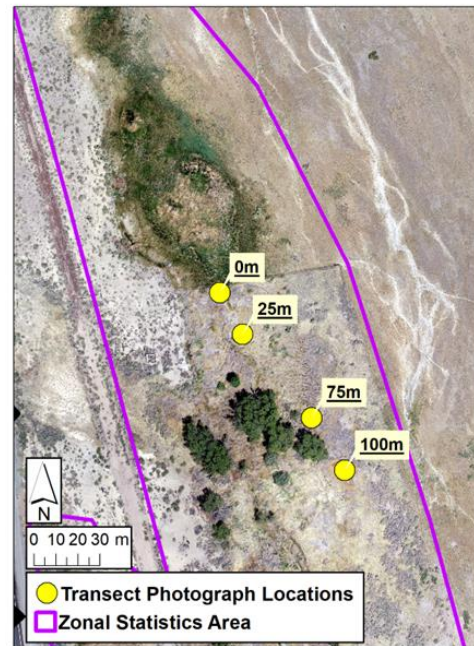


## Oasis Valley — West Torrance Ranch (AOI-3)



Dominant Landfire Groups	Western Herbaceous Wetland, Western Riparian Woodland and Shrubland, Salt Desert Scrub, Introduced Annual Grassland
Transect Field Notes	Dense graminoids dominate (65% cover class); secondary riparian trees and bullrush marsh (15% each); signs of past disturbance; invasive weeds

AOI-3: Transect 1



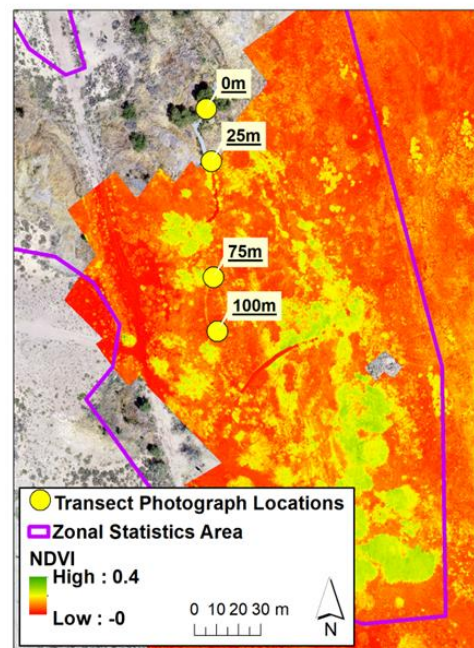
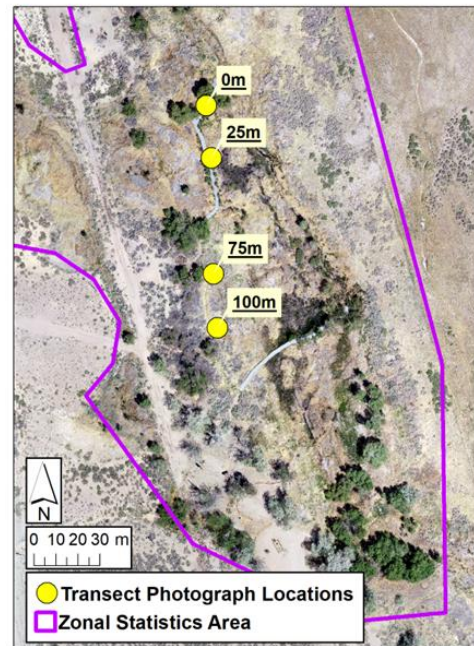


## Oasis Valley — West Torrance Ranch (AOI-3)



Dominant Landfire Group(s)	Western Herbaceous Wetland, Introduced Annual Grassland
Transect Field Notes	Dense graminoids (65% cover class), secondary marsh (30%) and riparian trees (30%); riparian tree mortality (bottom photograph); invasive weedy species

AOI-3: Transect 2



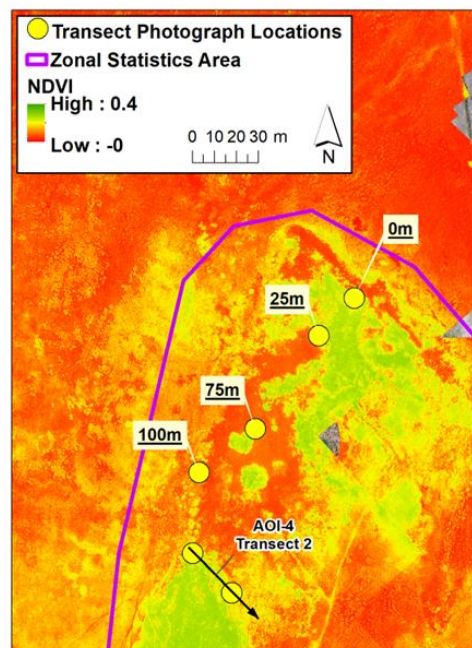
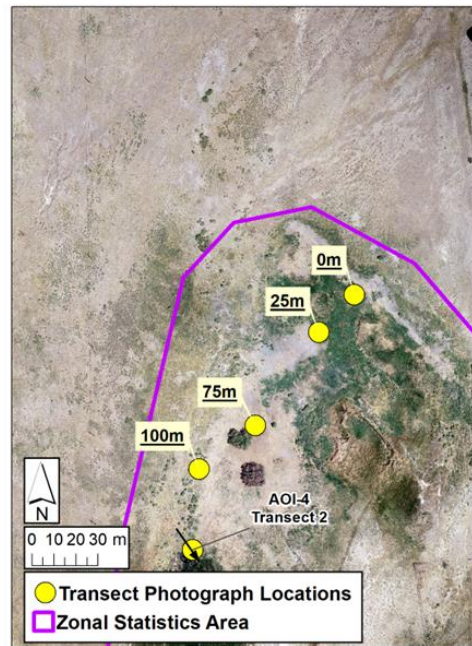


## Oasis Valley — East Torrance Ranch (AOI-4)



Dominant Landfire Group(s)	Western Herbaceous Wetland, Salt Desert Scrub, Developed- Herbaceous Upland
Transect Field Notes	Dense graminoids (65% cover class); some rabbitbrush (15%) and invasive trees (bottom photograph; 15%); extensive grazing activity and invasive species

AOI-4: Transect 1



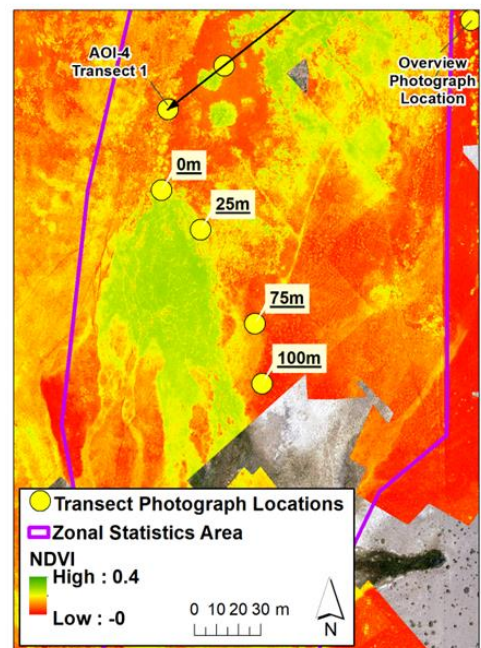
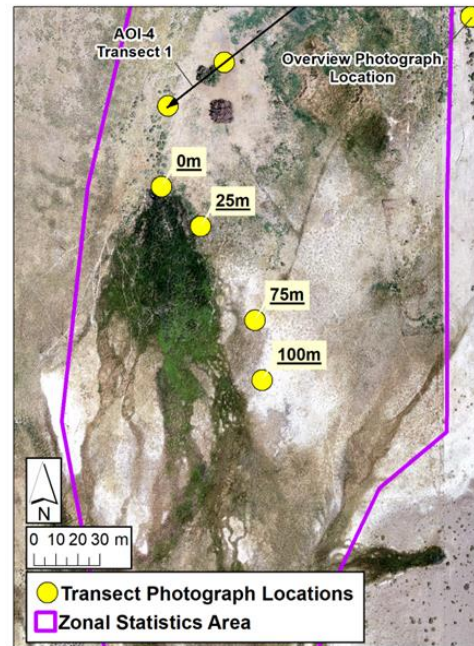


## Oasis Valley — East Torrance Ranch (AOI-4)



Dominant Landfire Group(s) in AOI	Western Herbaceous Wetland, Creosotebush Desert Scrub
Transect Field Notes	Dense graminoids (65% cover class); salt crust (30%), rabbitbrush (15%) and cow pies (15%); recent grazing activity and past disturbance; ~0 ft DTW (standing water)

### AOI-4: Transect 2



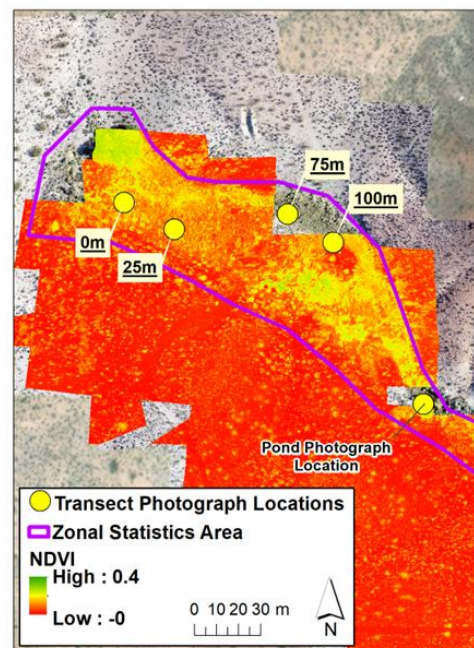
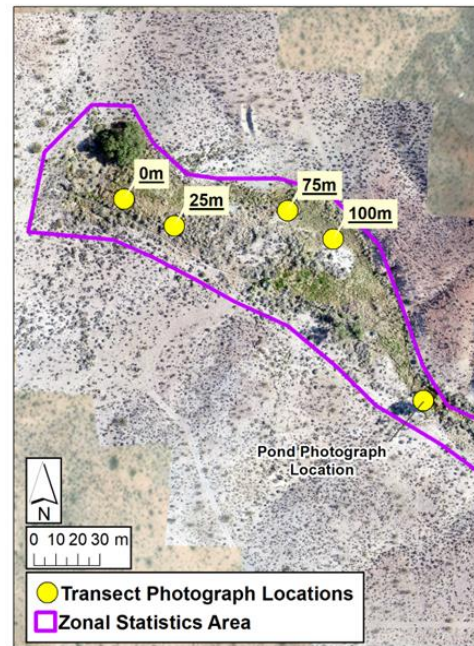


## Oasis Valley — Crystal Spring (AOI-5)



Dominant Landfire Group(s) in AOI	Creosotebush Desert Scrub, Desert Scrub, Chaparral
Transect Field Notes	Dense graminoids (65% cover class); salt crust (15%) and rabbitbrush (15%); past and ongoing spring development disturbance; DTW ~ 0 ft (ponded water)

AOI-5: Transect 1



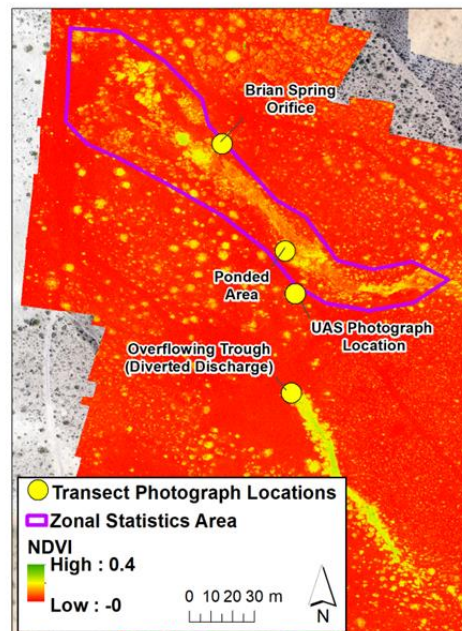
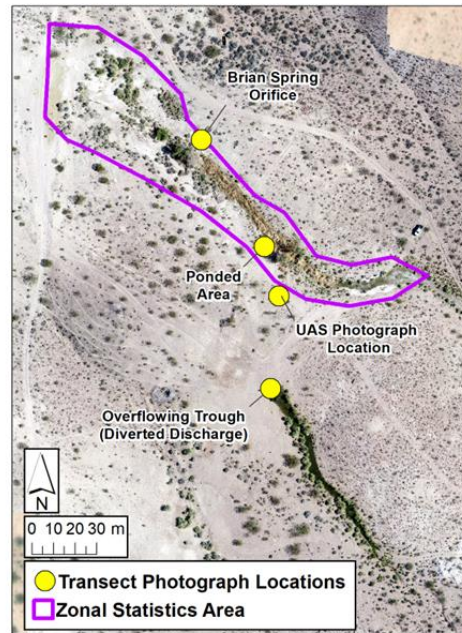


## Oasis Valley — Brian Spring (AOI-6)



Dominant Landfire Group(s)	Desert Scrub, Creosotebush Desert Scrub
Transect Field Notes	No transect conducted due to narrow width of spring corridor; GDE area dominated by graminoids near channel grading with distance into greasewood and rabbitbrush

### AOI-6: Overview



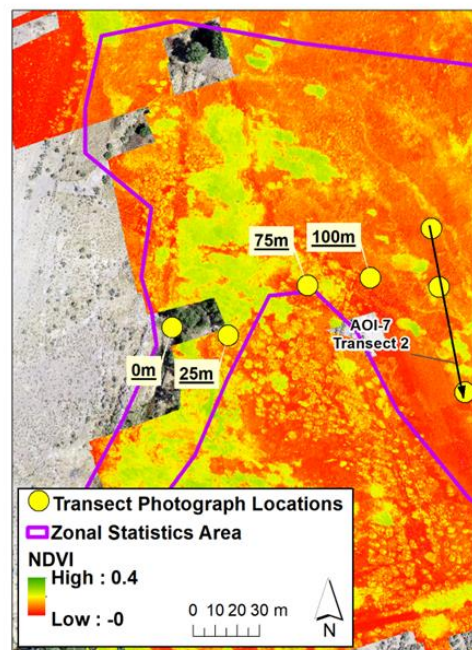
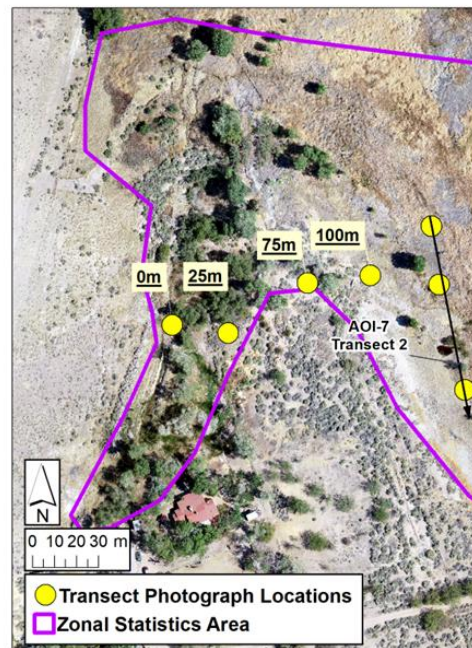


## Oasis Valley — Parker Ranch (AOI-7)



Dominant Landfire Group(s)	Western Herbaceous Wetland, Western Riparian Woodland and Shrubland, Salt Desert Scrub
Transect Field Notes	Transect co-dominated by rabbitbrush, graminoids, and riparian trees (all 30% cover class); invasive weeds and signs of past disturbance; minor riparian tree stress

### AOI-7: Transect 1



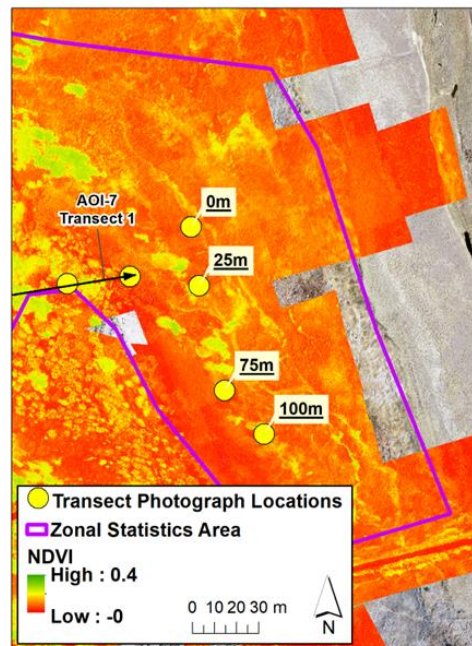
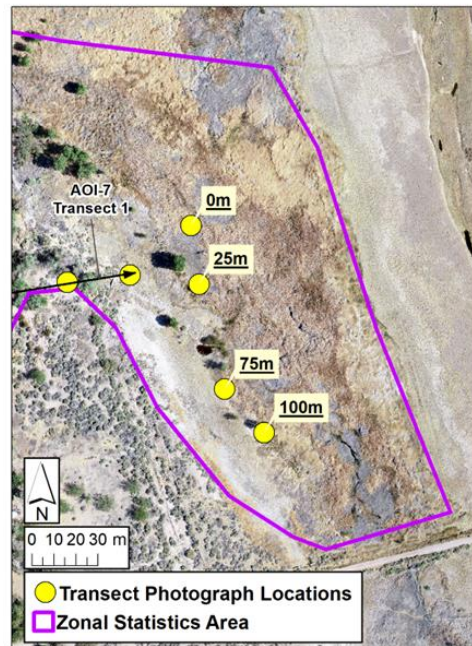


## Oasis Valley — Parker Ranch (AOI-7)



Dominant Landfire Group(s)	Western Herbaceous Wetland, Western Riparian Woodland and Shrubland
Transect Field Notes	Transect co-dominated by bullrush marsh and graminoids (both 65% cover class); invasive weeds and signs of past disturbance; saturation indicates ~ 0 ft DTW

AOI-7: Transect 2



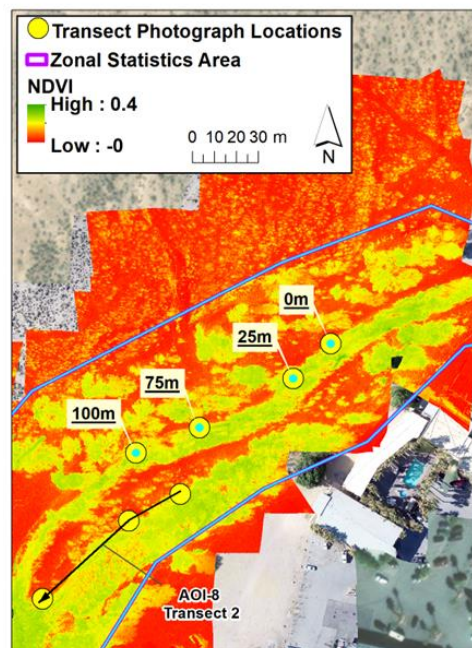
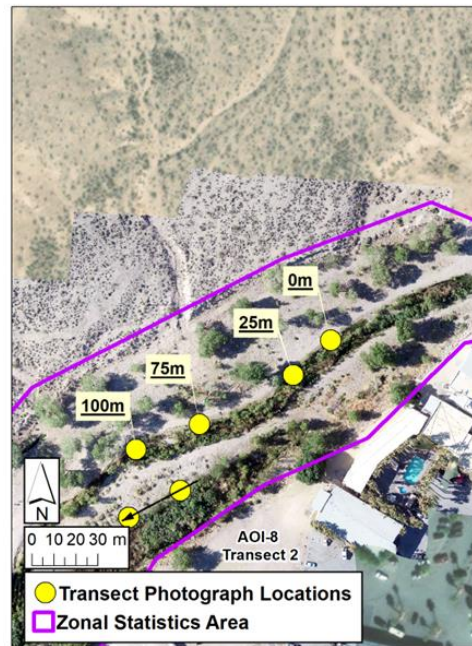


## Oasis Valley — Stagecoach (AOI-8)



Dominant Landfire Group(s)	Developed –Low Intensity
Transect Field Notes	Dominated riparian trees (65% cover class); some rabbitbrush, creosote bush, bare ground, and graminoids (all 15%); apparent disturbance from restoration efforts

AOI-8: Transect 1



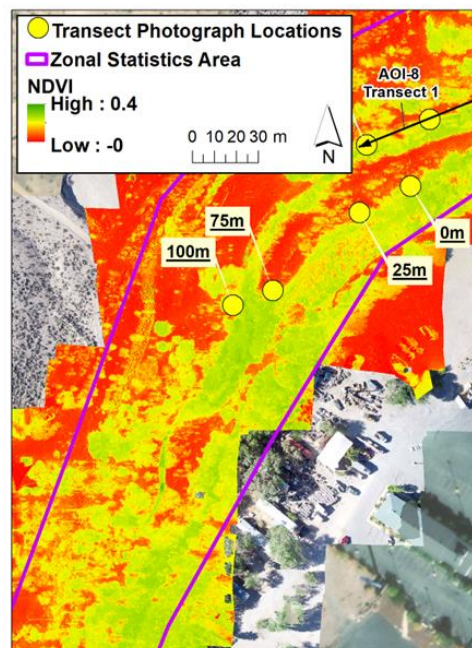


## Oasis Valley — Stagecoach (AOI-8)



Dominant Landfire Group(s)	Developed –Low Intensity, Developed- Upland Evergreen Forest
Transect Field Notes	Riparian trees (65% cover class); bullrush marsh (30%); some rabbitbrush, creosote bush, graminoids, and bare ground (all 15%); disturbance from restoration efforts

### AOI-8: Transect 2



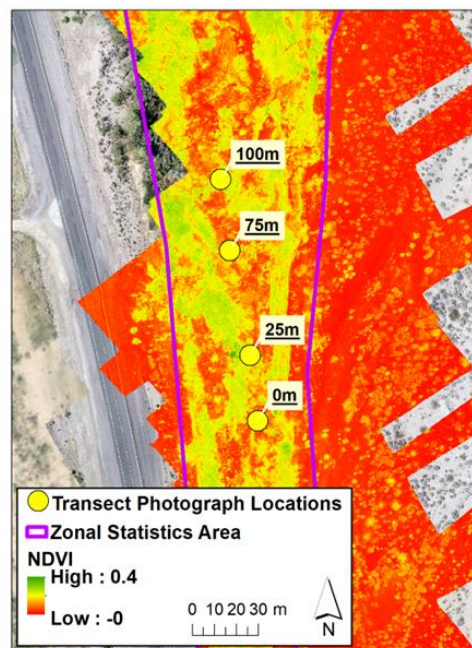


## Oasis Valley — Beatty Narrows (AOI-9)



Dominant Landfire Group(s)	Western Riparian Woodland and Shrubland, Western Herbaceous Wetland, Salt Desert Scrub
Transect Field Notes	riparian trees dominate (65% cover class); some rabbitbrush, marsh, and bare ground (all 15%); extensive invasive species and acute grazing disturbance apparent;

AOI-9: Transect 1



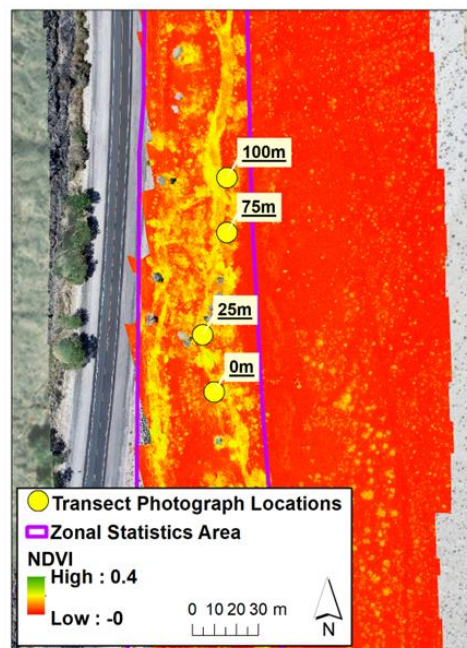


## Oasis Valley — Beatty Narrows (AOI-9)



Dominant Landfire Group(s)	Developed –Low Intensity
Transect Field Notes	Transect dominated by bare ground (65% cover class) with secondary riparian trees (30%) and some graminoids (15%); grazing, invasive, and restoration disturbances

AOI-9: Transect 2



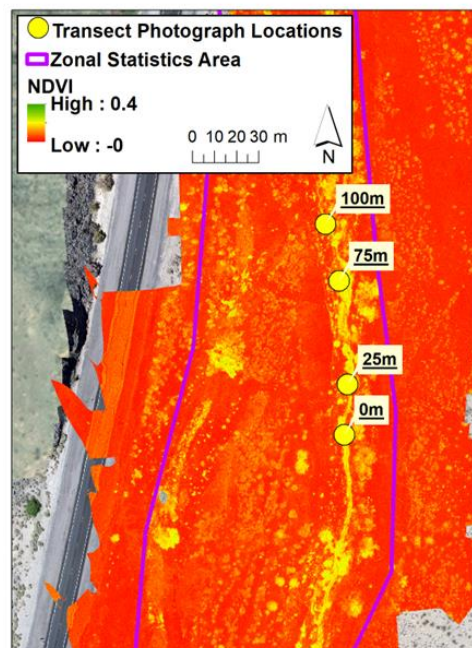
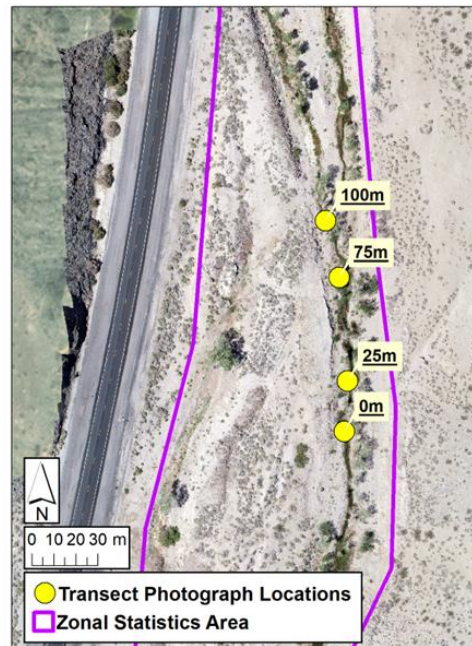


## Oasis Valley — Beatty Narrows (AOI-9)



Dominant Landfire Group(s)	Salt Desert Scrub, Introduced Upland Vegetation-Shrub, Developed-Medium Intensity
Transect Field Notes	Transect co-dominated by riparian trees, rabbitbrush, and bare ground (30% each); disturbance apparent from invasive trees, acute grazing, and restoration efforts

AOI-9: Transect 3





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