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memorandum

date	March 27, 2026
to	Vina Groundwater Sustainability Agency
cc	Rebecca Fairbanks, Butte County; Ryan Fulton, LWA
from	Byron Amerson, ESA; Jason Wiener, ESA
subject	Vina Groundwater Subbasin – Groundwater Dependent Ecosystem Technical Study

Summary of Findings

Key findings: A desktop analysis of groundwater dependent ecosystems (GDEs) in the Vina Subbasin using depth-to-groundwater (DTG) and rooting depth thresholds identified 464 likely GDEs under typical spring conditions (41 percent of all potential GDEs mapped in the Subbasin by the Natural Communities Commonly Associated with the Groundwater dataset were identified as likely GDEs). Likely GDEs were concentrated in the northwestern portion of the Subbasin between the Sacramento River and Southern Pacific Railroad. Groundwater levels at likely GDEs were found to exhibit high seasonal variability. For instance, only 38 of these likely GDEs (8 percent) maintained groundwater connectivity during typical fall conditions. Under drought conditions representative of 2015 and 2021, 78 to 86 percent of those GDEs identified as likely GDEs experienced DTG exceeding their rooting depths, indicating widespread vulnerability to groundwater level declines during dry periods.

Review of Normalized Derived Vegetation Index (NDVI) values, a widely used and reliable vegetation metric used to assess ecosystem health, at all potential GDEs identified as likely GDEs and not likely GDEs based on spring 90th percentile conditions for the period of record from 1985 through 2024 found median NDVI at likely GDEs was greater than median NDVI at not likely GDEs for all years in the record, suggesting groundwater related factors play a role in higher NDVI values at likely GDEs. During 2021 and 2022 NDVI values at all potential GDEs generally decreased, however values rebounded in 2023 and 2024 to pre-drought levels. While NDVI remains a promising tool for monitoring and assessing GDE ecological health in the Subbasin, uncertainties and data gaps remain regarding the relationship between shallow groundwater levels and GDE NDVI and how other biotic/abiotic factors and processes influence changes in NDVI.

Management implications: Based on likely GDEs being those whose associated rooting depths were hydrologically connected with groundwater levels during typical spring conditions (i.e., 90th percentile DTG levels), the region where the majority of likely GDEs were found to become disconnected between spring 90th percentile and spring 2015 conditions is recommended as a priority area for establishing potential monitoring sites. Likely GDEs in this region occupy the margin of groundwater accessibility and can provide an early warning of changes in regional groundwater levels that may be affecting GDEs. More generally, establishing fixed monitoring locations to assess ecological baseline conditions at representative GDEs and subsequent periodic monitoring of ecological conditions at the same monitoring locations can provide insight into how environmental conditions and groundwater management may be influencing GDE function, integrity, and ecological health through time. An approach for long-term GDE monitoring completed for the adjacent Wyandotte Creek Subbasin is described in ESA (2026) and could be applied to the Vina Subbasin.

While it is recommended that monitoring should focus on the transition zone near the Southern Pacific Railroad, where the boundary between likely and not likely GDEs is most pronounced. Additional monitoring sites that include representative GDEs from the northwestern portion of the Subbasin that maintain connectivity during typical conditions are recommended to establish baseline reference conditions for comparison.

Background

The original Vina Subbasin Groundwater Sustainability Plan (Vina GSP) submitted to the California Department of Water Resources (DWR) in 2022 creates the framework for sustainable management of groundwater in the Vina Subbasin (Subbasin) under the Sustainable Groundwater Management Act (SGMA). The Vina Groundwater Sustainability Agency (GSA) was established through a Joint Powers Agreement (JPA) between the County of Butte, the City of Chico, and the Durham Irrigation District (DID). The 2022 Vina GSP includes a detailed characterization of groundwater conditions in the Subbasin, establishment of a sustainability goal and sustainable yield, and description of projects and management actions the GSA will implement to maintain sustainable groundwater management through 2042 and beyond.

Pursuant to Recommended Corrective Actions (RCAs) provided in DWR's Determination Letter on the 2022 Vina GSP,[1] the GSA is required to submit an amended GSP to DWR by January 28, 2027. The amended Vina GSP and associated Periodic Evaluation are currently underway and will address DWR's RCAs and include updated Sustainability Management Criteria (SMCs) and monitoring networks for nearly all SGMA sustainability indicators. Findings and recommendations from this analysis will be incorporated into the amended GSP and Periodic Evaluation as determined by the GSA board.

Under SGMA, Groundwater Sustainability Agencies are required to identify and consider the interests and impacts to beneficial uses and users of groundwater, including environmental users of groundwater such as groundwater dependent ecosystems (GDEs). GDEs are defined by the State of California as "ecological communities of species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface" (23 CCR § 351(m)). These diverse habitats often host rare species like giant garter snakes and anadromous salmonids, many of which are protected under endangered species acts. Examples of GDEs include riparian forests, rivers, and oak woodlands. GDEs can generally be differentiated into vegetative GDEs and instream GDEs depending on whether they rely on shallow groundwater for root uptake or on groundwater discharging into surface water bodies. Vegetative GDEs typically consist of plant communities with root systems that tap directly into shallow groundwater, often termed phreatophytes. Instream GDEs are ecosystems within or immediately adjacent to water bodies that depend on the discharge of groundwater. These ecosystems are often essential for aquatic species, including fish and invertebrates that rely on consistent surface water flows. GDEs are also often closely tied to interconnected surface water (ISW), as groundwater pumping that reduces streamflows can harm the species that comprise or use GDEs.

Previous GDE Identification and Data Gaps

As summarized in DWR's *Statement of Findings Regarding the Approval of the Sacramento Valley Basin – Vina Subbasin Groundwater Sustainability Plan*[2], the Vina GSP utilized the Natural Communities Commonly Associated with the Groundwater (NCCAG) dataset to identify GDEs. Per the Vina GSP, the NCCAG dataset defines two habitat classes: wetland features commonly associated with the surface expression of groundwater under natural, unmodified conditions; and vegetation types commonly

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[1] https://www.vinagsa.org/files/1d5d486d9/Vina_GSP2023_Determination.pdf

[2] https://www.vinagsa.org/files/1d5d486d9/Vina_GSP2023_Determination.pdf

associated with the sub-surface presence of groundwater (phreatophytes). The Vina GSP provides figures showing the locations of all potential GDEs identified by the NCCAG database within the Vina Subbasin[3]. The Vina GSP states that GDE's dependence on groundwater was analyzed based on: land use changes; proximity to perennial surface water supplies; areas accessing supplemental water supplies; adjacency to irrigated agriculture; dependency on agricultural-dependent surface water; and non-survival of vegetation during drought years. Additionally, the potential GDE dataset was further reviewed against land use classifications to identify unlikely GDEs based on adjacency to agricultural operations[4]. Based on this analysis, the Vina GSP classified the potential GDEs as "Not likely a GDE" or "Likely a GDE" showing their locations on maps[5]. Additionally, the maps also show the location of Valley Oak Dominated Areas which are classified as "Likely a GDE" because, per the Vina GSP, this species can access groundwater over a wide range of depths[6].

DWR indicated that the Vina GSP "adequately describes the historical and current groundwater conditions related to chronic lowering of groundwater level." However, DWR found that "more information is required to fully understand groundwater conditions related to… depletions of interconnected surface water.[7]"

Data Gaps

Both the Vina GSP and the DWR Statement of Findings identified significant data gaps regarding shallow groundwater conditions and surface water depletion as it pertains to GDEs, including:

- Highly variable aquifer characteristics and uncertain vertical hydrologic connectivity between geologic units;
- Lack of available shallow groundwater data to fully characterize ISW and GDE conditions and set specific ISW SMCs;
- Uncertainty regarding the distribution and groundwater dependency of identified GDEs;
- Insufficient data to analyze interaction between surface water and groundwater pumping within the primary aquifer system;
- and lack of suitable tools to estimate the location, quantity, and timing of stream depletion due to basin-wide pumping.

Subsequent to DWR's 2023 Determination Letter the Vina GSP has completed the *Data Gap Identification and Data Improvement Project*[8], which enhances understanding of the hydrogeology and groundwater users in the Subbasin, and will support updates to the GSP and the successful management

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[3] Vina Subbasin GSP, Figure 2-28, p. 146, Figure 2-29, p. 147.

[4] Vina Subbasin GSP, Section 2.2.7.4, p. 150.

[5] Vina Subbasin GSP, Appendix 2-A, pp. 283-284.

[6] Vina Subbasin GSP, Section 2.2.7.4, p. 150, Appendix 2-A, pp. 283-284.

[7] Page 17 of DWR's determination.

[8] https://www.vinagsa.org/data-gap-identification-and-data-improvement-project

of the Subbasin. As part of that effort fourteen (14) additional shallow wells not included in the original Vina GSP monitoring network were identified that could fill spatial gaps in the monitoring network. These wells are located within the City of Chico as part of the City's nitrate monitoring program, on CSU Chico's campus, Neal Road landfill, and at other Department of Toxic Substances Control (DTSC) groundwater contamination monitoring sites (e.g., Chico Central Plume, municipal airport, etc.).

Desktop Analysis Objectives and Scope

This analysis was conducted to document the baseline condition of the Subbasin's GDEs, document GDE susceptibility to changing groundwater conditions, and address certain GDE data gaps identified in the 2022 Vina GSP. The analysis accomplished these objectives through:

- Characterization of shallow aquifer zone groundwater conditions (baseline hydrologic conditions) to refine the location and extent of GDEs within the Subbasin. This characterization can be used to improve understanding of potential impacts to GDEs associated with potential changes in groundwater levels.
- Characterization of ecological conditions of GDEs, where ecological condition refers to metrics related to vegetation growth, water stress, and general ecological vigor that provide a representative qualification of how a GDE is functioning with respect to providing habitat and hydrologic connectivity.

The overall approach for refining the existing mapping of potential GDEs was to compare seasonally estimated depth to groundwater (DTG) observations at potential GDEs with best available information on vegetation rooting depths to determine whether groundwater is accessible to the dominant plant communities present at potential GDEs under different hydrologic conditions. This "rooting depth threshold" method provides a consistent way to evaluate which mapped potential GDE features are supported by groundwater. The goal of this analysis was to create accurate GDE maps for SGMA compliance and aid selection of representative GDEs as part of potential future long-term GDE monitoring.

The overall approach for characterizing GDE ecological conditions was to assess regional trends in Normalized Derived Vegetation Index (NDVI) at all potential GDEs. NDVI is a widely used and reliable vegetation metric used to assess vegetation growth and water stress that is easily calculable and readily extractable from many long term satellite monitoring programs and is useful for inferring ecosystem health.

The step-wise process and data inputs used to conduct these analyses are described below. Notably, these analyses do not address data gaps or uncertainties related to surface water depletions that are being addressed under separate efforts that will be incorporated into the amended GSP and associated Periodic Evaluation currently underway.

Study Area

The Study Area for this analysis was the Vina Subbasin as described in the 2022 Vina GSP. The Vina Subbasin lies in the eastern central portion of the larger Sacramento Valley Groundwater Basin. It is bounded on the west by the Sacramento River and Butte Subbasin; on the south by the south by the Butte and Wyandotte Creek Subbasins; on the north by the Butte-Tehama county line; and east by the edge of the alluvial basin as defined by DWR Bulletin 118 - Update 2003 (DWR, 2003). It is surrounded by the Butte and Corning Subbasins to the west, the Los Molinos Subbasin to the north, the Butte and Wyandotte Creek Subbasins to the south, and the Sierra Nevada foothills to the east.

GDE Mapping Refinement Methods

Groundwater Connectivity of Mapped Potential GDEs

The NCCAG dataset remains the best available data for mapping potential GDEs in the basin and thus was used "as-is" as the starting point for the analysis. The NCCAG dataset undoubtably includes localized commission (e.g., inclusion of potential GDEs that are not GDEs) and omission (e.g., exclusion of potential GDEs) errors at spatial scales below the mapping accuracy of the individual datasets used to generate the NCCAG dataset (e.g., <1 acre). While an accurate mapping of potential GDEs is important and required under SGMA, it is also unrealistic to produce a "perfect" map that accounts for each vegetative community or patch of vegetation and aquatic habitat that may rely on groundwater. What is deemed more important for this analysis is a mapping that accurately captures the spatial distribution and relative ecological diversity of potential GDEs across the landscape. For instance, are potential GDEs generally mapped where they would be expected at appropriate densities and spatial configurations, and do they represent the mosaic of ecological communities that would be expected to be present. The NCCAG dataset, especially when coupled with other locally available data, does an excellent job in this regard. Therefore, the NCCAG mapping enables analysis of GDE hydraulic connectivity with regional groundwater conditions and provides an appropriate dataset for understanding the spatial distribution of GDEs and managing groundwater resources to avoid significant and unreasonable impacts to these beneficial uses/users.

The first preparatory step of the GDE mapping refinement was to assign vegetation rooting depths based on mapped vegetation in the NCCAG dataset. Rooting depths were taken from updated values developed in a 2024 statewide study of vegetation health in groundwater dependent ecosystems (Rohde et al., 2024). Following the methodology of Rhode et al. (2024) we assigned refined rooting depths based on the dominant plant species for each NCCAG polygon defined by the "Vegetation" field of that dataset (**Table 1**). We adopted these rooting depths because they better capture seasonal variation in groundwater levels and other conditions that influence plant growth across California. Compared to values from the Nature Conservancy's original Plant Rooting Depth Database[9], these revised rooting depths are generally deeper and provide a more realistic representation of rooting potential. Several species were not included in the Rhode et al. (2024) analysis (e.g., Alder). Rooting depths for these species were derived from either the TNC Rooting Depth Database or were based on vegetation proxies and professional judgment.

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[9] https://www.groundwaterresourcehub.org/where-we-work/california/plant-rooting-depth-database/

TABLE 1. ADJUSTED ROOTING DEPTH FOR DOMINANT VEGETATION FOR POTENTIAL GROUNDWATER DEPENDENT ECOSYSTEMS.

Genus	Common Name	Adjusted Rooting Depth (ft.)	Source
Acer	Box Elder	16.0	Rhode et al., (2024)[a]
Ailanthus	Tree of Heaven	5.0	Estimate[b]
Alnus	Alder	6.5	TNC rooting depth database[c]
Arundo	Arundo	9.1	Rhode et al., (2024)[a]
Baccharis	Coyote Bush	11.1	Rhode et al., (2024)[a]
Flooded Veg	Flooded Vegetation	7.1	Estimate[b]
Heterotheca	Aster sp.	1.0	Estimate[b]
Juglans	Walnut	13.2	Rhode et al., (2024)[a]
Leymus	Basin Wildrye	2.96	Estimate[b]
Persicaria	Knotweed	1.0	Estimate[b]
Platanus	Sycamore	16.3	Rhode et al., (2024)[a]
Populus	Cottonwood	11.9	Rhode et al., (2024)[a]
Quercus	Oak	18.2	Rhode et al., (2024)[a]
Rosa	Rose	6.54	Rhode et al., (2024)[a]
Rubus	Blackberry	9.9	TNC rooting depth database[c]
Sambucus	Elderberry	3.0	Estimate[b]
Salix	Willow	7.2	Rhode et al., (2024)[a]
Schoenoplectus	Tule	2.2	TNC rooting depth database[c]
Typha	Cattail	3.6	TNC rooting depth database[c]
Vitus	Grape	1.0	Estimate[b]
River	River	20.0	Estimate[b]

Notes:

a. https://doi.org/10.3389/fenvs.2019.00175
b. Estimates are based on professional judgment due to a lack of data and are subject to revision as better information becomes available
c. https://www.groundwaterresourcehub.org/where-we-work/california/plant-rooting-depth-database/

Those potential GDEs that were classified as “riverine” and “palustrine” in the “Wetland” field of the NCCAG dataset (Klausmeyer et al., 2018) were a special case because it was unclear if and how they were addressed in the Rhode et al. (2024) study. Based on the Cowardin classification in the “Wetland” field of the NCCAG data set and the corresponding “CalVegType” vegetation type from the VegCAMP data set, dominant species for each palustrine class were developed (**Table 2**). Cowardin riverine classes were assigned a composite “River” class. Adjusted rooting depths from Rhode et al. (2024) were then assigned to the former palustrine classes. A threshold DTG of 20 feet was assigned to the riverine class with the assumption that river and streambeds within 20 feet of the 90th percentile water table (e.g., 90 percent of DTG values were at least this deep or deeper over the period of record) are connected to the regional groundwater system (TNC, 2021).

TABLE 2. ROOTING DEPTHS FOR PALUSTRINE AND RIVERINE POTENTIAL GROUNDWATER DEPENDENT ECOSYSTEMS.

Cowardin Class	Common Name	Adjusted Rooting Depth (ft.)
Palustrine, Aquatic Bed, Permanently Flooded	River	20.0
Palustrine, Aquatic Bed, Rooted Vascular, Permanently Flooded	River	20.0
Palustrine, Aquatic Bed, Semipermanently Flooded	Blackberry	9.9
Palustrine, Emergent, Persistent, Seasonally Flooded	Blackberry	9.9
Palustrine, Emergent, Persistent, Semipermanently Flooded	Blackberry	9.9
Palustrine, Forested, Broad-Leaved- Evergreen, Seasonally Flooded	Sycamore	16.3
Palustrine, Forested, Emergent, Persistent, Seasonally Flooded	Sycamore	16.3
Palustrine, Forested, Scrub-Shrub, Seasonally Flooded	Sycamore	16.3
Palustrine, Forested, Seasonally Flooded	Sycamore	16.3
Palustrine, Scrub-Shrub, Broad-Leaved- Evergreen, Seasonally Flooded	Box Elder	16.0
Palustrine, Scrub-Shrub, Broad-Leaved- Evergreen, Seasonally Flooded, Alkaline	Box Elder	16.0
Palustrine, Scrub-Shrub, Broad-Leaved- Evergreen, Semipermanently Flooded	Box Elder	16.0
Palustrine, Scrub-Shrub, Emergent, Persistent, Seasonally Flooded	Box Elder	16.0
Palustrine, Scrub-Shrub, Seasonally Flooded	Box Elder	16.0
Palustrine, Unconsolidated Bottom, Permanently Flooded	Cattail	3.6
Palustrine, Unconsolidated Bottom, Semipermanently Flooded	Cattail	3.6
Riverine, Lower Perennial, Aquatic Bed, Floating Vascualar, Permanently Flooded	River	20.0
Riverine, Lower Perennial, Aquatic Bed, Rooted Vascular, Permanently Flooded	River	20.0
Riverine, Lower Perennial, Aquatic Bed, Semipermanently Flooded	River	20.0
Riverine, Lower Perennial, Unconsolidated Bottom, Permanently Flooded	River	20.0
Riverine, Lower Perennial, Unconsolidated Bottom, Semipermanently Flooded	River	20.0
Riverine, Lower Perennial, Unconsolidated Shore, Seasonally Flooded	River	20.0
Riverine, Unknown Perennial, Unconsolidated Bottom, Semipermanently Flooded	River	20.0
Riverine, Upper Perennial, Unconsolidated Bottom, Permanently Flooded	River	20.0
Riverine, Upper Perennial, Unconsolidated Shore, Seasonally Flooded	River	20.0
Seep or Spring	Cattail	3.6

After preparing the potential GDE dataset with rooting depths, we overlaid the geographic centroid of each polygon on DTG rasters to extract a representative DTG value for each polygon under different hydrologic conditions. The DTG datasets used in this analysis were developed in partnership with Larry Walker and Associates (LWA) who initially developed a series of seasonal (i.e., spring and fall) shallow groundwater elevation rasters at 230 ft x 230 ft resolution using shallow monitoring well data from 2000-2025. Wells used to generate these data include wells from the Vina GSP groundwater level monitoring network identified as shallow wells (i.e., those screened in the upper and lower Quaternary deposits) and additional shallow wells identified by the *Data Gap Identification and Data Improvement Project*. The result from LWA was a total of 50 shallow groundwater elevation rasters, one for spring and one for fall for each year between 2000 and 2025. The shallow groundwater elevation rasters were converted to DTG rasters through computing the difference between the bare earth ground surface and groundwater levels (earth surface elevation – groundwater elevation = DTG). Bare-earth elevation data were obtained as a ~1.6 ft resolution raster derived from 2018 Lidar collected for the 2018–2019 USGS QL2 Lidar: Northern California Wildfires project.[10] Regionally this produced DTG estimates across 25 years and a total of 50 spatially explicit DTG datasets covering the basin.

For each potential GDE, we evaluated six representative DTG conditions: (1) the spring and fall 90th percentile DTG value, representing DTG conditions that occurred 90 percent of the time, (2) spring and fall 2015, the second lowest water year since 2000, and (3) and spring and fall 2021, the lowest water year since 2000. The 90th percentile DTG values represent the upper threshold of regularly occurring groundwater conditions that would be encountered most of the time.

For each condition, each polygon was classified based on whether DTG remained within the revised rooting depths. Years 2015 and 2021 were both classified as critically dry by DWR[11] and represent low and very low water table elevations, respectively. These conditions provide a basis for documenting GDE conditions under drought conditions and potentially inform how groundwater management and associated SMCs (e.g., MO and MT) may affect the interests of beneficial uses and users of groundwater.

Polygons where DTG stayed within rooting depths for the spring 90th percentile were identified as likely GDEs, and polygons where DTG exceeded rooting depths were classified as not likely GDEs. For 2015 and 2021, those GDEs where DTG either remained within or exceeded the rooting depth were identified for comparative purposes (e.g., GDEs identified as likely GDEs may have become temporarily hydrologically disconnected under these conditions).

GDE-Surficial Geology Intersection

Surficial geology and the potential for soils that create localized perched soil water systems that are partly or fully disconnected from the deeper aquifer were spatially represented using the ‘restrictive depth layer’ attribute from the National Resource Conservation Survey (NRCS) Soil Survey Geographic Database (SSURGO).[12] The soils data was supplemented with 2018 mapping of vernal pool habitat by Witham (2021). Vernal pools are temporary wetlands that hold water for several months, due to impermeable hardpan or clay layers, and thus provide a secondary dataset for resistive soils/geologic formations. These data were overlain with potential GDEs to identify ecological communities that are likely supported by shallow perched water.

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[10] https://apps.nationalmap.gov/lidar-explorer/#/

[11] https://data.ca.gov/dataset/cdec-water-year-type-dataset

[12] Depth to nearly continuous layer that has one or more physical, chemical, or thermal properties that significantly impede the movement of water and air through the soil or that restrict roots or otherwise provide an unfavorable root environment. If no restrictive layer is described in a map unit, it is assumed no restrictions are present within 150 in (12.5 ft) of the ground surface.

Regional Potential GDE Health Methods

The ecological health[13] of GDEs are affected by several factors including climate, pests, land management, water quality, and access to groundwater (Brown et al., 2011; Groeneveld, 2008; Patten et al., 2008; Cooper et al., 2006; Elmore et al., 2006; Huntington et al., 2016). GDE health is commonly assessed through measurement of a variety of vegetation metrics, including growth, species diversity, reproduction, interactions between species, and survivorship (Rohde et al., 2019). These vegetation metrics essentially serve as an indicator of vegetation health for GDEs. Both ground-based and remotely sensed techniques are available for obtaining vegetation metrics. Remote sensing has the benefit of being more cost effective to apply at scale compared to ground-based measurements, can provide long term temporal trends of vegetation metrics, and many studies have demonstrated the utility of satellite remote sensing to monitoring metrics of vegetation health (Vogelmann et al., 2012; Huang et al., 2010; Asner et al., 2016; Healey et al., 2018). Normalized Derived Vegetation Index (NDVI), a derived product from remotely sensed satellite data, is the most widely used vegetation metric in the literature and is a reliable measure of the photosynthetic chlorophyll content in leaves and vegetation cover, which are proxies for vegetation growth and water stress and are variables for inferring ecosystem health (Rouse et al., 1974; Jiang et al., 2006). NDVI values range from +1.0 to -1.0. Areas of barren rock, sand, or snow usually show very low NDVI values (for example, 0.1 or less). Sparse vegetation such as shrubs and grasslands or senescing crops may result in moderate NDVI values (approximately 0.2 to 0.5). High NDVI values (approximately 0.6 to 0.9) correspond to dense vegetation such as that found in temperate and tropical forests or crops at their peak growth stage. NDVI is easily calculable and readily extractable from many long term satellite monitoring programs including the Landsat mission.

For this analysis, NDVI data available from the TNC GDE Pulse tool[14] were used to assess regional trends in NDVI at all potential GDEs for the available period of record from 1985 through 2024. Specifically, the TNC GDE Pulse tool provides average NDVI for all the Landsat pixels that fall within each potential GDE polygon for each year corresponding to the annual dry-month (June 1 to September 30) medoid producing one NDVI value for each potential GDE per year. These data were then stratified based on the classifications from the GDE mapping refinement to compare NDVI values between GDEs identified as likely GDEs and not likely GDEs. Lastly, the potential GDE-NDVI data was compared to local precipitation data available from the TNC GDE Pulse tool[15] and the LWA shallow groundwater data to document the interplay and correlations between regional scale GDE vegetation metrics, precipitation, and groundwater levels.

Results

GDE Mapping Refinement

The number and pattern of GDEs identified as likely GDEs versus not likely GDEs depended on the season (i.e., spring or fall) and the DTG condition used for evaluation (i.e., 90th percentile 2015, or 2021).

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[13] Health here generally refers to metrics related to vegetation growth, water stress, and general ecological vigor.

[14] https://gde.codefornature.org/#/methodology

[15] Annual precipitation for each GDE polygon derived from Parameter-elevation Regressions on Independent Slopes Model (PRISM) data.

For the spring 90th percentile condition, of the 1,228 potential GDEs in the Subbasin 464 were found to be hydrologically connected to groundwater (i.e., DTG was at or above rooting depths) and thus identified as likely GDEs (41 percent of total potential GDEs). For the spring 2015 and spring 2021 conditions 100 and 64 potential GDEs were found to be connected to groundwater, respectively. For fall conditions the number of GDEs connected to groundwater was 38 (3 percent), 21 (2 percent), and 17 (1 percent) for the 90th percentile, 2015, and 2021 conditions, respectively.

Of the 464 GDEs that were identified as likely under spring 90th percentile conditions (i.e., connected to groundwater) 100 stayed connected to groundwater under spring 2015 conditions. Thus, between the spring 90th percentile and spring 2015 conditions, DTG transitions from being within to exceeding the rooting depth for 364 potential GDEs. This amounts to 78 percent of likely GDEs identified under the spring 90th percentile condition becoming dewatered under groundwater conditions as low as spring 2015. Of the potential GDEs identified as likely GDEs under spring 90th percentile conditions, 400 became dewatered under fall 2021 conditions. This amounts to 86 percent of likely GDEs identified under the spring 90th percentile condition becoming dewatered under the spring 2021 conditions. A similar pattern of dewatering was found for the fall conditions for each DTG condition.

Of the 464 GDEs identified as Likely GDEs during spring under the 90th percentile conditions, only 38 (8 percent of Likely GDEs based on spring conditions) remained connected to groundwater during the fall 90th percentile condition, only 21 remained connected during the fall 2015 condition, and only 17 remained connected during fall 2021 conditions. This finding indicates a notable seasonal pattern in groundwater connectivity in the Vina Subbasin for likely GDEs.

Table 3 summarizes the aerial coverage of GDEs in the Subbasin for the three conditions.

TABLE 3. SUMMARY OF REFINED GDE MAPPING

	GDE Area (acres)		Percent of Subbasin	
Season and Condition	Connected	Disconnected	Connected	Disconnected
Spring 90th percentile DTG	3,442	4,032	1.9%	2.2%
Fall 90th percentile DTG	726	6,748	0.4%	3.6%
Spring 2015 DTG	1,005	6,469	0.5%	3.5%
Fall 2015 DTG	210	7,264	0.1%	3.9%
Spring 2021 DTG	437	7,037	0.2%	3.8%
Fall 2021 DTG	192	7,282	0.1%	3.9%

Notes: Spring 90th percentile condition were used as the basis for determination of likely versus not likely GDEs. Other season and DTG conditions are shown for comparative purposes.

Spatially, under typical spring conditions, represented by the 90th-percentile DTG value, DTG remained within the rooting zone for potential GDEs in the northwestern portion of the Subbasin along the Sacramento River. This area of elevated groundwater levels is bounded by the Sacramento River to the west and extends eastward to approximately the Southern Pacific Railroad and southward to around Bidwell Sacramento River State Park. Additional likely GDEs occur in the western portion of the Subbasin along many of the surface waters that are tributary to the Sacramento including along Dircus Slough, Pine Creek, Rock Creek, Mud Creek, Big Chico Creek, Little Chico Creek, Angel Slough, and Butte Creek. East of the railroad, and across much of the southern portion of the Subbasin, DTG is typically deeper than the rooting depth of potential GDEs (**Figures 1 and 2**). The region of elevated groundwater and likely GDEs is spatially consistent with the combined extent of the Sacramento River's 100-yr meanderbelt, historic meanderbelt, and adjacent undifferentiated stream alluvium as mapped by Helley and Harwood (1985). Fewer likely GDEs occur to the east in areas where surface geology mapped by Helley and Harwood (1985) as comprised of geologic controls of the Modesto, Red Bluff, and Riverbank formations or other basin deposits. The spatial pattern of likely GDEs is also consistent with findings from the 2022 Vina GSP indicating that:

- A continuous saturated zone (i.e., the floodplain sediments) exists within the floodplain of the Sacramento River connecting the shallowest aquifer to the river and the Sacramento River is generally a gaining river throughout most, if not all of its length throughout the Vina Subbasin.

- In the upland areas outside of the Sacramento River floodplain many of the Subbasin's creeks flow seasonally and often dry up in late summer or are dry for an entire year during dry conditions. The distance between the streambed and groundwater level of uplands streams upstream of the Sacramento River floodplain typically exceeds 20 feet and these upland streams are predominantly losing reaches that provide recharge to the aquifer.

Under fall 90th-percentile conditions the overall pattern and extent of DTG within the rooting zone of potential GDEs is similar to spring, but the area where DTG remains within the rooting zone contracts westward becoming largely constrained to areas immediately adjacent to the Sacramento River, Pine Creek and Mud Creek. Along much of the Sacramento River, DTG for potential GDEs that were within the rooting zone in spring deepens beyond the rooting zone by fall (Figures 1 and 2). Results for both spring and fall 2015 and 2021 were similar to the fall 90th-percentile condition (**Figures 3, 4, 5, and 6**).

From a plant community perspective, among potential GDEs identified as "not likely GDEs" under the spring 90th percentile condition, 77 percent were dominated by just five plant species: valley oak (25 percent), Himalayan blackberry (16 percent), willow sp. (15 percent), cottonwood (14 percent), and sycamore (6 percent). However, it is relevant to consider the relative abundance of different species in the basin when summarizing findings in this manner (i.e., vegetation of those GDEs identified as not likely GDEs). For instance, if willow *sp*. account for a large percentage of potential GDEs it might be expected that they also account for a large percentage of potential GDEs identified as not likely GDEs. Adjusting for the relative abundance of different dominant species in the basin,[16] the analysis revealed that 88 percent of potential GDEs classified as not likely GDEs were dominated by seven genera with forage ratios of 1.0 (Alder, Tule, knotweed, coyote brush, wildrye, Sambucus, and Tamarix), indicating these vegetation types appear in the not likely GDE category at rates consistent with random chance. In contrast, traditionally strong riparian and GDE-associated species, including willows, cottonwoods, valley oaks, and sycamores, all showed forage ratios below 1.0, meaning they were underrepresented among sites classified as not likely GDEs relative to their overall abundance in the Subbasin. This suggests that the screening methodology is working conservatively and that classifications of "not likely GDE" are

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[16] For each dominant vegetation type, the percentage of potential GDEs with that vegetation type identified as not likely GDEs was divided by the percentage of all potential GDEs with that vegetation type. This index is referred to as a "forage ratio" whereby values greater than one indicates a higher likelihood of being classified as not likely GDEs relative to simple random chance occurrence, whereas values ≤ 1 suggest the opposite.

driven primarily by factors other than vegetation type, such as proximity to irrigation, land use changes, or access to alternative water sources.

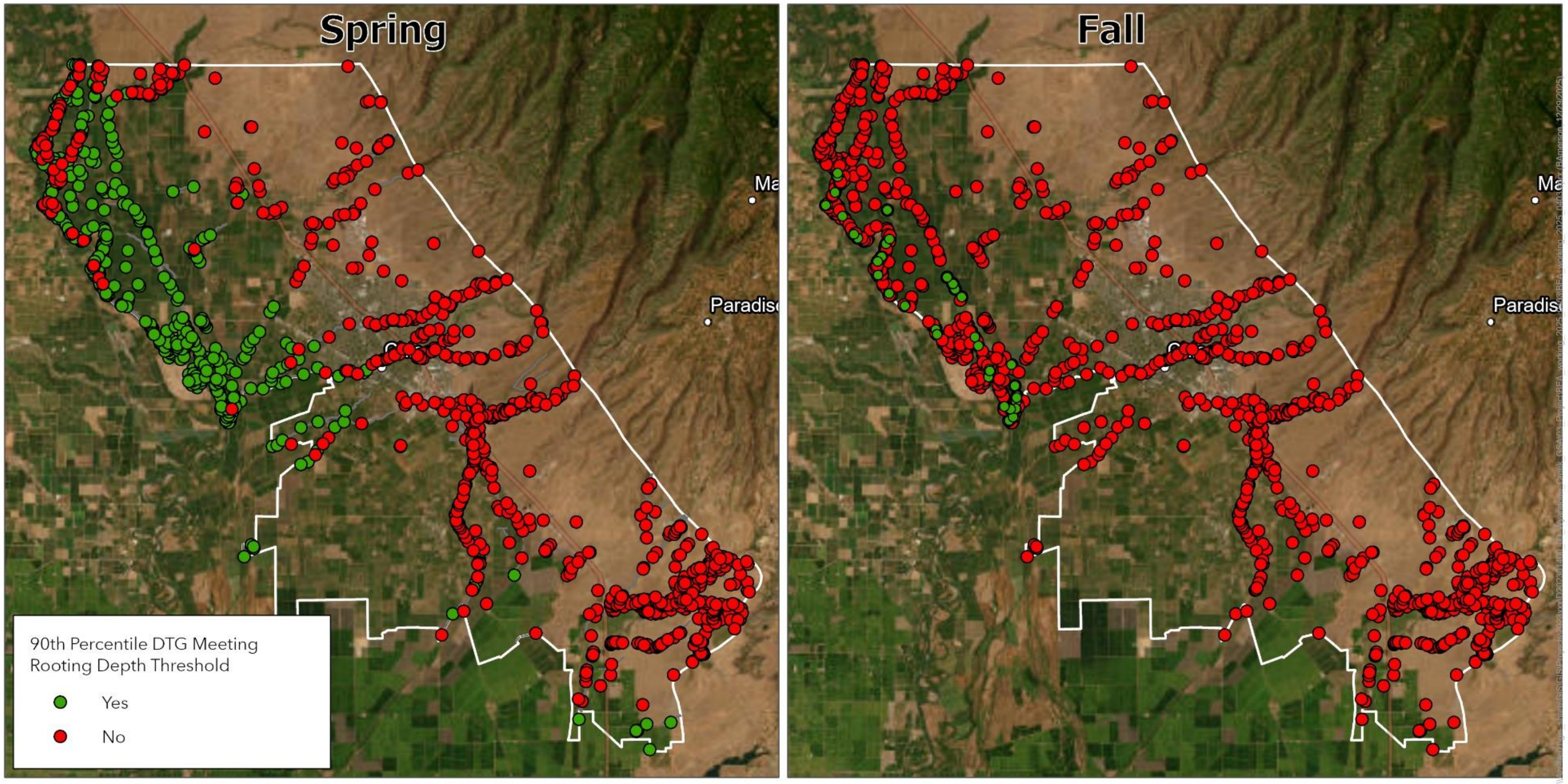

Figure 1
Potential groundwater dependent ecosystems meeting species rooting depth thresholds for typical (90th percentile) spring and fall groundwater elevations in the Vina subbasin.

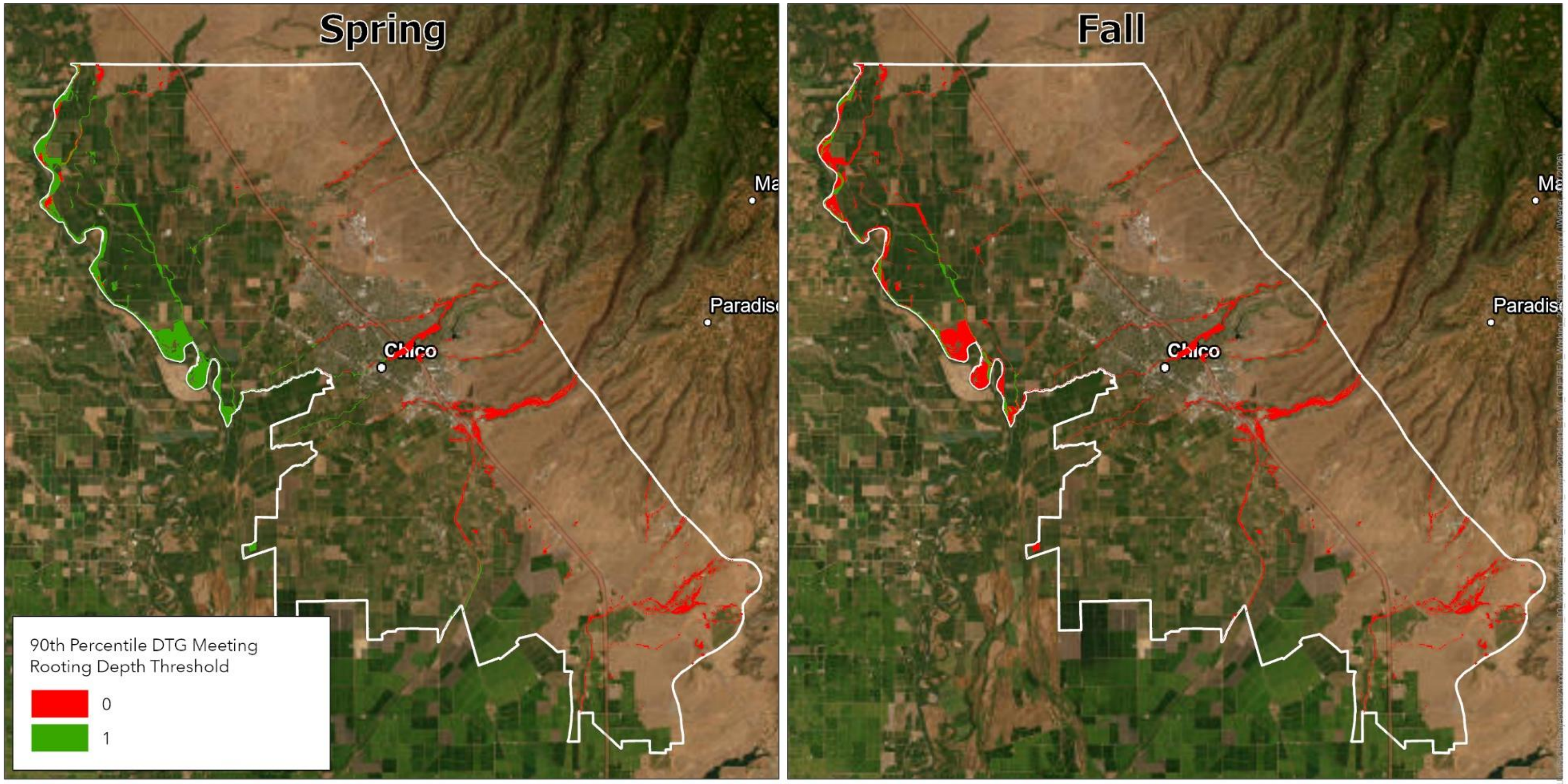

Figure 2
Polygons depicting potential groundwater dependent ecosystems meeting species rooting depth thresholds for typical (90th percentile) spring and fall groundwater elevations in the Vina subbasin.

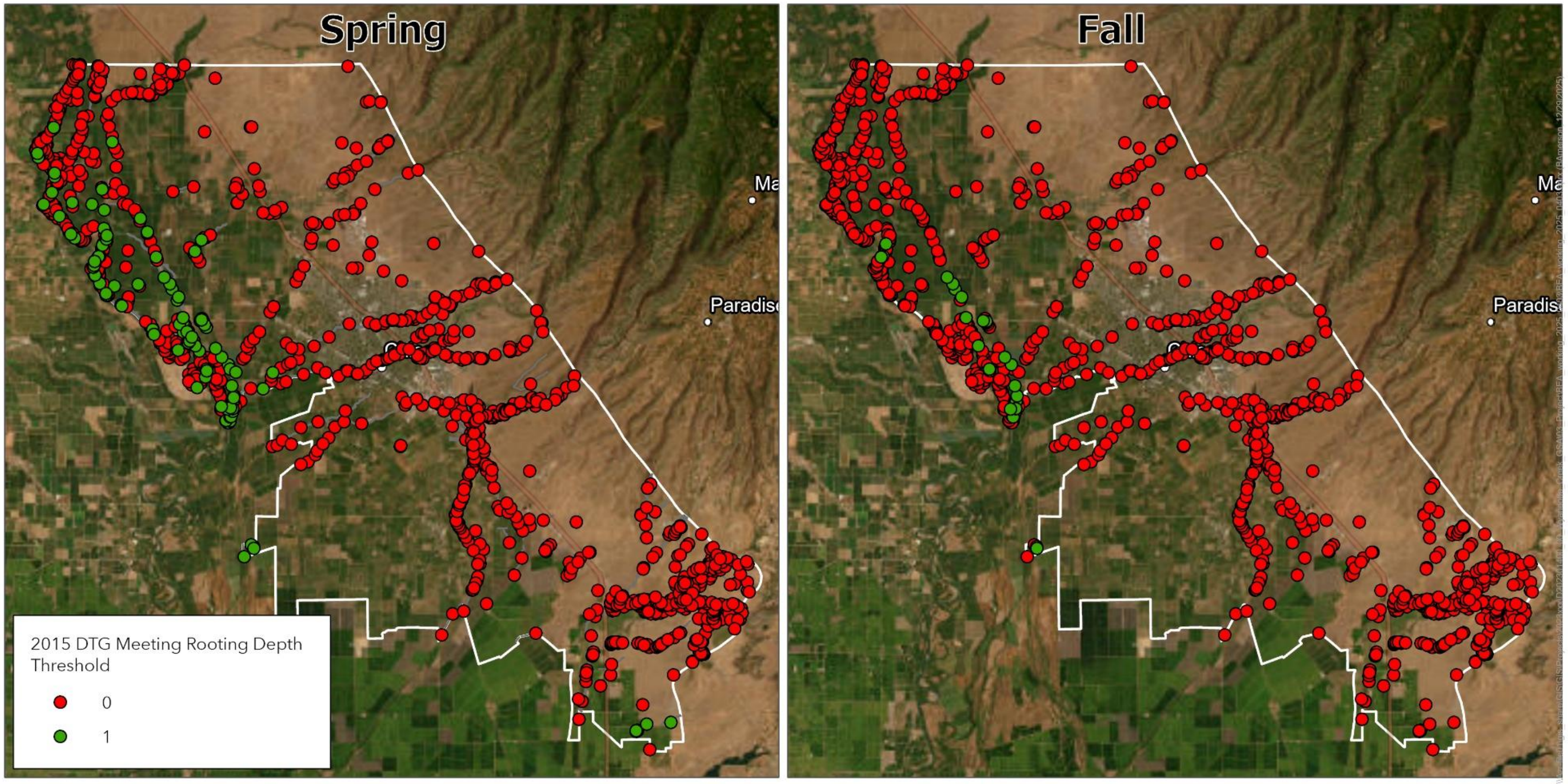

Figure 3
Potential groundwater dependent ecosystems meeting species rooting depth thresholds for spring and fall 2015 groundwater elevations in the Vina Subbasin.

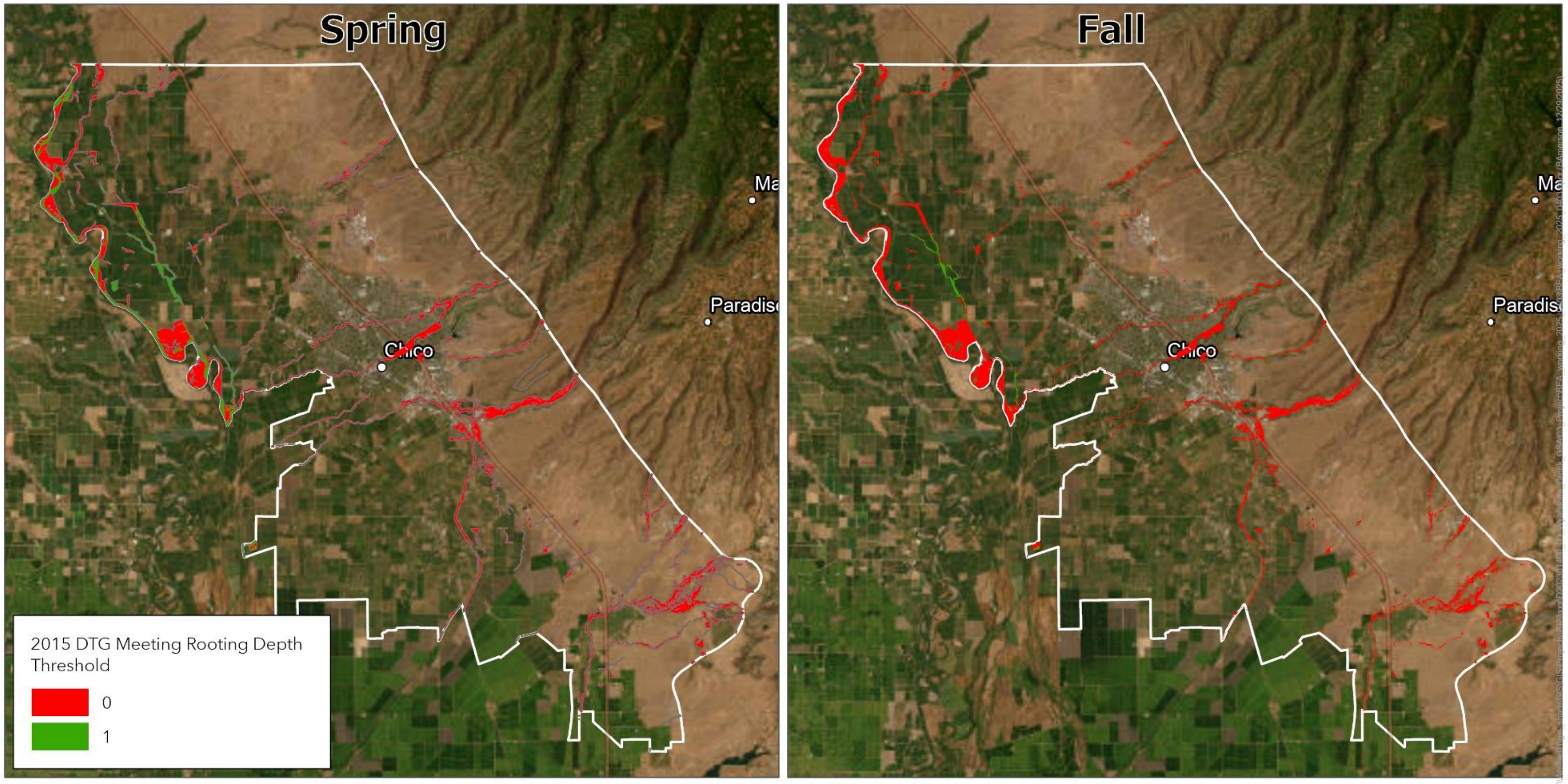

Figure 4
Polygons depicting potential groundwater dependent ecosystems meeting species rooting depth thresholds for spring and fall 2015 groundwater elevations in the Vina Subbasin.

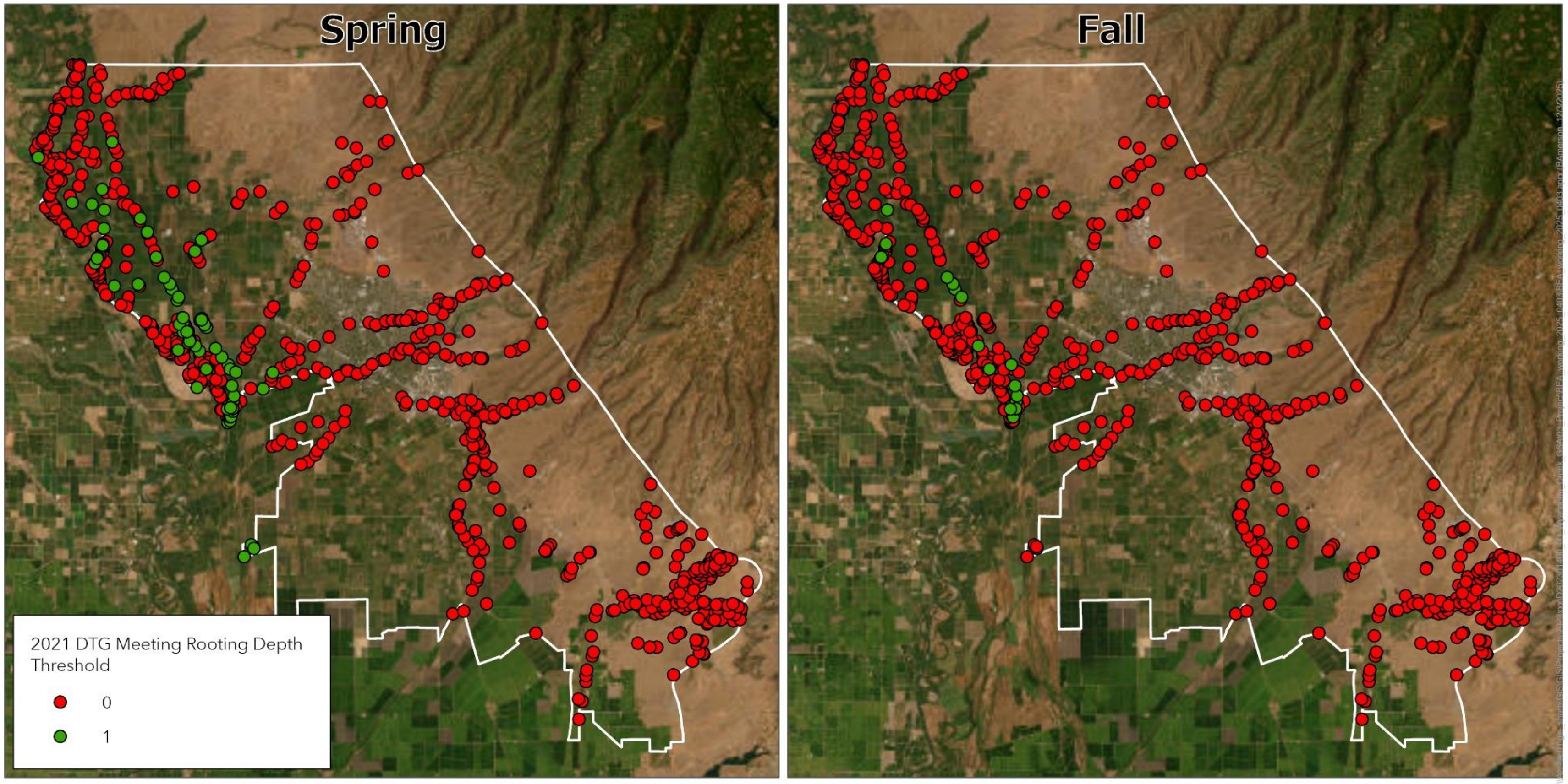

Figure 5

Potential groundwater dependent ecosystems meeting species rooting depth thresholds for spring and fall 2021 groundwater elevations in the Vina Subbasin.

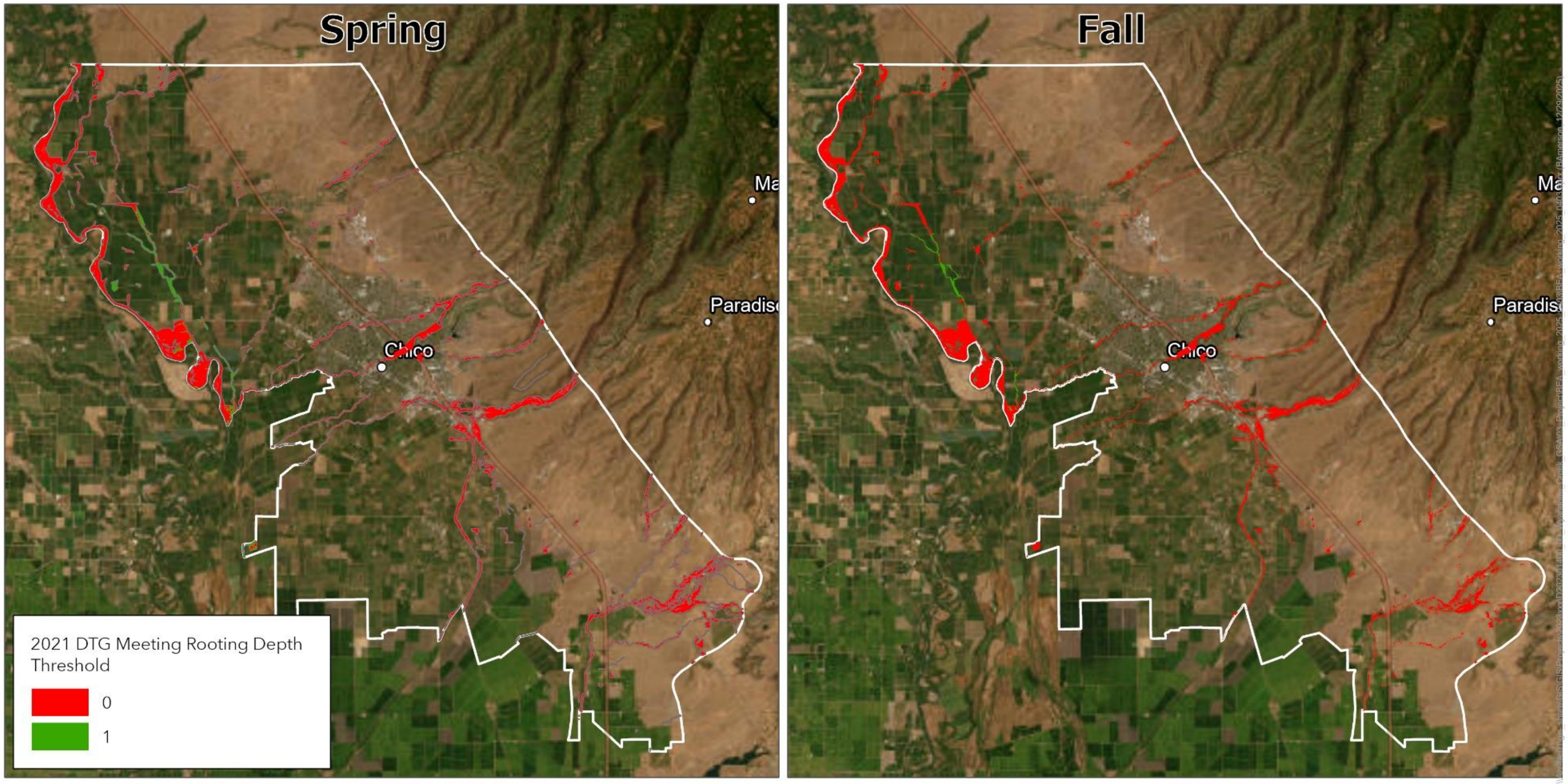

Figure 6
Polygons depicting potential groundwater dependent ecosystems meeting species rooting depth thresholds for spring and fall 2021 groundwater elevations in the Vina Subbasin.

GDEs and Surficial Geology

Depths to restrictive soil layers, mapping of areas likely to support vernal pool, and the refined GDE mapping results are depicted in **Figure 7**. Soils are generally deep (e.g., greater than 11 ft) in the western and central portions of the basin, along the Sacramento River and its floodplain, and along the basin's other creeks. Restrictive layers at depths between 3 and 7 feet are present in the southeastern and northern portion of the basin. The shallowest restrictive layers (e.g., less than 3 ft) occur along the eastern portion of basin.

Mapping of landscapes likely to support vernal pools was strongly co-located with soils having relatively shallow restrictive layers, nearly always occurring where restrictive layers were within 6 ft of the ground surface. Of the potential GDEs in the basin, 78 (6 percent) had their centroid in an area mapped with restrictive layers within 6 ft of the ground surface. Of these GDE 454 were identified by the refined mapping as not likely a GDE and 10 were identified as likely GDEs. Thus, approximately 2 percent of the 646 likely GDEs occurred in locations with relatively shallow restrictive soil layers. A total of 66 potential GDEs coincided with areas mapped as supporting vernal pools. Of these, based on the refined mapping 64 were identified as not likely GDEs and only 2 were identified as likely GDEs.

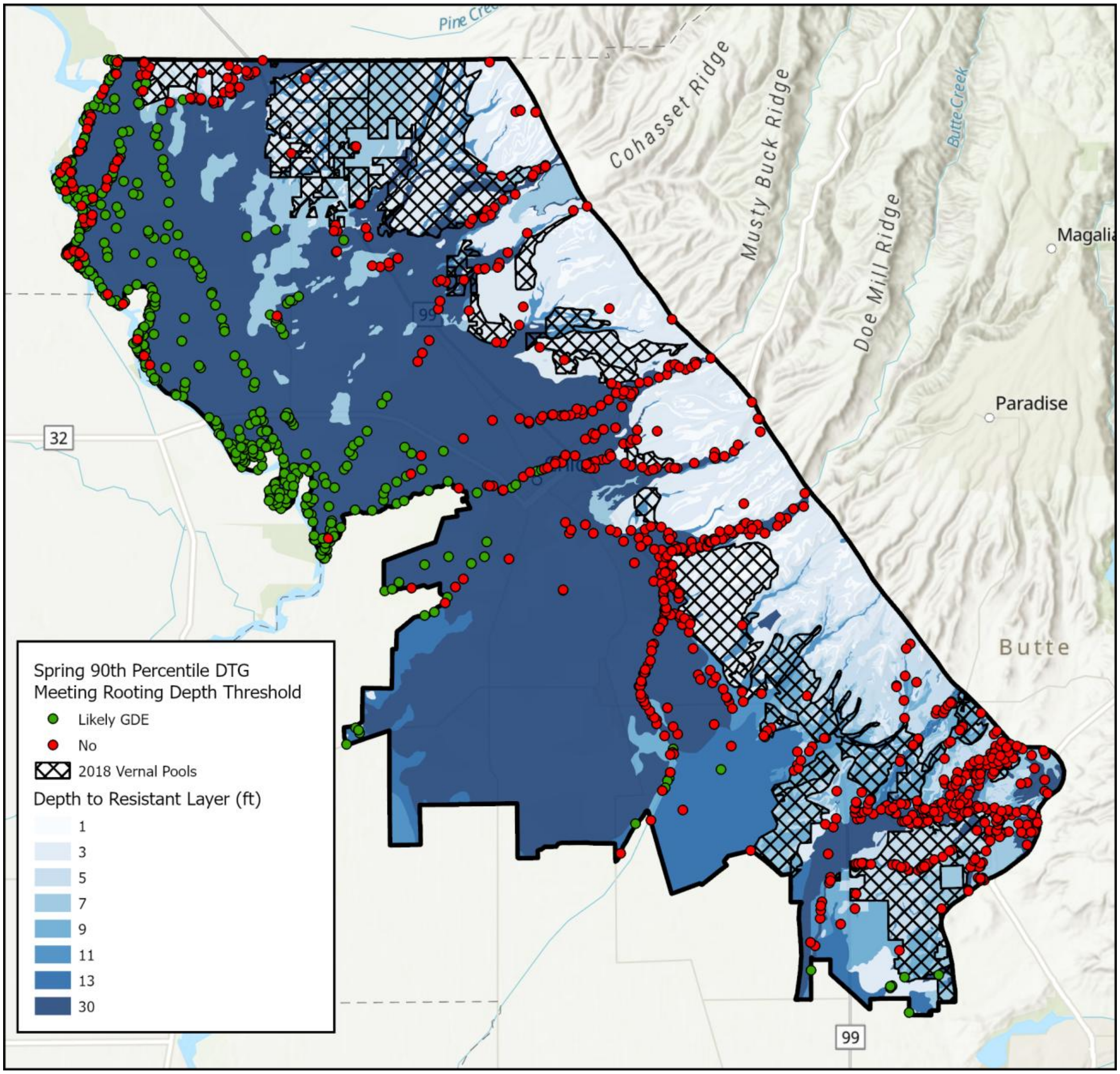

Figure 7 Depth to resistant soils layers, vernal pools, and centroids of potential groundwater dependent ecosystems meeting species rooting depth thresholds for typical (90th percentile) spring groundwater elevations in the Vina Subbasin.

Refined GDE Mapping and 2022 Vina GSP Mapping

We compared potential GDEs identified as "likely" and "not likely" in this analysis against those from the 2022 Vina GSP using the spring 90th percentile results (**Table 4**). Less than half (44 percent) were classified the same way by both methods. Only 530 of 1,228 potential GDEs showed agreement (diagonal cells in Table 4). Compared to the 2022 Vina GSP mapping, this analysis classified an additional 58 potential GDEs as likely GDEs (5 percent of all potential GDEs) but reclassified 640 potential GDEs from likely to not likely (52 percent of all potential GDEs).

The substantial difference in GDE likelihood determinations stems from methodological differences. The 2022 Vina GSP incorporated hydrologic conditions from prior years but did not use a repeatable, quantitative metric to screen potential GDEs. In contrast, as recommended by guidance from Rhode et al. (2018) this analysis used depth-to-groundwater (DTG) and rooting depth criteria as the primary determining factors. Such an approach was not able to be conducted during the 2022 Vina GSP development due to data limitations. The DTG time series method inherently captures historical groundwater hydrology through annualized DTG calculations based on observed groundwater levels and applies repeatable rooting depth thresholds derived from best available science.

TABLE 4 COMPARISON OF LIKELY AND NOT LIKELY GDES IDENTIFIED IN THIS ANALYSIS AND 2022 VINA GSP

Counts		2022 Vina GSP GDE Mapping	
		Likely	**Not Likely**
Refined GDE Mapping	**Likely**	406	58
	Not Likely	640	124

Regional Potential GDE Health Results

The NDVI values at all potential GDEs identified as likely GDEs and not likely GDEs based on spring 90th percentile conditions for the period of record from 1985 through 2024 are depicted as a time series of boxplots in **Figure 8**. NDVI values at all potential GDEs identified as connected and disconnected based on fall 90th percentile conditions for the same period are depicted in **Figure 9**. Mean annual precipitation at all potential GDEs for the same period is depicted in **Figure 10**. Several patterns emerge from these data:

- Median NDVI at likely GDEs is greater than median NDVI at not likely GDEs for all years in the record suggesting groundwater related factors play a role in higher NDVI values at likely GDEs.

- While there is year-to-year variability in the range and central tendency (e.g., median) of NDVI values for both GDEs identified as likely GDEs and not likely GDEs (e.g., 17 years where median NDVI decreases year-to-year and 22 years where year-to-year median NDVI increases for both classifications), the overall trend over the period of record is that of increasing NDVI values. Year-to-year changes in median NDVI at GDEs identified as likely GDEs and not likely GDEs are strongly correlated (i.e., correlation coefficient [r] value of 0.95) suggesting non-groundwater related factors play a strong role in regional NDVI trends at all potential GDEs.

- While NDVI values generally decreased during 2021 and 2022, values rebounded in 2023 and 2024 to pre-drought levels.

- The strength of increasing NDVI trends over the period of record is greater at GDEs identified as likely GDEs (i.e., NDVI values tend to increase more over the period of record at GDEs identified as likely GDEs compared to those identified as not likely GDEs).

- Over the period of record the majority of NDVI values at GDEs identified as likely GDEs range between 0.4 and 0.75, whereas values at GDEs identified as not likely GDEs range between 0.3 and 0.6. Both ranges are consistent with what would be considered as moderate NDVI values.[17]

- Year-to-year annual precipitation is volatile and while there is a slight positive correlation between median annual precipitation recorded across all potential GDEs and median annual NDVI across all potential GDEs ($r = 0.28$; higher precipitation results in slightly higher NDVI values),[18] the relationship is weak and generally not conclusive of the relationship between these metrics.

Beyond precipitation, the relationship between shallow groundwater levels and NDVI at potential GDEs was also explored. There was a slight negative correlation between median annual spring groundwater elevations across all potential GDEs and median annual NDVI across all potential GDEs ($r = -0.17$; deeper spring groundwater elevations result in slightly lower NDVI values),[19] however the relationship was weak and there was substantial variability between these metrics (**Figure 11**). [20] The strength of this relationship generally did not change when sub-setting potential GDEs to those identified as likely GDEs or identified as not likely GDEs as determined from the refined mapping.[21]

At the scale of individual GDEs the relationship between temporal trends in NDVI and spring groundwater elevations were also variable. For instance, across all potential GDEs, 45 percent had a negative relationship between NDVI and shallow DTG (i.e., as DTG increased [deeper groundwater levels] NDVI values decreased), 48 percent had a positive relationship (i.e., as DTG increased [deeper groundwater levels] NDVI values increased), and the remaining 7 percent had no relationship (i.e., slope equal to zero).[22] Sub-setting potential GDEs to those identified as likely GDEs and not likely GDEs had a slight effect on the breakdown of these trends, whereby likely GDEs shifted toward having more positive relationships and not likely GDEs shifted toward having more negative relationships. Spatially, there was no regional pattern in terms of potential GDE's relationships between changes in shallow groundwater elevations and GDE NDVI values (**Figure 12**). Rather, there appear to be patches of GDEs that exhibited similar relationships (e.g., positive trend vs negative trend) but these were intergraded across the Subbasin. Takeaways from these findings are summarized below and recommendations for how NDVI may be used to monitor and assess changes to GDEs are described in the *Recommendations* section.

- At the Subbasin scale the relationship between shallow groundwater elevations and GDE NDVI values is not straightforward or linear likely due to other factors that influence GDE ecological health, autoregressive or antecedent (e.g., previous conditions) factors that result in delayed

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[17] https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing-phenology

[18] For each year, median precipitation and median NDVI across all potential GDEs were calculated and compared.

[19] For each year, median spring groundwater elevation from LWA shallow groundwater elevation data and median NDVI across all potential GDEs were calculated and compared.

[20] Note, there was a slightly negative correlations between median NDVI at GDEs and median spring groundwater elevations (e.g., shallower spring groundwater elevations result in slightly higher NDVI values).

[21] The direction of the relationship (i.e., positive) and magnitude (i.e., r value) did not change when comparing median annual spring groundwater elevations across and median annual NDVI at GDEs identified just as likely and just as not likely, respectively.

[22] Relationships are based on least-square linear regression slope between NDVI values and LWA shallow groundwater elevations between 2000 and 2024.

responses, resiliency (e.g., lack of response), or masked responses due to mortality, recovery, or succession.

- At the individual GDE level relationships between changes in shallow groundwater elevations and GDE NDVI values were also not straightforward, likely owing to several of the same factors as described at the regional scale.
- While rates of change in NDVI values were relatively small, typically within ±0.01 per ft of change in groundwater elevation, potential GDEs experienced a range of changes in NDVI values from 2000 to 2024 with the largest increase being 0.79 and the largest decrease being -0.35. Interpretation of changes in NDVI remains a challenge with no broadly accepted threshold for changes that indicate significant shifts in vegetation health, density, or land cover. Available studies suggest that increases in NDVI on the order of 0.1 correspond to reduced mortality and increased greenspace but depend on initial NDVI values (e.g., Martinez and Labib, 2023). Between 2000 and 2024 approximately 33% of potential GDEs (404 of 1228) experienced an increase in NDVI greater than 0.1 and approximately 5% of potential GDEs (67 of 999) experienced a decrease in NDVI greater than 0.1 (Figure 12). Sub-setting potential GDEs to those identified as likely GDEs and not likely GDEs had a slight effect on the breakdown of these trends, whereby likely GDEs shifted toward having more NDVI increases and not likely GDEs shifted toward having more NDVI decreases.
- While NDVI remains a promising tool for monitoring and assessing GDE ecological health in the Subbasin, uncertainties and data gaps remain regarding the relationship between shallow groundwater levels and GDE NDVI and how other biotic/abiotic factors and processes influence changes in NDVI.

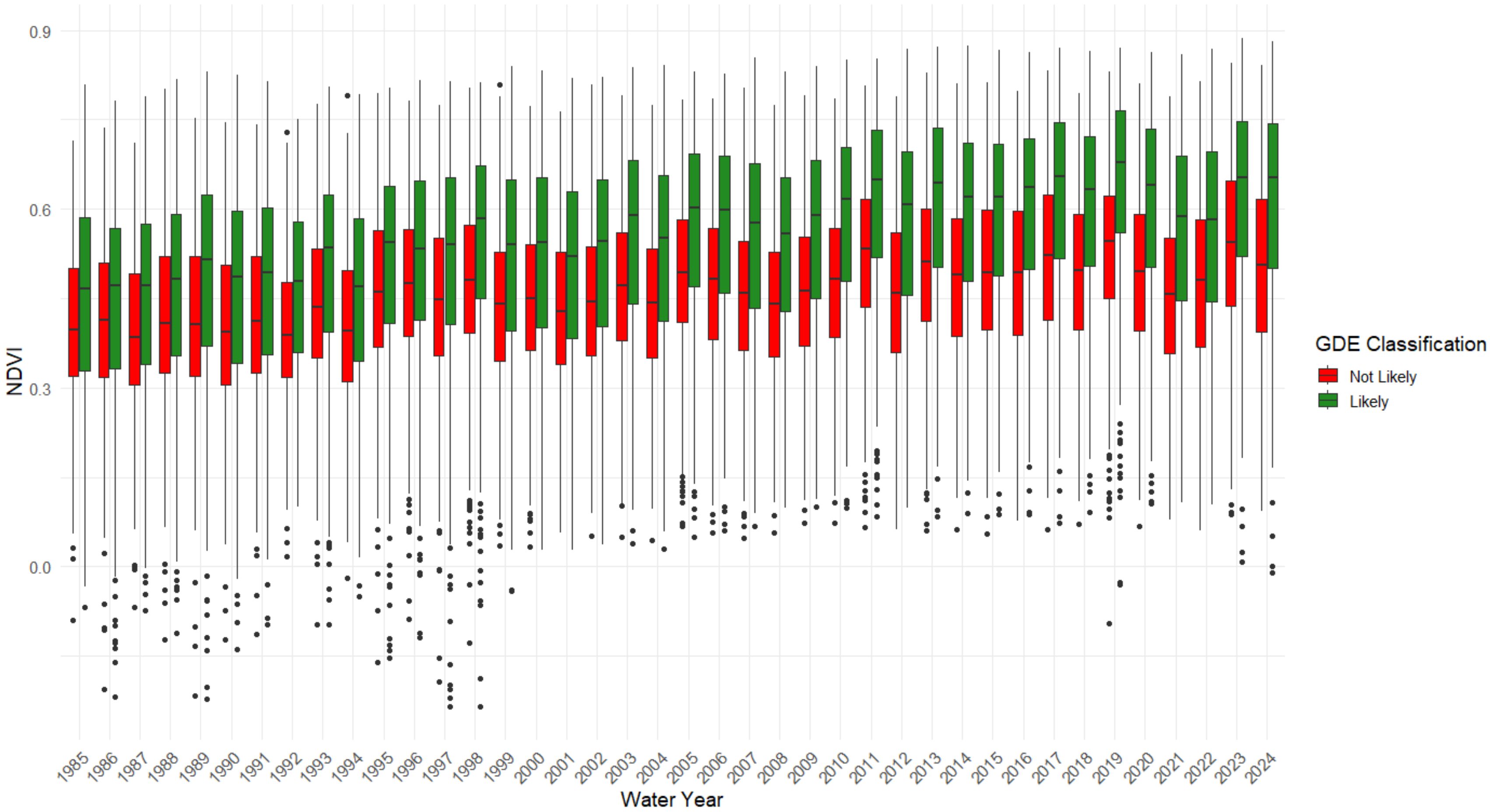


Figure 8 Box plots of NDVI at GDEs identified as likely GDEs and not likely GDEs based on spring 90th percentile conditions from 1985 to 2024.

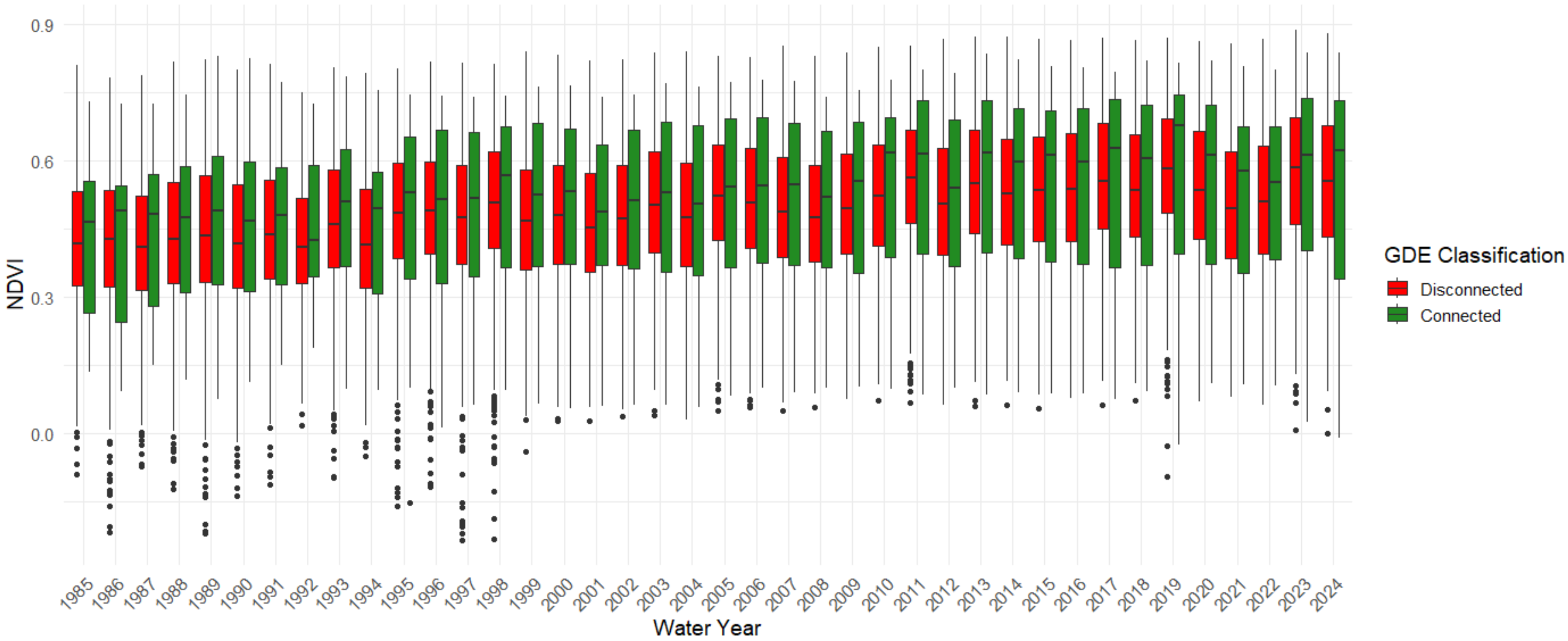


Figure 9 Box plots of NDVI at connected and disconnected GDEs based on fall 90th percentile conditions from 1985 to 2024.

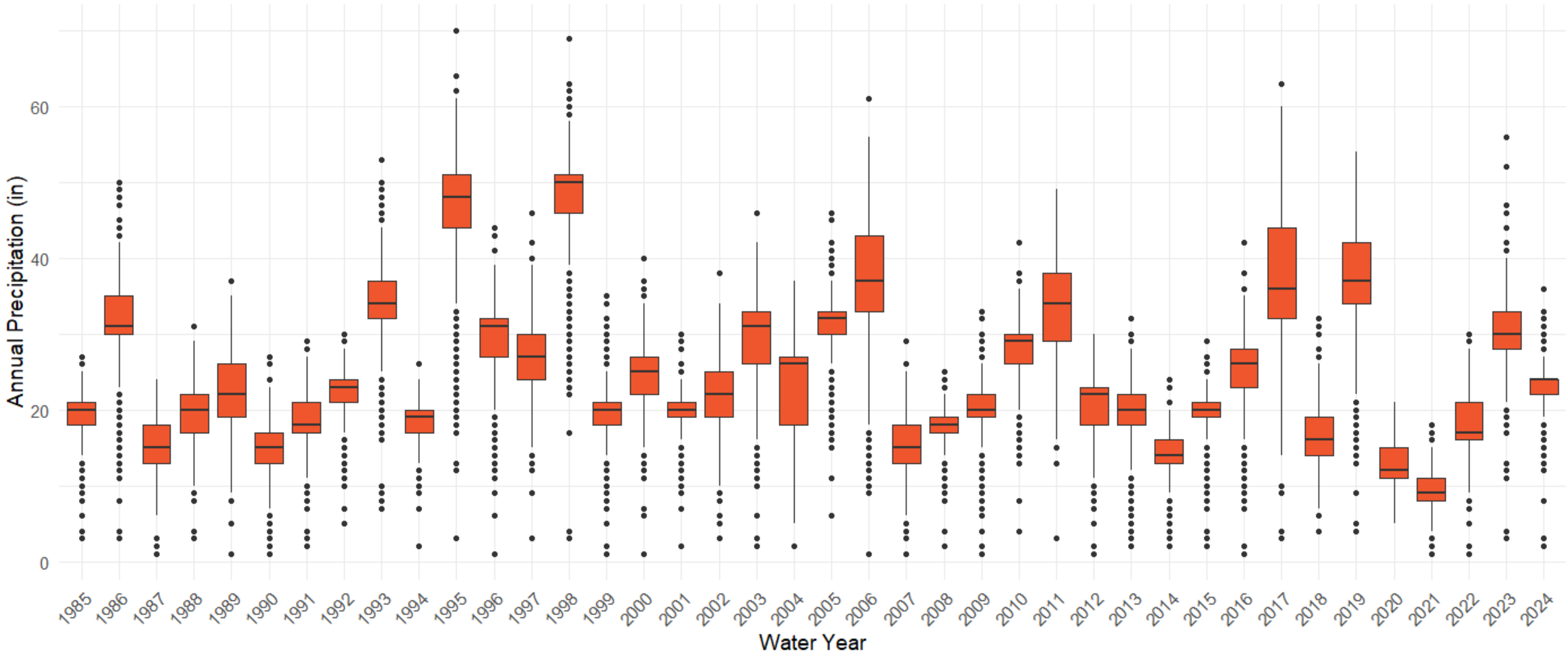
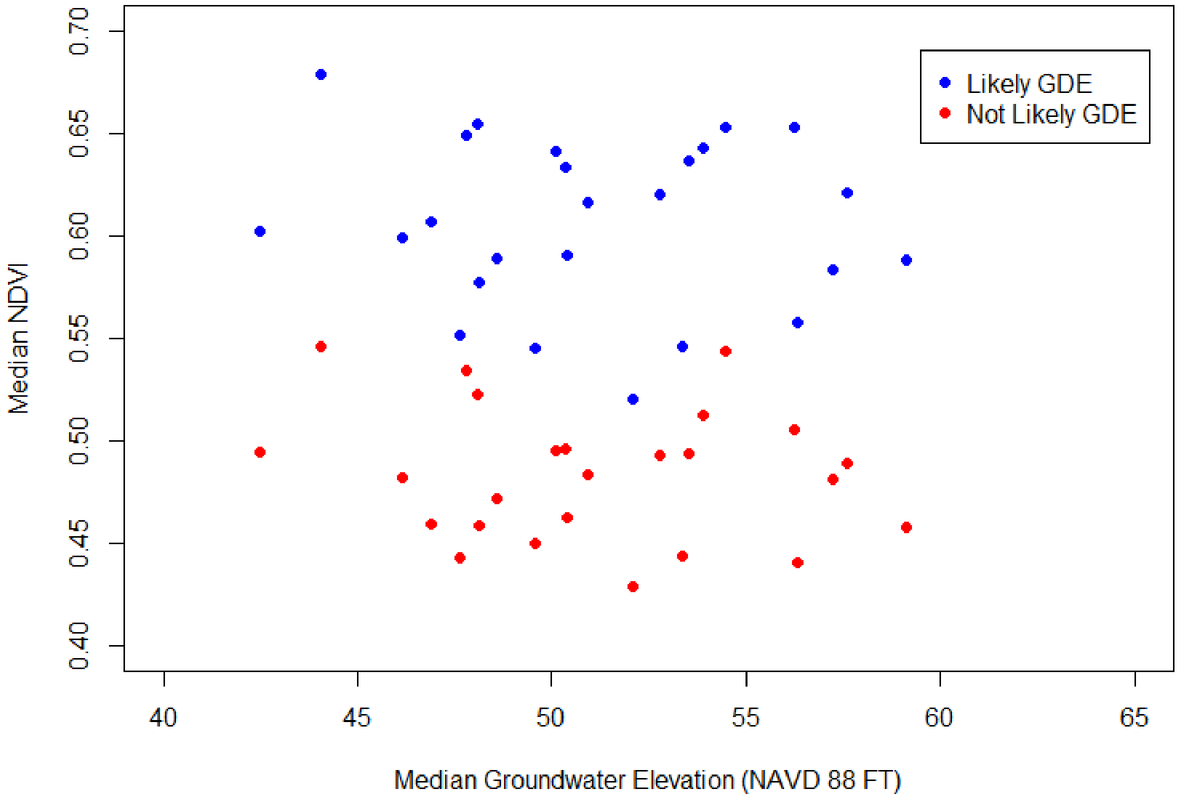
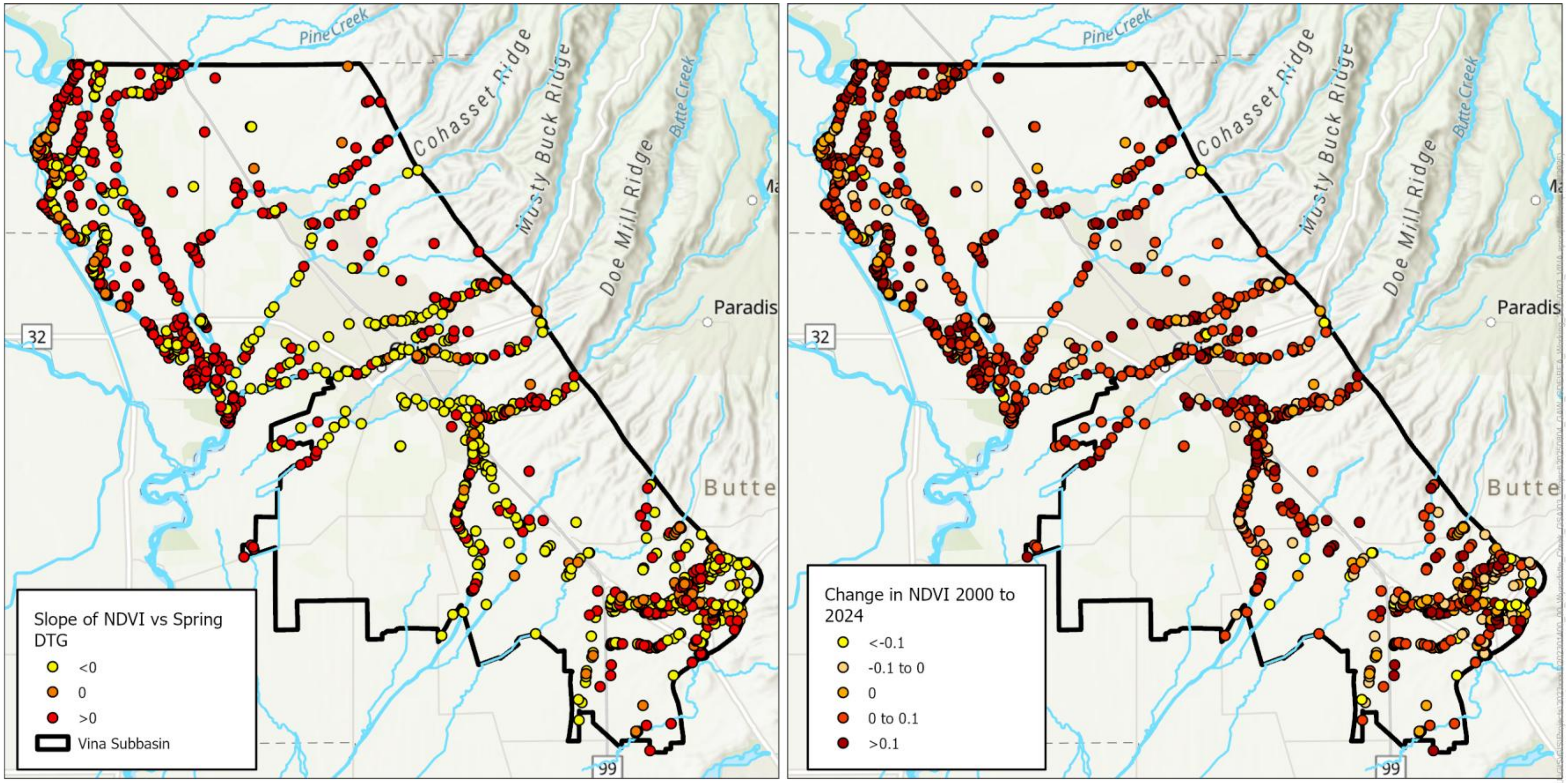


Figure 10 Box plots of annual precipitation at all potential GDEs from 1985 to 2024.



Note: Each point represents one year of data.

Figure 11 Median NDVI at all potential GDEs versus median groundwater elevation at all GDEs from 2000 to 2024.



Notes: Negative slopes indicate NDVI decreased as DTG increased and positive slope indicate NDVI increased as DTG increased.

Figure 12 Left Panel: Linear regression slope of NDVI vs spring DTG from shallow groundwater rasters at all potential GDEs from 2000 to 2024. Right Panel: Change in NDVI from 2000 to 2024 at all potential GDEs.

Discussion

GDEs Recommended to be Considered Under SGMA

The GDE mapping refinement analysis for the spring 90th percentile groundwater elevation conditions identified a total of 464 of the 1,228 potential GDEs from the NCCAG dataset as being identified as likely GDEs. These likely GDEs were generally located along the Sacramento River and its floodplain and along lowland valley portions of Dircus Slough, Pine Creek, Rock Creek, Mud Creek, Big Chico Creek, Little Chico Creek, Angel Slough, and Butte Creek. Moving eastward from the Sacramento River floodplain, a northwest-southeast trending boundary line traverses the central part of the Subbasin where DTG begins to exceed GDE rooting depths, and most potential GDEs east of this boundary had DTG deeper than rooting depth thresholds and were identified as not likely GDEs (Figure 1 and Figure 2). This boundary corresponds to increasing landscape elevation toward the eastern foothills, where the regional groundwater table begins to separate from the land surface, consistent with the geologic setting. Overall, the potential GDEs identified as likely GDEs under the spring 90th percentile groundwater elevation conditions are likely to function as GDEs, whereas those east of the northwest-southeast boundary would not, under contemporary conditions (i.e., 2000-2025), be considered GDEs because DTG is consistently too great. Therefore, the set of GDEs mapped as likely GDEs based on the spring 90th percentile groundwater elevation conditions are recommended as the set of GDEs to be considered by the GSA when assessing impacts to GDEs.

Likely GDEs located along the northwest-southeast boundary provide a good opportunity for monitoring potential impacts to GDEs as they appear most susceptible to historic changes in groundwater conditions. It is recommended that these GDEs be prioritized for monitoring network development, with field teams assessing the ecological health of a representative subset of these GDEs to support monitoring of GSA management impacts on GDE beneficial users. It is also recommended that monitoring efforts include a set of representative GDEs found to be less susceptible to historic changes in groundwater conditions to act as a ‘control’ group for comparison to GDEs that may be more susceptible to changes in groundwater conditions (see *Recommendations* section for additional discussion).

Hydrologic Sensitivity of Recommended GDEs

Subsurface hydrologic conditions at the recommended set of GDEs appear to exhibit high seasonal and drought condition variability. For instance, 78 percent (364 of 464 GDEs) of potential GDEs identified as likely GDEs under the spring 90th percentile conditions were found to transition to being disconnected under spring 2015 conditions, which represent critically dry conditions and the second lowest regional groundwater levels during the 2000-2025 period of record. Geographically the GDEs that went from connected to disconnected were scattered along the Sacramento River, the Sacramento River floodplain, and along other Subbasin surface waters. Under spring 2021 groundwater conditions, the lowest water year on record since 2000, a larger 86 percent (400 of 464 GDEs) of potential GDEs identified as likely GDEs under the 90th percentile conditions were found to transition to being disconnected. The spatial distribution of these GDEs that would become hydraulically disconnected was slightly broader than those under the spring 2015 conditions. If groundwater levels as low as those observed in spring 2021 were to persist and degrade the ecological health of GDEs, that outcome would likely be considered a significant and unreasonable impact, that is, an Undesirable Result, on these beneficial users of groundwater (e.g., Kibler et al., 2021).

Variation in seasonal conditions is exemplified by comparing spring and fall conditions. For example, between spring and fall 90th percentile conditions, 92 percent (426 of 464 GDEs) of potential GDEs identified as likely GDEs under the spring 90th percentile conditions were found to transition to being disconnected under fall conditions (Figure 1 and Figure 2).

GDEs, SMCs, and Monitoring Networks

As discussed in the *Background* section, SGMA requires Groundwater Sustainability Agencies to identify GDEs in their GSPs and to consider how SMCs for each sustainability indicator, including minimum thresholds (MTs) and measurable objectives (MOs), may affect the interests of beneficial uses and users of groundwater such as GDEs. To demonstrate progress toward achieving overall sustainability goals, monitor changes in conditions relative to MOs and MTs, and demonstrate progress toward achieving SMCs GSPs must develop appropriate monitoring networks for each sustainability indicator. SGMA also requires agencies to monitor impacts to beneficial users of groundwater.

Initial SMC's for SGMA's six sustainability indicators for the Subbasin were defined in the 2022 Vina GSP, which included interim SMCs for the Interconnected Surface Water (ISW) sustainability indicator. The 2020 Vina GSP also described the monitoring network proposed for each sustainability indicator including representative monitoring sites, data to be collected including the frequency of monitoring at each site, identification of data gaps, and plans to fill data gaps. The amended GSP and associated Periodic Evaluation currently underway will include updates to the SMCs and monitoring network from the 2022 Vina GSP including but not limited to:

- Updated SMCs that include description of new data collected since the 2022 Vina GSP, description of data gaps that remain, and description of active and future plans for ongoing data collection efforts and Project and Management Actions that will address data gaps and inform future updates.
    - Specifically related to GDEs, updates include description of how SMCs impact environmental beneficial users of groundwater such as GDEs.
    - Interim SMCs for ISW are expected to be updated with new, more targeted preliminary SMCs with the understanding that additional data will be collected for five more years to fill data gaps and finalized SMCs would be developed for the 2032 periodic evaluation.
- Updated monitoring networks that include description of ongoing and proposed monitoring network expansion.
    - Specifically related to GDEs, since the 2022 Vina GSP new stream gages, new wells near stream channels, and new wells for the shallow aquifer have been installed growing the ISW network and filling data gaps.

When monitoring impacts to beneficial users of groundwater such as GDEs, it is crucial to establish clear linkages between the data collected by monitoring networks and the resources being evaluated. For instance, representative monitoring site (RMS) wells are drilled and screened at different depths with each well designed to measure groundwater elevations at a selected zone in the underlying aquifer. RMS wells and SMCs for the Groundwater Level sustainability indicator are often drilled and screened in the deeper aquifer system and thus may not be representative of conditions in the shallow aquifer, which are more relevant too and representative of water available to support GDEs. This can result in observed DTG at RMS wells that are not representative of the shallow aquifer system. Such conflation can lead to mischaracterization of impacts to GDEs if MTs and MOs at these locations were used directly to assess impacts. Such issues, highlight the need to use appropriate monitoring network data (e.g., wells screened in the shallow aquifer) and the need to scrutinize and develop clear linkages between SMCs and beneficial users when assessing impacts.

Recommendations

GDE Management and Sustainable Management Criteria Considerations

GDEs within the Subbasin are assumed to depend on shallow groundwater to support mature vegetation and seedling establishment (Rood et al., 2003). Shallow groundwater level decline may result in reduced plant growth and, in more severe cases, lead to plant mortality (Shafroth et al., 2000; Kibler et al., 2023). However, seasonal fluctuations in groundwater levels are normal and once established, riparian species can survive periodic declines (Stromberg & Patten, 1992). Under SGMA, there is no sustainability indicator specific to GDEs. Rather management of GDEs is intertwined with SGMA's other sustainability indicators whereby it is required to assess how SMCs (e.g., MO and MT) may affect the interests of beneficial uses and users of groundwater. It is also required to monitor impacts to beneficial users of groundwater and define Undesirable Results[23] and assess potential effects of Undesirable Results on beneficial uses and users of groundwater. The recommended approach for the Vina Subbasin for monitoring impacts and managing groundwater in consideration of GDEs is to define management criteria that account for the natural variability in depth to groundwater and surface vegetation composition represented by NDVI across the Subbasin to avoid previously un-observed conditions (defined by historical variability in groundwater and GDEs), whereby criteria are measured in terms of groundwater level and NDVI.

Groundwater Level Criteria

With regard to groundwater levels, the first recommendation is to manage shallow groundwater levels such that, based on rooting depths developed in this analysis, the area of GDEs that are connected to shallow groundwater (i.e., shallow groundwater levels are at or above rooting depths) does not persistently fall below the 2021 minima, as this is an indicator of potential impacts to GDEs in excess of natural variability. For instance, conditions during 2021 appear to correspond to a decrease in regional NDVI values compared to adjacent years (Figure 8) potentially indicating declines in GDE health

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[23] Undesirable results occur when significant and unreasonable effects for any of the sustainability indicators are caused by groundwater conditions occurring throughout the basin.

occurred during this period, though as discussed in the *Regional Potential GDE Health Results* section there is uncertainty regarding the direct relationship between shallow groundwater levels and GDE NDVI. More specifically, it remains unknown if plant mortality occurred during this period and if the subsequent rebound in GDE NDVI values observed in 2023 through 2024 is associated with vegetation recovery or due to re-colonization that could include rapid colonization by non-native or invasive species (e.g., Kibler et al., 2023).

In addition to magnitude, the duration of groundwater decline is ecologically important to consider when determining potential impacts to GDEs, as prolonged periods of hydrologic disconnection with root zones increase potential for degrading plant health (Kibler et al., 2023). While 2021 was the lowest water year on record since 2000, the 3-year period of 2021-2023 was generally characterized by depressed groundwater levels. Thus, a possible interim criteria to defining an Undesirable Result that considers likely impact to GDEs is that the area of connected GDE (i.e., based on rooting depths and shallow groundwater levels) falls to levels observed during 2021 and remains there for three consecutive years.[24]

Notably, the proposed criteria is based on findings from this analysis and best available science but is not based on observed decline in plant heath (e.g., Shafroth et al., 2000; Rood et al., 2003; Kibler et al., 2023). Additional analysis of GDE responses to groundwater levels and field-based long-term monitoring of representative GDEs could be used to further support and refine the proposed interim criteria. Alternative monitoring approaches using existing and planned RMS wells and a subset of GDEs in close proximity to those wells that serve as a representative sample of Subbasin GDEs are also possible, but the details of such approaches would need to be refined as part of future Vina GSP amendments or Periodic Evaluations.

GDE ecological health (NDVI) Criteria

With regard to NDVI values, the recommendation for assessing potential impacts to GDEs in excess of natural variability is based on a statistical approach modified from the California Environmental Flow Framework (CEFF) for assessing flow alteration. To assess alteration of GDE ecological health the distribution of historical (water years 2000 to 2025, which generally corresponds to the historical period in the 2022 Vina GSP) NDVI values at likely GDEs would be compared to the distribution of future NDVI values at the same set of GDEs. The following rules would be used to assign an alteration status (**Figure 13**):

- If the future median NDVI value falls below the historical NDVI 25th percentile interval, then GDE ecological health is considered "likely altered" and could cause declines in GDE ecological health.
- If the future median NDVI value falls within 25th-75th percentile interval of historical NDVI values and more than 50% of future values fall within 10th-90th percentile, then GDE ecological health is considered "likely unaltered" and would not constitute an Undesirable Result.

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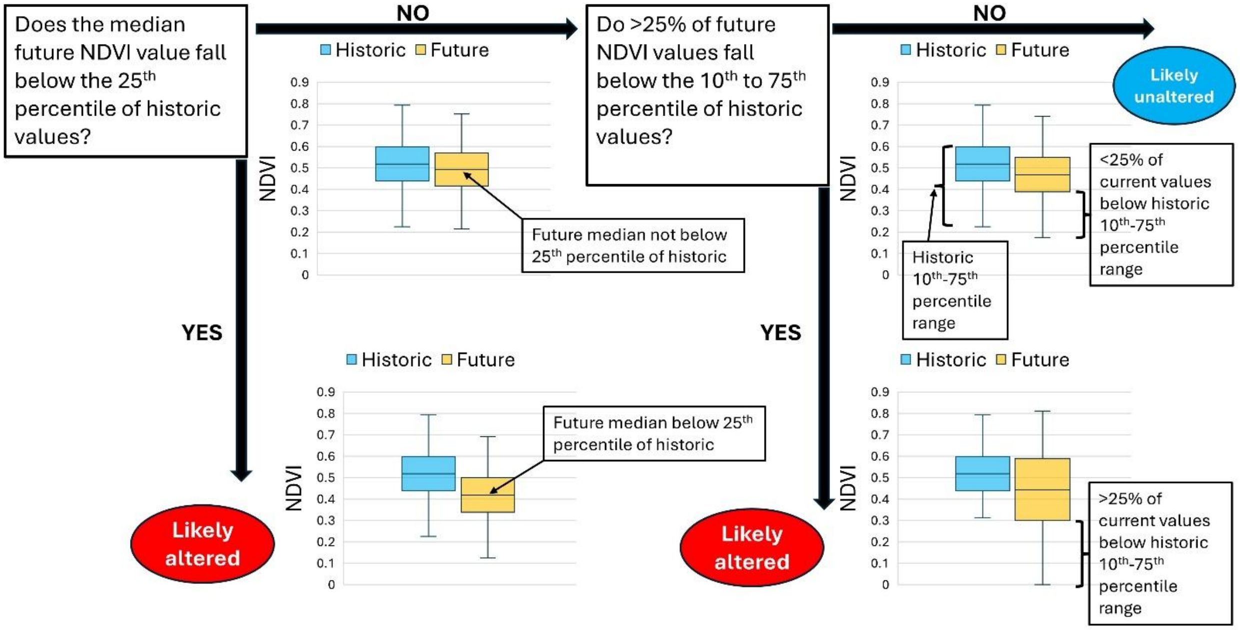
[24] This approach does not necessarily mean shallow groundwater levels are the same as those observed during fall 2021 but that observed levels result in the area of GDEs that are connected to shallow groundwater is at or below what was mapped in 2021 (i.e., 437 acres [Table 3]).

- If the future median NDVI value falls within the historical NDVI 25th-75th percentile interval, but more than 25% of future values fall below the historical NDVI 10th-75th percentile (i.e., there is a downward shift of future NDVI values such that a large percentage of future values fall within the lower range of historic values), then GDE ecological health is considered "likely altered" and could cause declines in GDE ecological health.



Notes: Flowchart starts in top-left corner. First check if future median NDVI value falls below the historical NDVI 25th percentile interval. If no move right, if yes move down. Next check if future median NDVI value falls below 25th-75th percentile interval of historical NDVI values or more than 50% of future values fall within historic 10th-90th percentile. If no move right, if yes move down. Next check if more than 25% of future values fall below the historical NDVI 10th-75th percentile. If no move right, if yes move down.

Historic and future NDVI data are shown as boxplots. 'Whiskers', horizontal lines at top and bottom of boxplots, are the 10th and 90th percentile values, respectively. The shaded boxes are the 25th-75th percentile range. The horizontal line in the shaded boxes is the median value.

Figure 13 Conceptual flowchart model for assigning GDE ecological health (NDVI) Criteria alteration status based on historic and future NDVI values at likely GDEs.

For the situations above that could constitute impacts to GDEs in excess of natural variability it is important to assess the cause(s) for declines in GDE ecological health. Within the context of SGMA, declines in GDE ecological health would only be considered an impact if declines were correlated with declines in groundwater levels due to groundwater management. Such correlations would need to be determined in the future based on monitoring of groundwater levels that would already be occurring in accordance with SGMA requirements and assessing compliance with other sustainability indicators. This could be achieved through statistical analysis comparing annual median NDVI values at all likely GDEs with area-weighted groundwater levels similar to the methods used in the TNC GDE Pulse tool.[25]

When determining the future distribution of NDVI values to use for comparison it is recommended that a five-year moving window is used as this is more representative of present-day conditions during the implementation horizon than using data from a single year (e.g., if the intent was to assess GDE health in the year 2030 the future distribution of NDVI values would be derived from NDVI data for the 2025-2030 period). Future NDVI values at likely GDEs should be calculated in the same manner as the historical dataset using the same methods as the TNC GDE Pulse tool. The ready availability of remote sensed satellite data (e.g., Landsat, Sentinel, etc.) makes this easily achievable.

Summary

Collectively, the Groundwater Level Criteria and GDE ecological health (NDVI) Criteria are viewed as complementary as they assess potential for impacts based on changes to GDE area and health, respectively. Thus, during an implementation year, even if GDE area may appear constant according to Groundwater Level Criteria, the GDE ecological health (NDVI) Criteria will provide an alternative lens into GDE conditions, and visa-versa. The specific approaches, including frequency and datasets used for GDE monitoring, would need to be defined as part of future Vina GSP amendments or Periodic Evaluations. Preliminary recommendations for monitoring implementation are as follows:

- On an annual basis, use spring shallow groundwater levels to estimate the area of likely GDEs that are connected to shallow groundwater (i.e., shallow groundwater levels are at or above rooting depths) and compare that to the area observed during spring 2021. If the area of likely GDE falls below levels observed during spring 2021 for two consecutive years early intervention may be warranted.

- On a 5-year basis, use NDVI derived from Landsat (~30 m resolution) or Sentinel (~10 m resolution) satellites to generate a distribution of future NDVI values to compare to the distribution of historical values. GDE NDVI values should be derived following the same method as those derived by the TNC GDE Pulse tool.[26] Analysis of future NDVI values on an annual basis could be completed to provide additional interim checks on GDE health, especially during drought periods, and may help to build a better understanding of the relationship between GDE NDVI and shallow groundwater conditions.

As described in the sections above, many factors besides groundwater levels can affect the ecological health of GDEs including but not limited to climate, surface hydrology, land use changes, and the occurrence of invasive species. It will be necessary to consider, and to the extent that data are available, to account for these factors when monitoring how GSA management actions affect the beneficial users represented by GDEs.

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[25] Like the TNC pulse methods, it will be necessary to control for covariates that may influence GDE ecological health such a climate, precipitation, and land use changes.

[26] https://gde.codefornature.org/#/methodology

Future monitoring and assessment of potential impacts to these GDEs should also acknowledge and consider the role of surface water and applied water at these locations. For instance, if monitoring indicates declines in the ecological health of these GDEs it will be necessary to decouple the relative roles of changes to groundwater elevations and surface water conditions (e.g., streamflows or applied water volumes). Further, it is important to acknowledge that applied water for irrigated agriculture, managed wetlands, or urban applications at or near these GDEs often represents a translation of groundwater pumped from the deep aquifer to the surface that supports multiple, direct, beneficial uses and users (e.g., agriculture and environmental) and has ancillary benefits to GDEs. As noted, changes to pumping and subsequent applied water may have negative consequences to the direct beneficial uses and users of that applied water but also to GDEs.

Ecological Condition and Long-term Monitoring

Identifying the ecological value of each potential GDE can help to prioritize limited resources as well as prioritize legally protected species or habitats that may need special consideration when setting sustainable management criteria (Rohde et al. 2018). The ecological value of a potential GDE is higher for those that possess natural or near-natural conditions or include species or habitats that have legal protection (Serov et al. 2012). An approach for assessing GDE ecological conditions completed for the adjacent Wyandotte Creek Subbasin is described in ESA (2026) and a similar approach could be applied to the Vina Subbasin to define beneficial users and ecological value of potential GDEs in the Vina Subbasin and inform possible future GDE monitoring.

Establishing fixed monitoring locations to assess ecological baseline conditions at representative GDEs and subsequent periodic monitoring at the same monitoring locations can provide insight into how environmental conditions and groundwater management may be influencing GDE function, integrity, and ecological health through time. An approach for long-term GDE monitoring completed for the adjacent Wyandotte Creek Subbasin is described in ESA (2026) and could be applied to the Vina Subbasin.

Data Gaps and Uncertainties

Several data gaps or uncertainties remain related to relationship between shallow groundwater levels and GDE health, and ecological processes in the Subbasin that influence the abundance, distribution, and ecological health of GDEs. These are summarized below along with possible options to fill these gaps.

- At both the Subbasin and individual GDE scales the relationship between shallow groundwater elevations and GDE NDVI values is not straightforward or linear and uncertainties and data gaps remain regarding how other biotic/abiotic factors and processes influence changes in NDVI. Additional analysis of relationships between shallow groundwater elevations and GDE NDVI values that include data on other biotic/abiotic factors (e.g., precipitation, surface water application, land use change) could help to better understand such relationships. Establishment of long-term monitoring sites at representative GDEs that include repeat surveys of critical baseline data such as canopy closure, diversity, regeneration, structural diversity, and ecosystem function (as measured by percentage of native species) along with ongoing monitoring of shallow groundwater levels would also help better understand ecological trends and relationships between GDE health and groundwater conditions.

- Modification of the flow regime and associated ecological and geomorphic processes along the Sacramento River and other Subbasin surface waters should to be considered when monitoring GDEs and assessing potential impacts under SGMA. For instance, modified flow regimes and construction of levees have resulted in a more channelized river systems, with reduced sinuosity, reducing the amount of adjacent riparian terrestrial habitats. Limitations on recruitment processes mean the health of many riparian communities may decline or experience succession to other community types regardless of groundwater conditions as late successional species die without replacement. The relative effect of changes in groundwater versus surface flow related factors will need to be decoupled as part of future monitoring and reporting under SGMA. Ongoing expansion of the monitoring network along with additional analysis will help address this topic.

- The potential for observed DTG at RMS wells to not be representative of the shallow aquifer system highlights the ongoing need to use appropriate monitoring network data (e.g., wells screened in the shallow aquifer) when monitoring GDEs and the need to scrutinize and develop clear linkages between SMCs and beneficial users when assessing impacts. Ongoing expansion of the monitoring network along with additional analysis will help address this topic. Specifically, additional wells and stream gages installed since the 2022 Vina GSP will collect data that will help fill this data gap.

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