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Regreening, restoring, and reconnecting a southwestern wetland ecosystem – the Zeedyk wetland

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ABSTRACT

Alluvial wetland ecosystems are vital as biodiversity hotspots but are increasingly threatened by anthropogenic stressors and drought. These pressures are especially acute in arid and semi-arid regions, where eco-hydrologic connectivity is fragile and recovery is slow. This study quantifies the efficacy of nature-based solutions, particularly the ‘Zeedyk approach,’ which employs low-tech Natural Infrastructure in Dryland Streams (NIDS)—including rock detention structures—to slow surface water, raise groundwater tables, and restore wetland function at a spring-fed wetland in Cebolla Canyon, New Mexico, U.S.A. Our results depict a Restoration Feedback Loop that captures stages of change from a healthy wetland in 1935, altered by 20th-century agriculture and grazing, to the re-establishment of the historical flow regime by 2024 documented through an 89-year archive of aerial imagery (1935–2024). By the end of our study period, the Spring-Fed Wetland had expanded by roughly 229% of the original 1935 area, to 4.13 ha. Using 40 years of satellite data, we assess changes in vegetation and hydrology with remote sensing indices. Spatial and temporal analyses reveal significant increases in vegetation greenness and wetness, particularly in an Expanded Wetland subregion, which exhibited ~3.5x higher wetness and ~1.5x higher greenness trends compared to adjacent areas. Monthly metrics highlight seasonal variability, with increases in greenness linked to monsoonal rainfall and lateral water redistribution, indicating that restoration impacts extend beyond the primary wetland. This study demonstrates the utility of cloud-based platforms like Google Earth Engine and USGS Earth-Explorer for long-term monitoring of wetland restoration, while quantifying the efficacy of the ‘Zeedyk approach’ and demonstrating its potential as a scalable method to restore and conserve wetland meadows in other arid and semi-arid landscapes.

1. Introduction

Wetlands, wet meadows, coastal wetlands, and dryland ciénegas are globally distributed wetland ecosystems that play a critical

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role in water cycling, carbon sequestration, and biodiversity support (Gibbs, 2000; Hendrickson and Minckley, 1985; Norman et al., 2024; Pollock and Norman, 2025; Zeedyk et al., 2014). Despite their ecological significance, these systems face widespread degradation, driven primarily by stream incision, which lowers water tables and reduces plant viability and alters plant community composition (Pollock and Norman, 2025). Groundwater pumping, surface water diversions, channel incision, and the extirpation of American beavers (*Castor canadensis*) in many North American streams have reduced the water available to dryland ciénegas, in some cases causing complete loss of the wetlands, exacerbated by drought (Minckley et al., 2013; Norman et al., 2025a; Wolkis, 2016). Globally, we are learning that our planet is losing soil water storage space over time (Seo et al., 2025), and soil carbon storage as well (Wang et al., 2025); this riparian and channel degradation in arid and semi-arid environs is described by Norman et al. (2022). Multi-decadal drought conditions across the southwestern United States (U.S.) paired with increasing temperatures (Cook et al., 2015; Williams et al., 2020) and yearly variability in seasonal weather patterns (Cai et al., 2015; Cook and Seager, 2013) provide additional challenges to alluvial wetland meadows tied to their influence on groundwater levels and streamflow (Hanson et al., 2006; Pollock and Norman, 2025).

Various restoration techniques – including using rock detention structures, reintroducing beavers and their dams or analogs, all as Natural Infrastructure in Dryland Streams (NIDS) – are used to restore natural hydrological conditions by detaining surface-water runoff and retaining sediment (Norman et al., 2022b). These approaches have demonstrated the potential to increase water availability and carbon storage in alluvial aquifers, and support vegetation during drought conditions (Callegary et al., 2021; L. M. Norman et al., 2014a; L. M. Norman et al., 2014b; Norman et al., 2016, 2017, 2019; Norman, 2020; Norman et al., 2025b; Norman and Niraula, 2016; Wilson and Norman, 2018, 2022).

One approach has been introduced by Bill Zeedyk, the “water wizard” (*Thinking Like Water*, 2025), who described a structured approach to collecting and analyzing evidence, including data, recollections, and literature, where degradation has occurred, with a primary goal to reconstruct events and identify causality. From there, he can first halt the degradation and then assist to return a landscape to its pre-degradation layout and remedy this using simple restoration techniques and a combination of innovative structures, such as one-rock dam NIDS or armoring gullies. Zeedyk-style restoration is designed to arrest head-cut development, spread water, and reduce flow velocities above a head cut, and around the main incised channel, and to conserve moisture for enhanced plant growth (B. Zeedyk and Clothier, 2009). Rocks are used to capture sediments, debris, seeds, and plant propagules, and act as mulch that protects young plants (Zeedyk, 2006a; B. Zeedyk and Clothier, 2009). In the North American desert southwest, Bill Zeedyk’s restoration approach (hereafter, referred to as the ‘Zeedyk approach’) is quickly gaining favor (*Thinking Like Water*, 2025) (Fig. 1). This approach builds on the geomorphologic studies of meanders and channels (Langbein and Leopold, 1968, 1970; Leopold, 1968; Leopold et al., 2012) and natural channel design (Rosgen, 1994, 1996, 2006, 2013), and mimics local indigenous practices for dryland farms (Pailes et al., 2023). The ‘Zeedyk approach’ has been documented to enhance resiliency by slowing water down, reconnecting floodplains,

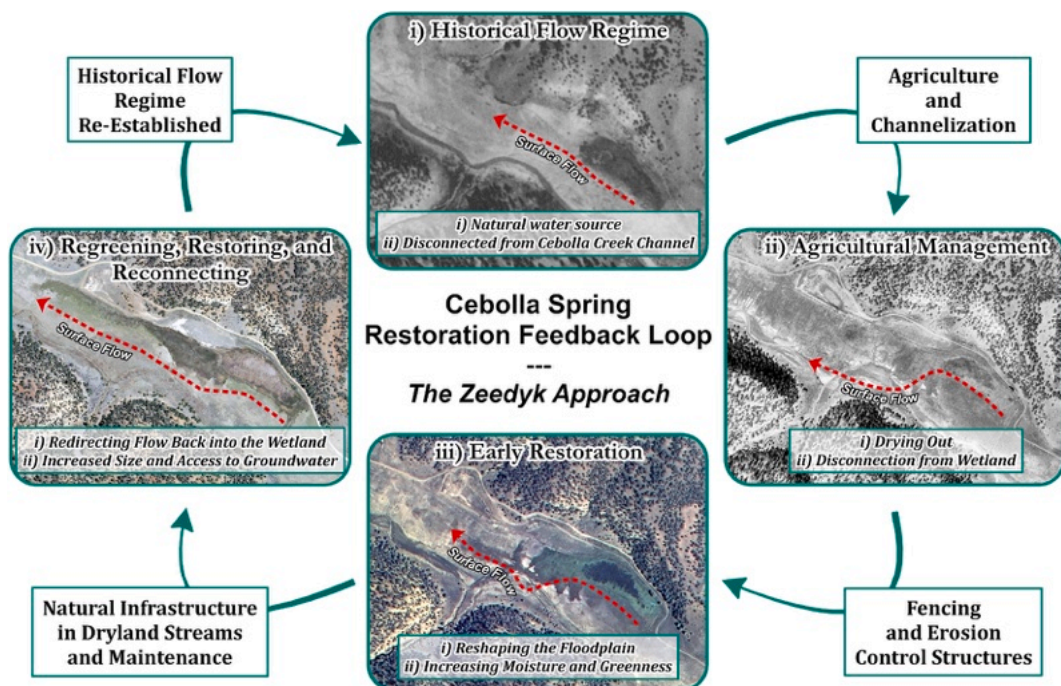


Fig. 1. The Cebolla Spring Restoration Feedback Loop shows the four stages of the ‘Zeedyk Approach’ used to re-establish the historical flow regime using aerial photography, beginning with the (i) historical flow regime in 1935 and transitioning to documented effects of (ii) agricultural management in 1997. This is then followed by (iii) restoration applications, including fencing and Natural Infrastructure in Dryland Streams (NIDS), in 2005. And finally, the (iv) regreening, restoring, and reconnecting of the wetland system and re-establishing the historical flow regime in 2024.

increasing sediment storage, wetland vegetation, habitat and improving rangeland condition (Gellis et al., 1995; Matherne et al., 2018; Laura M. Norman et al., 2021a; Laura M. Norman et al., 2021b; Norman et al., 2022b, 2025b; Rondeau et al., 2023; Silverman et al., 2019; Wilson and Norman, 2022).

The Cebolla Spring Restoration Feedback Loop (Fig. 1) demonstrates restoration techniques structured to regreen, restore, and reconnect a southwestern alluvial wetland analyzed through the scientific analysis applied in this study (W. D. Zeedyk and Clothier, 2009). We quantify the impacts of the Zeedyk approach restoration on wetland conditions using image analyses of digital aerial imageries acquired via aircraft and satellite. High-resolution aerial photography is typically acquired through the use of mapping cameras equipped to aircraft from a vertical position above the site (Earth Resources Observation and Science (EROS) Center, 1937). Depending on the desired objective of the image, processing steps affecting overall quality and clarity of the image can vary, and challenges such as limited temporal availability and less consistency between radiometric resolutions can complicate efforts to derive output products over time. However, aerial imagery can be available at a site for multiple decades prior to satellite-based sources and provide a detailed observation of point-in-time conditions with up to sub-meter spatial resolutions allowing for detailed analyses over time (Morgan et al., 2010).

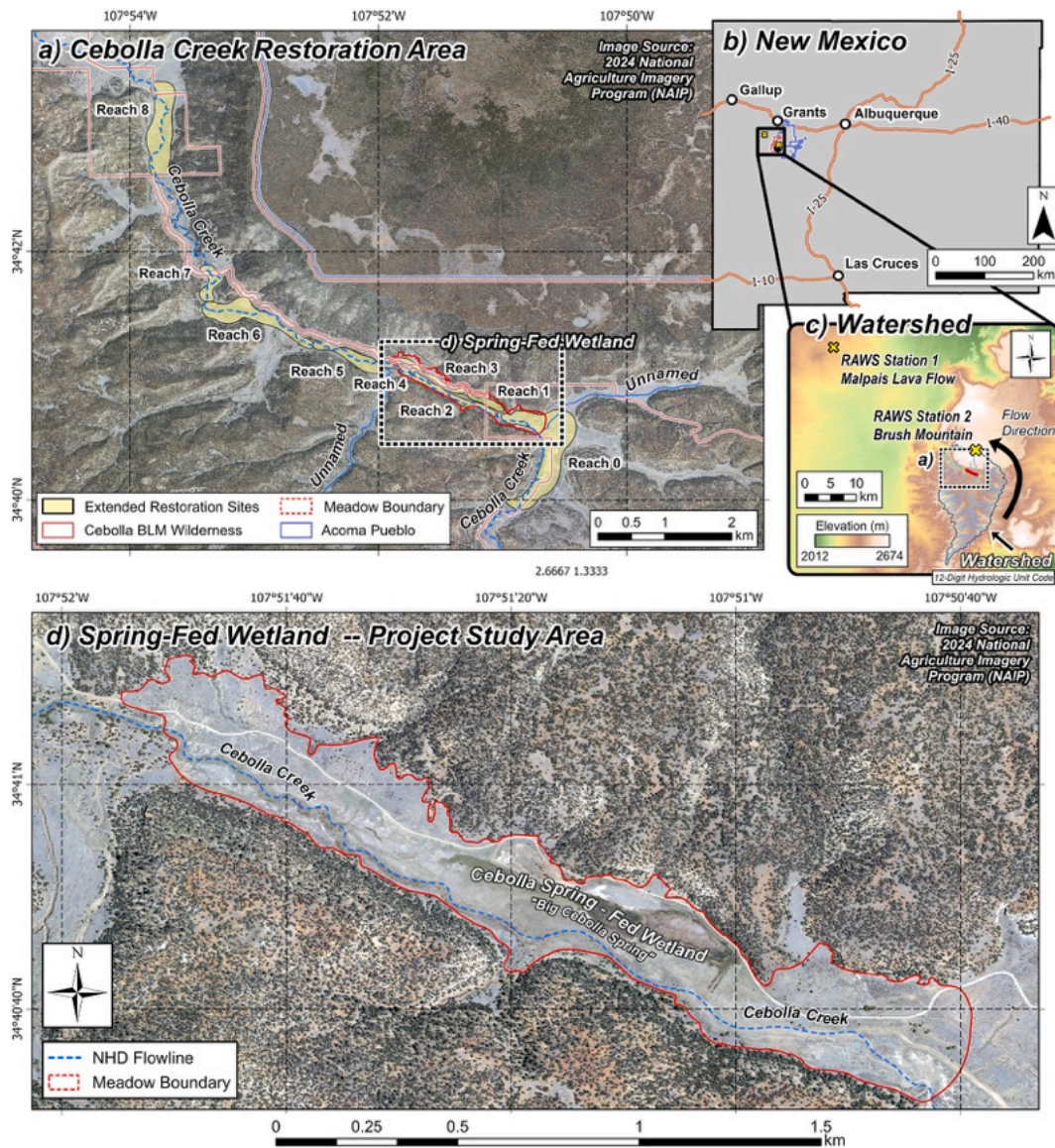


Fig. 2. Map of the (a) Cebolla Creek Restoration Area in (b) east-central New Mexico. Submap (c) shows the extent of the Cebolla Creek watershed (12-Digit Hydrologic Unit Code: 130202060501) and the location of the RAWs Meteorological Stations (Western Regional Climate Center, 2025). The (d) spring-fed wetland study site is among a series of reaches where restoration has been applied in the Cebolla Canyon (undesigned area) (McGraw, 2014) extending west, following flow direction, from the end of Reach 0 to Reach 5. The basemap image is from the National Agriculture Imagery Program in 2024 (USDA, 2021).

Satellites, such as the Landsat program (U.S. Geological Survey, 2025), have been collecting near-continuous, multispectral imagery of Earth's surface for 53-years (Goward et al., 2006; Wulder et al., 2022). Multispectral satellite imagery allows for more robust calculations of vegetation conditions by measuring conditions beyond the visible spectrum (Xue and Su, 2017). Landsat, for instance, ranges from four spectral bands (i.e., Landsat 1 through 3) to eleven (i.e., Landsat 8/9), and collects data across the Near Infrared (NIR) and Shortwave Infrared (SWIR) bands, which are not visible to the human eye and can document unique vegetative properties and water content (Roy et al., 2014; U.S. Geological Survey, 2025; van Leeuwen, 2009). Most aerial imagery sources collect data using a single band or across the Visible bands (i.e., red, green, blue). However, lower spatial resolutions (i.e., 30-m) limit the capacity of Landsat, and other satellite imagery products, for detailed analysis of landscape change. Many studies utilize a combination of both aerial and satellite imagery sources to quantify changes on the landscape (Petrakis et al., 2017, 2023; Villarreal et al., 2016).

Cloud computing environments like Google Earth Engine (GEE) (Gorelick et al., 2017) and the U.S. Geological Survey Earth-Explorer public data repository (Houska, 2012) are public data repositories for satellite and aerial imagery products. GEE allows for additional computational analysis to produce secondary metrics. For instance, using GEE in this study, we produce time series of the Normalized Difference Infrared Index (NDII) wetness metric (Hardisky et al., 1984) and the Normalized Difference Vegetation Index (NDVI) greenness metric (Tucker, 1979), in addition to satellite estimated measurements of actual evapotranspiration (ETa), to quantify changes in vegetation and wetland conditions. The greenness and wetness metrics provide quantifications related to plant vegetation condition and soil and plant canopy wetness especially critical to observing wetland environments in dryland regions (Norman et al., 2025a; Wilson et al., 2016; Wilson and Norman, 2018). Evapotranspiration, which is a measurement of water lost to the atmosphere through transpiration from plants and evaporation from soil/water (Petrakis et al., 2024), is variable within wetlands in response to changed water tables in relation to the root zone, vegetation height, and plant senescence (Lott and Hunt, 2001). However, accurate quantification of ETa can inform on impacts tied to restoration and changes in land cover (Liu et al., 2008; Norman et al., 2025b; Petrakis et al., 2024).

Overall, this research uses high-tech satellite imagery analyses and computer processing to examine and quantify the impacts of low-tech Zeedyk restoration approach (Fig. 1) at a degraded historical wetland at Cebolla Spring in the Cebolla Canyon Closed Basin (undesignated area), Cibola County, New Mexico, USA. By developing a series of comprehensive imagery collections, including aerial imagery ranging from 1935 to 2024 and continuous satellite coverage on a monthly scale from January 1985 to December 2024, we quantify spatially and temporally explicit changes on the landscape in response to variable human occupation and management activity periods. Then, by isolating unique subregions associated with changes across multiple management periods, we assess the relationship between temporal signatures of vegetation greenness, wetness, and evapotranspiration to better understand how wetland restoration using NIDS influences vegetation metrics across the wetland basin. This remote sensing approach is designed to be broadly applicable for monitoring temporally and spatially explicit effects of restoration applications and to assess the efficacy of the 'Zeedyk approach' at the Cebolla Spring wetland.

2. Methods

2.1. Study site

The Bureau of Land Management maintains 24,930 ha of Cebolla Wilderness Area, just south of the town of Grants, in Cibola County, New Mexico (Fig. 2a and b). The Wilderness is located within the El Malpais National Conservation Area, bordered by the Acoma Pueblo, a Native American village that sits on top of a high mesa ("Sky City"), and the El Malpais National Monument, composed of rugged volcanic lava fields, tubes, and sandstone bluffs. Cebolla Wilderness Area combines these sandstone mesas, canyons, and grassy valleys with juniper, piñon, and ponderosa pine forests. We detail the human occupation, historical agricultural and modern restoration below (Table 1).

The Cebolla Creek maintains a spring-fed *slope wetland* supported by both groundwater discharge along sloping elevation gradients and extreme seasonal rainfall events occurring during summer months (e.g., monsoons), that move larger soil particles and form

Table 1

Listing the temporal breakdown of human occupation and land use by respective years.

Years	Human Occupation	Land Use	Additional Notes
1000 to 1300	Pueblo II Period	Dry-farming, terracing, irrigation	Drought Likely Contributed to Reduced Human Population
1881 to 1930	Railroad into Grants, NM (1881); homesteaders	Light agriculture; introduction of sheep and cow grazing	Left seeking employment during World War II
1930 to 1994	Private rangeland ownership	Continued cattle grazing	
1994 to 2000	Bureau of Land Management (BLM) Jurisdiction	Fencing enclosure	
2000 to 2008	Albuquerque Wildlife Federation (AWF)	Volunteer restoration and wetland protection	
2008 to 2015	New Mexico Environment Department Surface Water Quality Bureau Wetlands Program	Zeedyk restoration and Natural Infrastructure in Dryland Streams (NIDS)	
2015 to 2023	BLM and AWF	Maintenance of restoration structures	

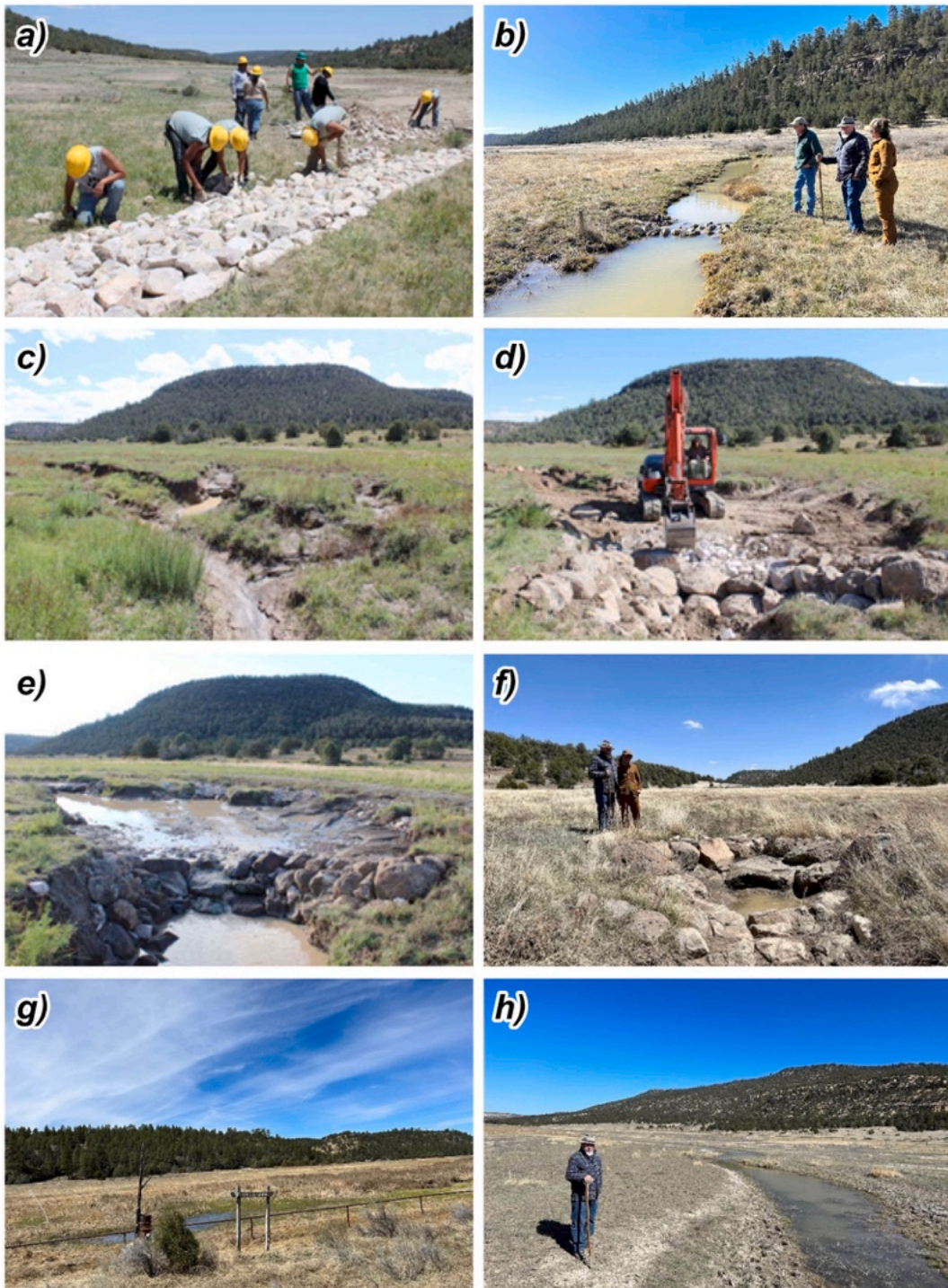


Fig. 3. Photographs showing construction of restoration structures, including (a) a one rock dam being constructed with the Acoma YCC crew in May 2012 and (b) a decade later in new stream channel with G. Norman, B. Zeedyk, and C. Weber looking east, in addition to (c) a head cut before work in reach, (d) downstream restoration work with C. Sponholtz on machine, (e) the finished Zuni bowl in 2013, and (f) a decade later with B. Zeedyk and C. Weber. Additional photographs show the condition of Cebolla Creek wetland in 2023, including from the (g) headwater spring facing south and (h) looking west along the restored stream channel with B. Zeedyk. Photographs (a), (c), (d), (e) are from (McGraw, 2014). Photographs (b), (f), (g), and (h) were taken by L. Norman on April 19, 2023.

alluvial fans from sedimentation (Fig. 2c) (Zeedyk et al., 2014). This ‘spring-fed’ slope wetland exists on a hillslope where groundwater is stored or maintained in deeper sedimentary aquifers, faults, and other structural conduits, and discharges at the surface (Zeedyk et al., 2014). As such, Cebolla Spring maintains perennial surface water through the dry season, supporting palustrine wetland development and intermittent flows in Cebolla Creek within the North Plains Closed Basin watershed (8-Digit Hydrologic Unit Code: 13020206; 12-Digit Hydrologic Unit Code: 130202060501) (McGraw and Johnson, 2013). The site is primarily classified as a Shrub/Scrub system by the National Land Cover Database (NLCD), with no canopy cover (Homer et al., 2012).

2.1.1. Historical human occupation and agricultural land use

Cebolla Canyon has an extensive history of human occupation tied to various land uses and management approaches (Table 1). Archeologists have identified remains from the Pueblo II period (CE 950–1100) (i.e., Pueblo of Acoma) and an extensive number of Paleo Indian sites within Cebolla Canyon, irrigating water from the creek and spring, and using dryland farming techniques that relied on multiple fields to compensate for the sporadic rainfall to harvest corn, squash, beans, and cotton, likely consisting of some terracing (McGraw and Johnson, 2013; Pailes et al., 2023). It is believed that the Ancestral Puebloans vacated this area around A.D. 1300—potentially due to a long-term drought (McGraw and Johnson, 2013).

Following the construction of the railroad to Grants, New Mexico in 1881 and through the 1930's, large flocks of domestic sheep (*Ovis aries*) grazed the area with timber harvesting occurring on the mesas. However, drought and economic hardships in the U.S. (i.e., Dust Bowl, Great Depression) led several Hispanic and Euro-American homesteading families to move to the canyon and nearby areas. Cebolla Spring, a reliable water source near the former Pablo Pino homestead, provided water to many local residents of that time-frame, who transported it to their homes in barrels (Burghardt, 2014). Homesteaders primarily cultivated beans, corn, and sugarcane, kept a milk cow (*Bos taurus*) and chickens (*Gallus gallus*), and built root cellars to store canned goods. They sold or traded beans and eggs to obtain essentials like sugar, coffee, flour, cornmeal, and animal feed in Grants (Burghardt, 2014; Towner and Creasman, 2010). However, with the onset of World War II, many were compelled to leave in search of outside employment (Burghardt, 2014).

Following World War II, the canyon valley was drained, diverted, and earthen berms were constructed to impound water from the spring in an irrigation pond (reservoir with pipes) for agricultural use on the north side (McGraw, 2014). Adjacent to this, a road created a gully which captured the ephemeral flow from the canyon. To the west, sediments from the outflow created an alluvial fan that blocked Cebolla Creek and created a slope wetland upstream of the blockage. The pattern is repeated downstream at the mouth of the next canyon that flows into Cebolla Creek (Zeedyk et al., 2014). The irrigation systems failed over time (Burghardt, 2014), and what had once been a continuous grassland channel through the 1940s eroded into a massive gully ~25 to 30 m wide and ~10 to 15 m deep. Similar deep head cuts and gullies scarred the valley bottom downstream of the spring-fed wetland (i.e., Reach 5 and below) (Fig. 2a). These geomorphological changes, exacerbated by cattle grazing, reduced historical wetlands to a small fraction of their original extent and showed no signs of natural recovery (McGraw, 2014).

2.1.2. Modern restoration of Cebolla Canyon

In 1988, the U.S. government established the El Malpais National Monument and Cebolla Wilderness Area (24,686 ha) (Fig. 2), and in 1994 the Bureau of Land Management (BLM) gained jurisdictional control of Cebolla Springs (McGraw and Johnson, 2013). At the time, as a demonstration, a 2.83-ha enclosure was constructed to reduce livestock use of the Cebolla Spring (McGraw and Johnson, 2013; Rio Puerco Alliance, 2008). Since the Fall of 2000, the Albuquerque Wildlife Federation (AWF) has been organizing volunteer groups to restore and protect wetlands in Cebolla Canyon Closed Basin (McGraw, 2014; Zeedyk et al., 2014). From 2008 through 2015, the New Mexico Environment Department Surface Water Quality Bureau Wetlands Program, in cooperation with the Rio Puerco Alliance, the AWF, and other partners worked with the Rio Puerco Field Office of the BLM to complete a wetlands restoration demonstration project across a series of 8 reaches (Fig. 2a), extending a length of ~11 km, with the intent of returning Cebolla Creek to its *pre-agricultural* condition (McGraw, 2014) (Fig. 3).

Field reconnaissance was used to develop an integrated ‘Zeedyk approach’ project with a variety of innovative structures to (i) capture storm water and sediment, (ii) fill and heal head cuts and entrenched channels, (iii) cut off flow paths that still carried water to adjacent irrigation ditches, (iv) reduce or convey sediment from gullies and nearby dirt roads, and (v) to guide water across the floodplain which would support increased wetland vegetation growth and diversity (McGraw, 2014). Following, the groups worked to implement best management practices to spread water over the valley and the saturated zone spread to over a 16-ha area and “rewet the meadow” using a series of restoration applications were applied across the 8 reaches within the Cebolla Canyon (Fig. 2a). Treatments consisted of NIDS including one-rock dams, rolling dips, and plug and ponds, rock rundowns, filter dams, berm repairs and removal, and earthen plugs to promote the spreading of flow from small, incised channels to expand wetland obligate species and groundwater infiltration across the valley floor, in addition to road and channel re-construction (Fig. 3) (McGraw, 2014; Newman et al., 2025; Norman et al., 2022b; Zeedyk, 2006b; B. Zeedyk and Clothier, 2009; Zeedyk and Vrooman, 2017).

Restoration in Reach 0, the furthest upstream, focused on the use of plug and pond structures to reduce headcuts and increase sinuosity along the floodplain (McGraw, 2014). For Reach 1, the abandoned diversion channel that led from Cebolla Spring to the storage reservoir was plugged to re-connect groundwater flow from the spring to the former wetland. Restoration in Reaches 3 and 4 focused on road restoration to reduce head-cutting and gullying and the use of one rock dams, Zuni bowls, and media luna to slow and spread surface flows (McGraw, 2014). Specifically in Reach 4, grade control structures were installed to raise the bed of Cebolla Spring where it was deliberately ditched and drained (Rio Puerco Alliance, 2008). The upstream Reaches, including Reaches 5–7 and Reach 8, primarily focused headcut mitigation and induced meandering in critically incised locations (McGraw, 2014). Ongoing workshops are held on an annual basis to maintain structures and continue efforts throughout the canyon (Table 1).

This study focuses on quantifying changing vegetation and surface conditions (i.e., greenness and wetness) occurring within and

immediately below and above the primary water source, which is the spring-fed wetland (i.e., Big Cebolla Spring). This region extends from the western edge of Reach 0 at the confluence of Cebolla Creek and an unnamed stream to a patch of juniper trees just upstream of Reach 5 and the confluence with another unnamed stream (Fig. 2a), covering the area of Reaches 1 through 4 (Fig. 2c).

2.1.3. Climate

Located in the semi-arid Southwest U.S., New Mexico experiences primarily a bimodal climate regime with complex spatial diversity as a result of localized topography (Gulzler, 2013; Tuan and Everard, 1964). Summers are generally warm to hot and

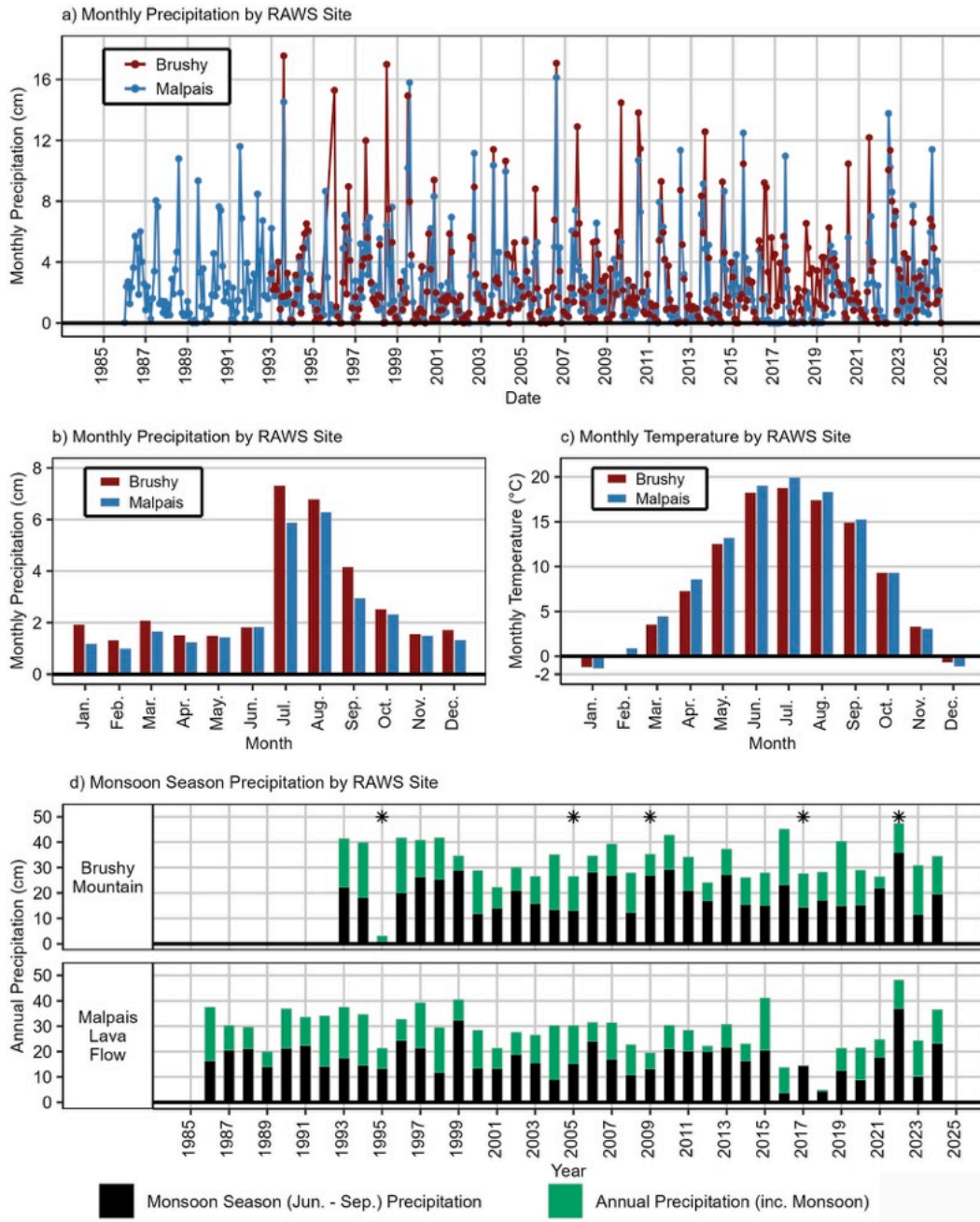


Fig. 4. Precipitation at the two Desert Research Institute (DRI) RAWS climate stations (i.e., Brushy Mountain, Malpais Lava Flow) (Western Regional Climate Center, 2025) surrounding the Cebolla Wilderness Area (a) monthly from 1985 – current, (b) monthly averages depict reliance on monsoon season, and (d) annual summations from 1985 – current with monsoon season summations (June-September) overlaid. “*” in (d) represent years with known missing monthly values or monthly values where extreme outliers were removed (i.e., <0 cm, >25.4 cm) at the respective collection station. (c) Monthly mean temperatures are also shown at each station.

experience heavy precipitation rainfall events tied to southeasterly circulation from the Gulf of America fueling the North American Monsoon (Adams and Comrie, 1997), accounting for roughly 60% of the annual rainfall (Western Regional Climate Center, 1999). During the winter months, precipitation is largely tied to frontal activity from the Pacific Ocean providing occasional snow and rainfall, mostly across the northern and western mountain ranges; temperatures are cool during the day and reach below freezing at night (Western Regional Climate Center, 1999).

Weather variables were collected from the Desert Research Institute (DRI) Remote Automatic Weather Stations (RAWS) climate stations (Western Regional Climate Center, 2025) located at Malpais Lava Flow, New Mexico and Brushy Mountain, New Mexico. The Malpais Lava Flow station (Fig. 2c; RAWS 1) is located ~32.2 km to the northwest of Cebolla Creek at an elevation of 2,274 m (i.e., North American Datum of 1983; NAD83). Air temperature and precipitation data is available from May 1985 through present day (i.e., September 2025). Meanwhile, the Brushy Mountain station (Fig. 2c; RAWS 2) is located ~4 km to the north at an elevation of 2,671 m. Similarly, air temperature and precipitation data are available from August 1992 through present day. To align with the temporal resolution of the remote sensing analysis described below, we extract data beginning in January 1986 and January 1993, respectively, for the Malpais Lava Flow and Brushy Mountain stations, extending through December 2024 at both sites.

Precipitation data from the two RAWS stations (i.e., Malpais Lava Flow, Brushy Mountain) show spatial climate variability surrounding the Cebolla Creek wetland (Fig. 4a). The Malpais Lava Flow station (hereafter, Malpais station) experiences a significant declining linear slope in precipitation across the period of availability (i.e., slope = -0.0016 cm/month; *p*-value = 0.002), while the Brushy Mountain station (hereafter, Brushy station) experiences an insignificant increasing slope (i.e., slope = 0.0006 cm/month; *p*-value 0.43).

Both stations received similar precipitation amounts, on average, for May, June, and November, which are typically drier months in the region (Fig. 4b). However, the Brushy station has greater total precipitation for remaining months. July through September represents the monsoon season, which typically has more extreme spatial and temporal variability, but also favors higher elevation areas. Similarly, the months of December through April represent the winter and spring precipitation season fueled by cool frontal systems from the north Pacific Ocean, which also favor higher elevations due to orographic lifting. The Malpais station is generally warmer for most months except for the winter months of November through January (Fig. 4c).

Monsoon season (i.e., June – September) seasonal total and yearly percentage precipitation varies on a year-to-year basis for both stations (Fig. 4d). For Brushy station, the percentage of monsoon precipitation to total precipitation ranged from 36.5% (i.e., 2019; 14.76 of 40.46 cm) to 82.7% (i.e., 1999; 28.73 of 34.72 cm). For Malpais station, the monsoon percentage ranged from 26.8% (i.e., 2016; 3.66 of 13.64 cm) to 98.4% (i.e., 2017; 14.38 of 14.61 cm).

2.2. Image analyses

Using a series of aerial images over a period of 89 years (i.e., 1935 to 2024), we periodically explore various characteristics of the wetland over time, including its spatial extent, shape, and flow design. Aerial imagery was available from the New Mexico Resource Geographic Information System (NM RGIS) (Earth Data Analysis Center, 2015) and from the U.S. Geological Survey (USGS)

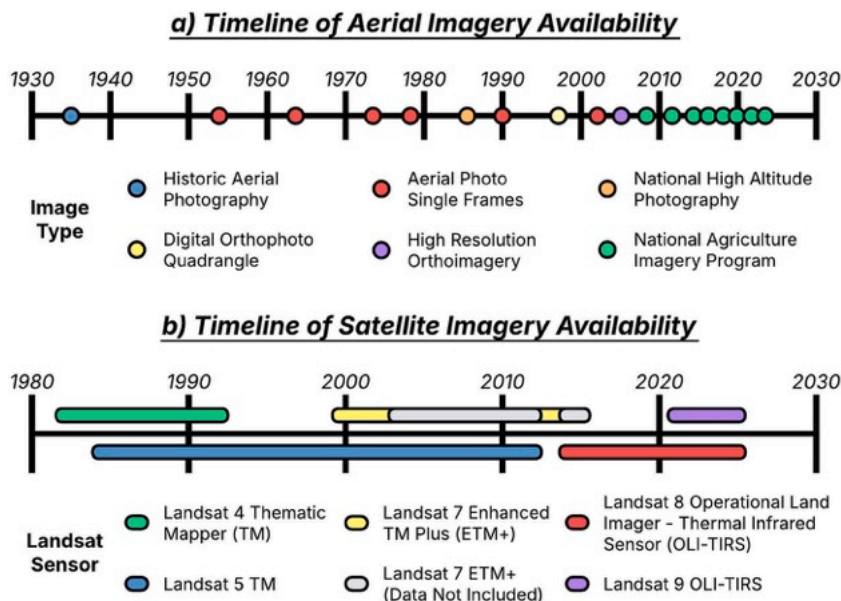


Fig. 5. Timeline of (a) aerial imagery availability for Cebolla Spring wetland from 1935 to 2024 (Earth Data Analysis Center, 2015; Houska, 2012) and (b) satellite imagery availability for Landsat data from 1982 through 2024 (Earth Resources Observation and Science (EROS) Center, 2020, 2013, 1999; U.S. Geological Survey, 2021). The color indicates the image type and Landsat Sensor.

EarthExplorer image data repository (Houska, 2012) for the following years: 1935, 1954, 1963, 1973, 1979, 1982, 1986, 1990, 1997, 2002, 2005, 2009, 2011, 2014, 2016, 2018, 2020, 2022, and 2024 (Fig. 5a).

Images for dates prior to 2009 required a georeferencing process, in which each image was georeferenced to the 2022 National Agriculture Imagery Program (NAIP) imagery (USDA, 2021) using the best available control points. NAIP imagery from 2024 was not available at the time of georeferencing. A 2nd Order Polynomial Transformation was applied due to the complex topography of the land surface, variable source image quality and radiometric resolutions, and to increase the accuracy at Cebolla Creek, which was generally located at the center of the respective image scene. Then, we digitized the boundary of the wetland extent for each date; the boundaries were collated into a single maximum wetland extent region.

2.2.1. Remote sensing vegetation conditions

We developed and collected a series of satellite images for application in this study. Using Google Earth Engine (GEE) cloud computing software, we developed a series of monthly mean images for two vegetation indices, the Normalized Difference Infrared Index (NDII) and the Normalized Difference Vegetation Index (NDVI). The NDII applies the Near Infrared (NIR) and Shortwave Infrared (SWIR) bands to quantify canopy and soil moisture (Hardisky et al., 1984). The index ranges from -1 to 1 , where values closer to 1 suggest full saturation and values closer to -1 are drier. The NDVI is a vegetation metric that is commonly used to quantify vegetation greenness (Tucker, 1979). Similarly, NDVI ranges from -1 to 1 , where increasing positive values represent increasing greenness conditions and negative values are typically fully water-saturated pixels.

For this analysis, we use Landsat satellite imagery. The Landsat series consists of a series of sensors which have been collecting continuous multispectral, digital satellite images from 1972 to present-day. Landsat imagery has a spatial resolution of 30 m and temporal resolution of 16-days, with increased temporal availability during periods with overlapping sensors. Imagery is from the Landsat 4, 5, 7, 8, and 9 Level 2/Collection 2/Tier 1 products with improved radiometric and geometric calibration for increased compatibility between sensors over time (Earth Resources Observation and Science (EROS) Center, 2020, 2013, 1999; U.S. Geological Survey, 2021). Each sensor has a range of dates (Fig. 5b). Landsat 7 imagery was limited due to failure of the scan line corrector (SLC) in May 2003 (Markham et al., 2004) and was not included between 2003 and 2012; Landsat 7 imagery was included to in 2012 to fill the period between Landsat 5 and Landsat 8.

In GEE, we produced monthly mean NDII and NDVI images from January 1985 through December 2024 for the area surrounding the wetland meadow. Monthly mean images were produced by averaging all values for a pixel within a single month. The monthly composites for NDII and NDVI were then exported from GEE and reprojected to NAD83 Zone 13 North (EPSG:26913) using a bilinear interpolation in ESRI ArcGIS Pro version 3.4.3 for additional analysis. Both NDII and NDVI monthly collections consist of 480 images each.

We also extracted monthly actual evapotranspiration (ETa) from GEE using the OpenET Ensemble Monthly Evapotranspiration v2.0 dataset (hereafter referred to as OpenET) (Google Earth Engine, 2025; Melton et al., 2022). The OpenET dataset provides monthly ETa estimates beginning in October 1999 based on an ensemble collection from multiple ETa algorithms with a spatial resolution matching Landsat (i.e., 30 m) and a monthly temporal resolution. In GEE, we clipped the OpenET dataset to the area surrounding the wetland meadow and extract monthly ETa estimates from January 2000 to December 2024. The ETa monthly collection consists of 300 images. ETa is an environmental process that is responsive to changes in greenness and wetness through evaporation from soil, rock, water surfaces, and plant interception and transpiration by plants (Petrakis et al., 2024); we quantify greenness and wetness conditions before associating changes in ETa.

2.2.2. Spatial and temporal analyses

We completed a series of spatial data analyses to assess the effects of restoration on the overall wetland ecosystem. First, based on the temporal history of human occupation and activity (Table 1), we identified four management periods within the temporal

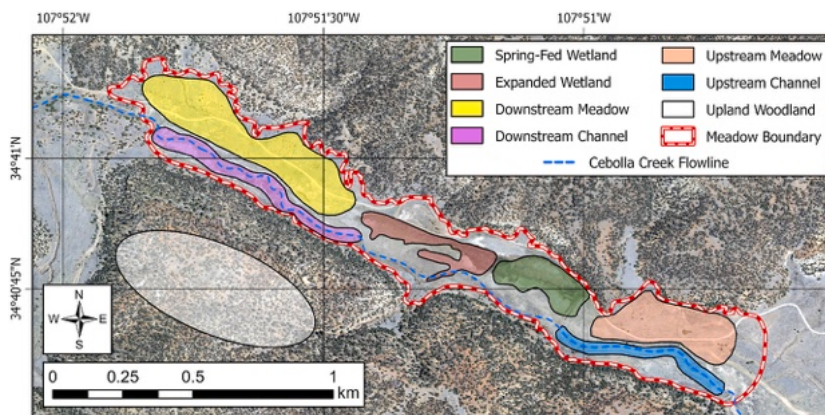


Fig. 6. Showing the seven subregions with their locations based on changes identified in the Management Period Analysis over 2024 National Agriculture Imagery Program (NAIP) (USDA, 2021) imagery.

framework of the satellite imagery data (i.e., January 1985 to December 2024). The four management periods follow: (i) Pre-Restoration – January 1985 to December 1994 representing pre-restoration period, (ii) Fencing – January 1995 to December 2000 representing a period with fencing enclosure, (iii) Early Restoration – January 2001 to December 2008 representing a period of initial restoration efforts, and (iv) Natural Infrastructure in Dryland Streams (NIDS) and Maintenance – January 2009 through December

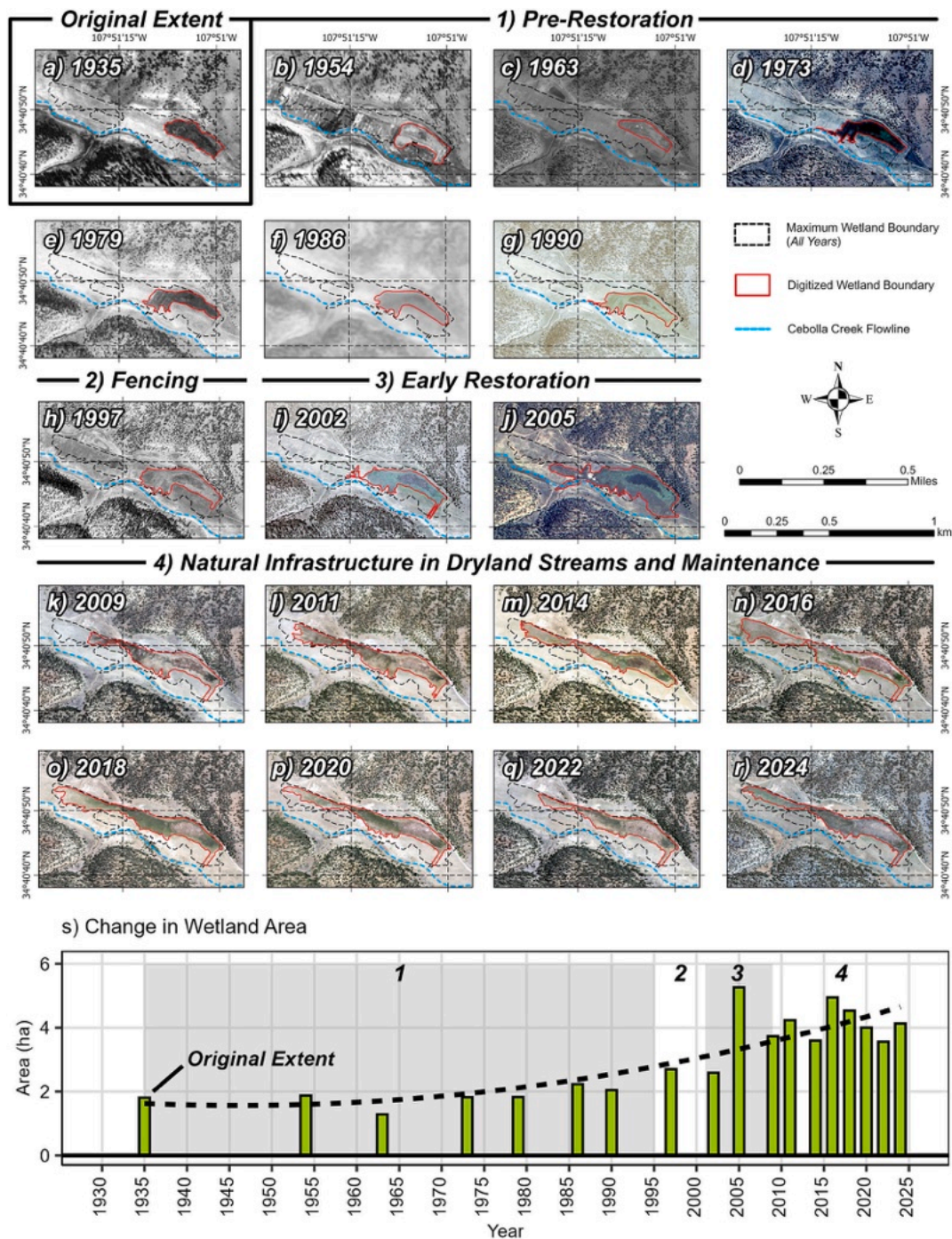


Fig. 7. Showing the spatial extent of the Cebolla Creek wetland for each year that imagery is available (Earth Data Analysis Center, 2015; Houska, 2012). Subsets a – g (i.e., 1935 – 1990) represent Period 1 – Pre-Restoration with subset a representing the original extent, while subsets h – j (i.e., 1997 Fencing, 2002 – 2005 Early Restoration) show Period 2 – Fencing and Period 3 – Early Restoration and subsets k – r (i.e., 2009 – 2024) show Period 4 – Natural Infrastructure in Dryland Streams (NIDS) and Maintenance. Subset (s) shows the spatial extent of the Cebolla Creek wetland for each year, delineated by each management period. A 2nd order polynomial regression line (black) shows the increasing trend in area.

2024 representing the full establishment of NIDS and maintenance of the restoration structures. For each index, we averaged all monthly images across each management period using the Cell Statistics tool in ArcGIS Pro to produce a mean value representing surface conditions present respective to each management period. We then differenced the mean images to quantify where and when changes occurred, and we differenced the first and fourth periods to quantify overall change across the study period.

We then delineated a series of subregions associated with landscape characteristics that highlight changes that occurred in response to management applications. The subregions include the (i) Spring-Fed Wetland, (ii) Expanded Wetland, (iii) Downstream Meadow, (iv) Downstream Channel, (v) Upstream Meadow, (vi) Upstream Channel, and (vii) an upland site consisting primarily of woodland vegetation that is disconnected from the meadow (e.g., Upland Woodland) (Petrakis and Norman, 2025) (Fig. 6). For each of the subregions, we quantified the spatial and temporal variability within the meadow through a time series of NDII, NDVI, and ETa and calculated linear Sen's slopes (Sen, 1968) across each time series. We then calculated Pearson correlations between the monthly time series of ETa with precipitation, NDII, and NDVI to assess potential drivers of ETa response on a subregional basis. Lastly, we produced a monthly conflation of NDII, NDVI, and ETa for each subregion to assess how conditions changed for all months throughout the year.

3. Results

3.1. Aerial imagery analysis

An imagery analysis overview (Fig. 7) portrays a series of unique periods of flow characteristics and associated vegetation response for the Cebolla spring-fed slope wetland delineations in response to management shifts and natural drivers (Petrakis and Norman, 2025). In the earliest available imagery (1935), representing the original extent and historical flow regime (Fig. 1), the wetland was small but green, discharging to the northwest, parallel to Cebolla Creek (Fig. 7a). After agricultural fields were established and earthen dams constructed to retain water, the wetland's natural flow regime was redirected toward Cebolla Creek to support dryland crop rows. As a result, much of the water drained from within the original wetland boundary, as observed in the 1954 and 1963 imagery

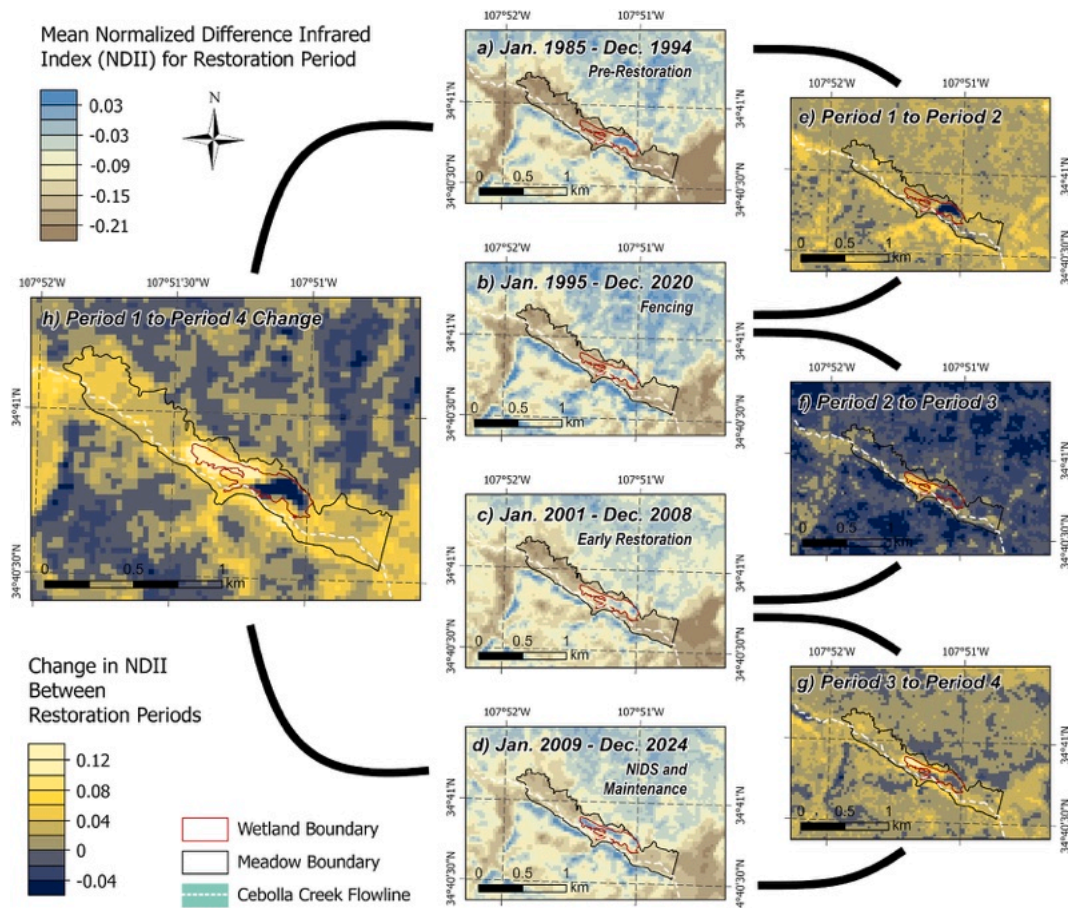


Fig. 8. Showing the spatially explicit mean Normalized Difference Infrared Index (NDII) value across all months within (a) Period 1 (i.e., Jan. 1985 – Dec. 1994), (b) Period 2 (i.e., Jan. 1995 – Dec. 2000), (c) Period 3 (i.e., Jan. 2001 – Dec. 2008), and (d) Period 4 (i.e., Jan. 2009 – Dec. 2024), in addition to the change in NDII from (e) Period 1 to Period 2, (f) Period 2 to Period 3, (g) Period 3 to Period 4, and (h) Period 1 to Period 4.

(Fig. 7a/b). As agricultural activity declined—first evident in the 1973 imagery (Fig. 7d)—the impoundments that had been holding water from Cebolla Creek began to erode. Thus, historical irrigation diversions and impoundments dried out the wetlands causing gully formation, head-cutting, and deepening of the Cebolla Creek main channel. With the irrigation systems no longer functioning and the impoundments breached, Cebolla Creek was diverted from its natural drainage path. This led to severe head-cutting in the valley bottom, with some areas incised as deeply as ~15 m — preventing wetland recovery. This degraded creek and floodplain extended until the beginning of the restoration period in the mid-1990s (Fig. 7e–g) and the Spring-Fed Wetland area increased slightly from 1935 (i.e., 1.81 ha) to 1990 (i.e., 2.04 ha), representing the Pre-Restoration period.

Although the site was enclosed with fencing prior to the 1997 imagery, no significant changes were visible in the aerial photographs at that time (Fig. 7h). However, beginning in 2000 and continuing through 2008, the initial installation of rock structures (NIDS), combined with fencing, began to extend the wetland west and southwest into Cebolla Creek, as observed in the 2002 and 2005 imagery (Fig. 7i/j). Additional wetland expansion to the south was also evident in the 2005 imagery. During the Early Restoration period, the wetland had expanded to its largest extent of 5.26 ha, roughly 291% of the 1935 area (Fig. 7s).

Beginning in 2008, with the full-scale restoration of the wetland and expanded placement of NIDS structures (e.g., NIDS and Maintenance period), the most significant and widespread changes became evident in the 2009 and 2011 imagery (Fig. 7k/l). During this period, a major shift in flow direction occurred: the wetland expanded northwest, parallel to Cebolla Creek, and became disconnected from the creek’s active channel. This marked a reconnection and *reestablishment* of the historical flow regime, allowing water to be redistributed across a broader floodplain, promoting wider dispersion and increasing the overall wetland area.

This large-scale transformation persisted in the imagery from 2014 through 2024 (Fig. 7m–r), with annual fluctuations in wetland size in the northwesterly direction likely indicating variability in seasonal precipitation and total yearly rainfall. By the end of our study period, the Spring-Fed Wetland had expanded to 4.13 ha, roughly 229% of the original 1935 area (Fig. 7s). This growth aligns with findings from (McGraw, 2014; McGraw and Johnson, 2013), who reported that both active and passive restoration efforts led to visible improvements in wetland conditions.

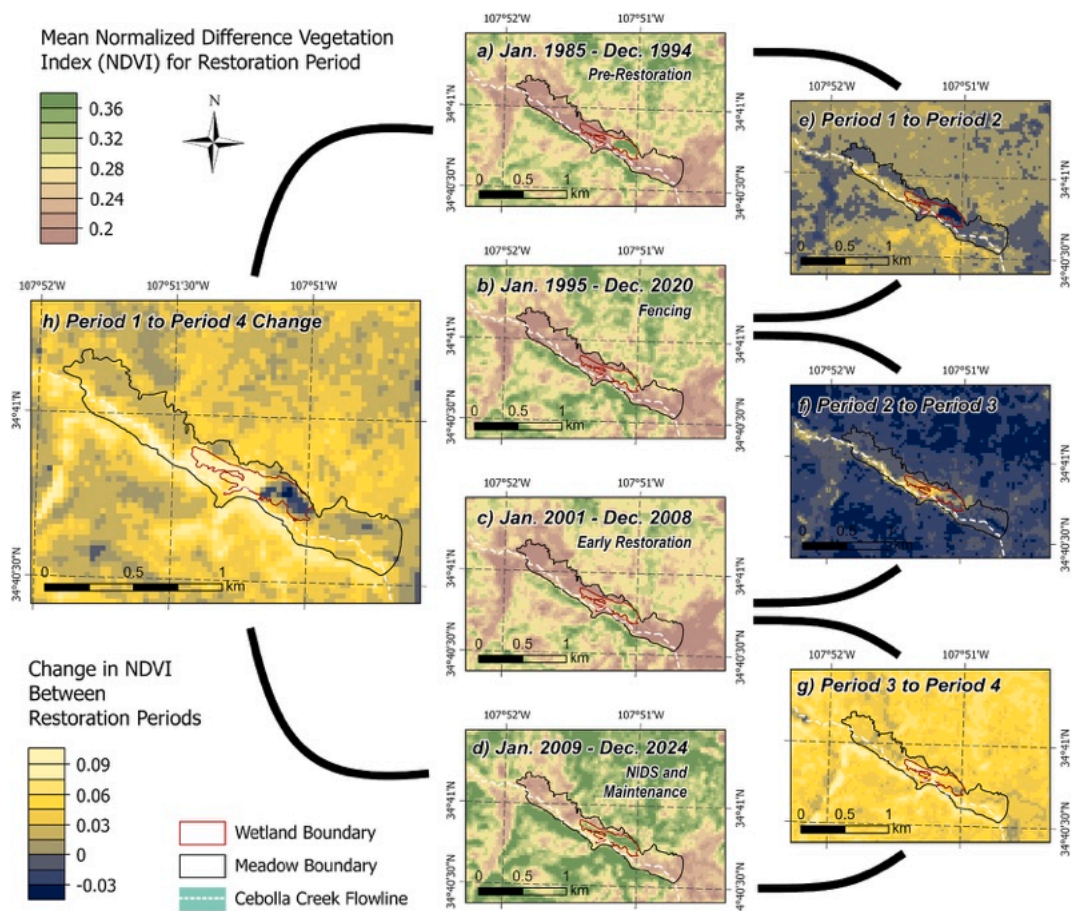


Fig. 9. Showing the spatially explicit mean Normalized Difference Vegetation Index (NDVI) value across all months within (a) Period 1 (i.e., Jan. 1985 – Dec. 1994), (b) Period 2 (i.e., Jan. 1995 – Dec. 2000), (c) Period 3 (i.e., Jan. 2001 – Dec. 2008), and (d) Period 4 (i.e., Jan. 2009 – Dec. 2024), in addition to the change in NDVI from (e) Period 1 to Period 2, (f) Period 2 to Period 3, (g) Period 3 to Period 4, and (h) Period 1 to Period 4.

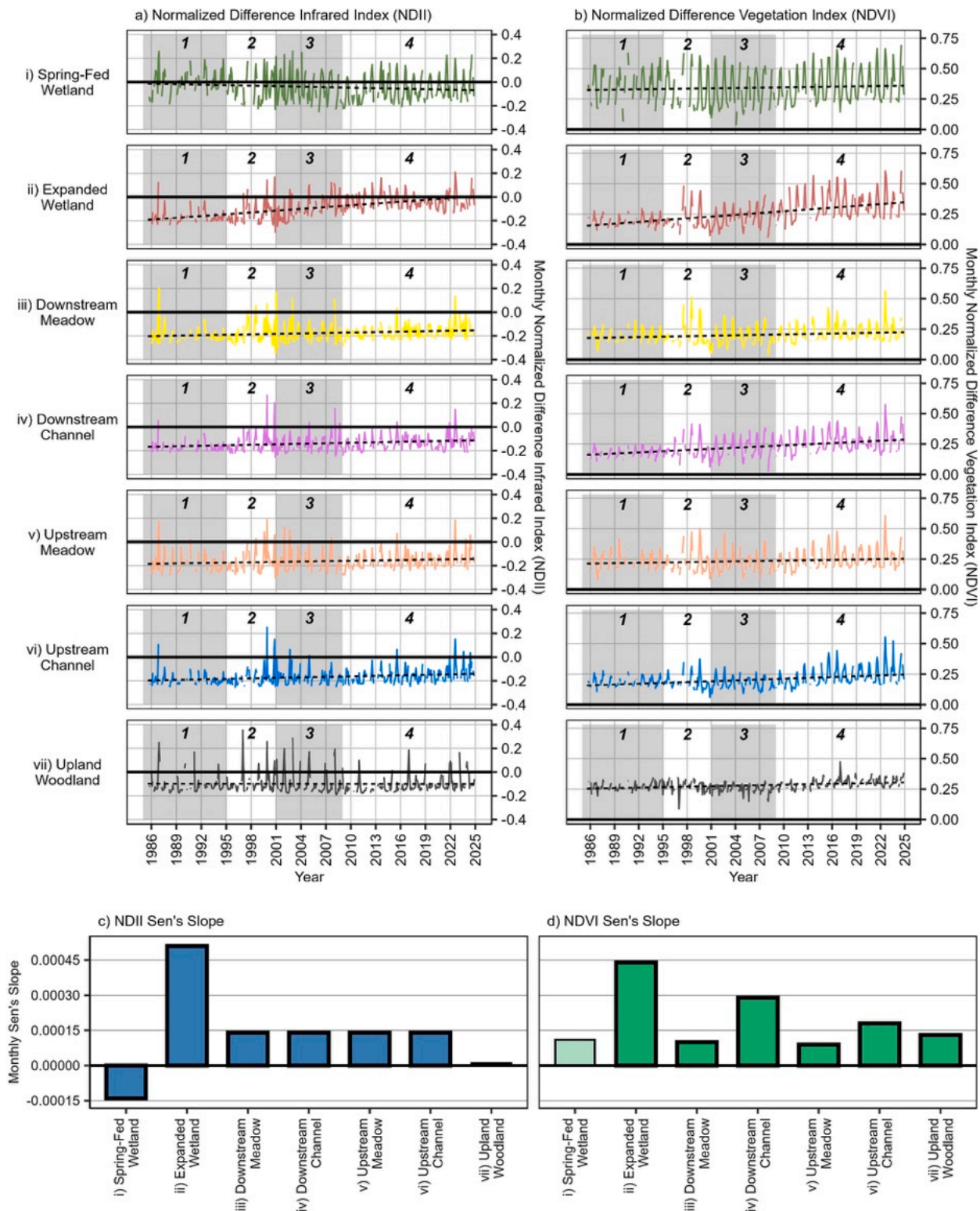


Fig. 10. Showing the time series of (a) the Normalized Difference Infrared Index (NDII) and (b) the Normalized Difference Vegetation Index (NDVI) for each seven subregions with a linear regression slope as a visual aid. Linear Sen's slope values are shown for (c) NDII and (d) NDVI, with significant slopes (i.e., p-value < 0.05) shown without transparency.

3.2. Management Period Analysis

At the Malpais Lava Flow RAWs Station site, increasing, but insignificant, linear Sen's slopes were documented for precipitation across each of the four unique management periods, despite an overall declining linear Sen's slope over the full study period. However, the monthly mean precipitation value declined from 2.72 cm in the Pre-Restoration period 1 to 2.11 cm in NIDS and Maintenance period (i.e., Fencing Period: 2.66 cm, Early Restoration: 2.31 cm), showing an overall decline in total precipitation.

We identified spatially and temporally explicit changes in the mean NDII and NDVI values within the Cebolla Creek wet meadow, which corresponded with shifts in management practices aimed at achieving specific restoration objectives. We highlight results associated with the six subregions within the meadow, which illustrate direct and offset effects of the restoration interventions.

A small blue (i.e., NDII; Fig. 8a) and green (i.e., NDVI; Fig. 9a) area within the wetland boundary for the Pre-Restoration period (i.

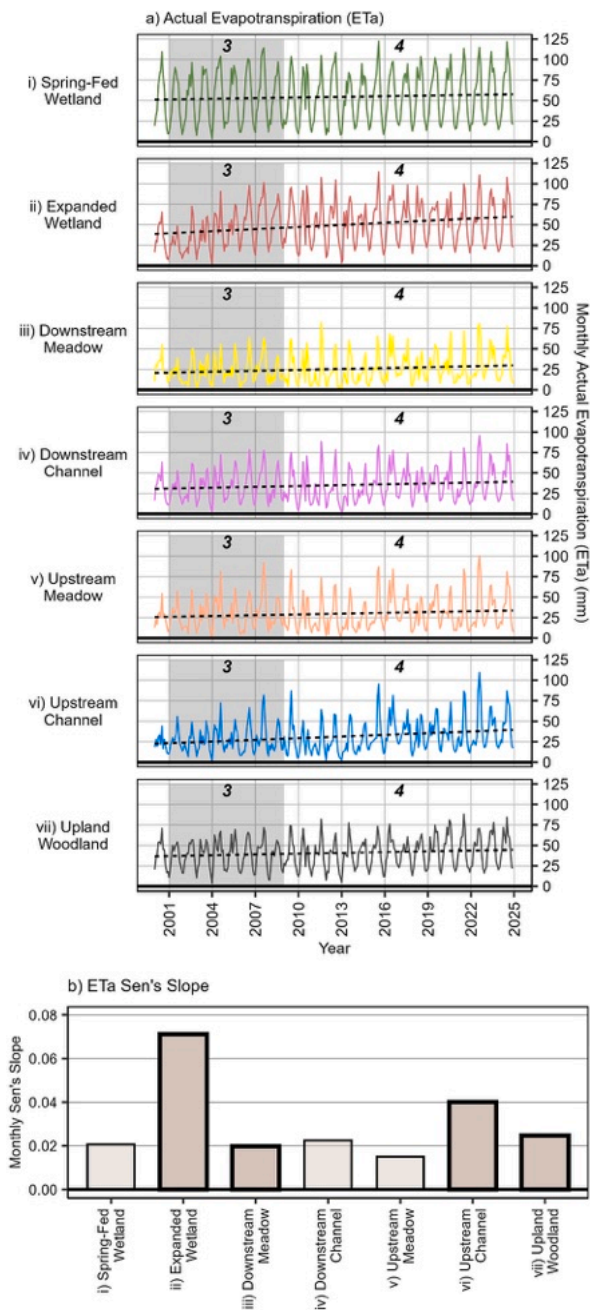


Fig. 11. Showing the time series of (a) actual evapotranspiration (ETa) for each seven subregions with a linear regression slope as a visual aid. Linear Sen's slope values are shown for (b) ETa, with significant slopes (i.e., p-value <0.05) shown without transparency.

e., 1985 to 1994) represents the Spring-Fed Wetland site. When mapping the difference between period 1 and 2 (1995 to 2000) mean values, a relatively substantial decline was documented for NDII (Fig. 8e) throughout the Spring-Fed Wetland, largely greater than -0.04 change in mean NDII and by as much as -0.13 . NDVI was similar at that site, with declines largely by greater than -0.03 and by as much as -0.1 (Fig. 9e). The Spring-Fed Wetland site experienced negative change values between periods 2 and 3 (i.e., 2001 to 2008) in NDII (Fig. 8f), and NDVI (Fig. 9f). From periods 3 to 4 (i.e., 2009 to 2024), NDII declined slightly at the Spring-Fed Wetland site (Fig. 8g) while NDVI increased widely throughout the wetland meadow (Fig. 9g). Overall, from period 1 to period 4, the Spring-Fed Wetland declined by roughly -0.02 and as high -0.06 in NDVI (Fig. 9h) and at a greater rate in NDII, widely by greater than -0.04 and by as much as -0.17 (Fig. 8h). These declines are likely driven by movement of water fed from the natural spring downstream, culminating in less water detained directly at the spring-fed wetland source.

Coupled with decline metrics across the Spring-Fed Wetland area, the Expanded Wetland increased in both NDII and NDVI across all four periods. However, both metrics initially increased along the southern portion of the Expanded Wetland, primarily from period 1 through period 2 following fencing at the site (Fig. 8e/9e). Later, from period 2 to period 3, increasing NDII (Fig. 8f) and NDVI (Fig. 9f) within the Expanded Wetland occurred within the northern portion of the subregion, highlighting the potential of lateral surface and subsurface water flow away from the Cebolla Creek channel and along the historical flow regime tied to early restoration. Generally, NDII increased at a greater rate than NDVI in this direction, supporting the lateral spread of wetness prior to ingrowth of greenness. However, from period 3 to period 4, we observed an expansive and intensive increase in both metrics to along the historical flow regime, parallel to the channel (Fig. 8g and 9g). Overall, this site showed an expansion of the wetland area following restoration applications applied throughout the study period. This result aligns with observations made in McGraw (2014), in which it was documented that the saturated zone associated with the Cebolla Spring has expanded downstream along the first terrace adjacent to Cebolla Creek.

Other areas of change include within the Downstream Channel subregion, which experienced a wide increase in NDVI from period 2 to period 3 (Fig. 9f) into the Early Restoration period, signifying an increase in vegetation cover. This result suggests that areas beyond the active wetland site (i.e., Spring-Fed Wetland, Expanded Wetland) benefited from restoration efforts. A lesser increase in NDVI was observed along the Upstream Channel, particularly from periods 3 to 4 (Fig. 9g) because of NIDS and Maintenance.

Both the Downstream and Upstream Meadows experienced change in NDII (Fig. 8) and NDVI (Fig. 9) from period to period that largely aligned with conditions observed in the upland regions. However, both subregions experienced increased NDII and NDVI across the study period overall.

3.3. Subregion vegetation metric time series

The six subregions (Fig. 3) exhibited differences in their respective time series of NDII (Fig. 10a), NDVI (Fig. 10b), and ETa (Fig. 11a) across the study period in response to management applications. For instance, the Expanded Wetland experienced the largest increase in for all metrics, including NDII – with a significant monthly linear Sen's slope of 0.00051 (Fig. 10c), NDVI – with a significant monthly linear Sen's slope of 0.00044 (Fig. 10d), and ETa – with a significant monthly linear Sen's slope of 0.071 mm/month, which is equal to an increase of 0.245 (NDII) and 0.211 (NDVI) over the 480-month (i.e., 40-year) study period, and 21.3 mm (ETa) over the 300-month (i.e., 25-year) period of data availability for ETa. For ETa, the largest increase occurred primarily between 2000 (i.e., the first year with data availability) and 2006, occurring during the Early Restoration period. Following 2006, the ETa time series remained relatively stable and aligned more directly with the ETa time series of the Spring-Fed Wetland. A similar temporal pattern was documented for NDII after 2000, though NDVI increased more substantially from 2008 through 2013 implying a delayed response in increased greenness for the Expanded Wetland during the NIDS and Maintenance period.

In contrast, the Spring-Fed Wetland experienced a significant decline in NDII (i.e., slope = -0.00014 ; 480-month total = -0.067), and though linear Sen's slopes for NDVI and ETa were positive, they were insignificant (i.e., p -value > 0.05). These results show that the Spring-Fed Wetland became drier over the study period but experienced no significant change in NDVI or ETa.

The Downstream and Upstream Meadow subregions had similar temporal trends in addition to similar significantly increasing slope values for both the vegetation metrics and for the Downstream Meadow for ETa. However, the monthly linear Sen's slope values for the Downstream Meadow were higher than or equal to the Upstream Meadow slope values for all metrics (i.e., NDVI: 0.0001 vs. 0.00009; NDII: 0.00014 vs. 0.00014; ETa: 0.021 vs. insignificant 0.015).

Greater variability was present within the Downstream and Upstream Channel subregions. For instance, monthly linear Sen's slopes were larger for NDVI than NDII (Downstream Channel – NDVI slope = 0.00029, NDII slope = 0.00014; Upstream Channel NDVI = 0.00018, NDII = 0.0014) (Fig. 10), resulting in a greater increase in greenness compared to wetness over the study period. This difference was more substantial for the Downstream Channel than the Upstream Channel. However, for ETa, the Upstream Channel has a much higher and significant monthly linear Sen's slope (i.e., Upstream ETa slope = 0.040) compared to the Downstream Channel, which had an insignificant increasing slope (Fig. 11). This contrast was driven by high ETa years in the Upstream Channel, including in 2004, 2007, 2009, 2015, and 2021–2022, which were not present in the greenness and wetness metrics.

The timing of wetness and greenness peak events highlights differences in the subregions. For instance, during the Fencing Period (i.e., 1995 to 2000), an increase in peak greenness and wetness is observed across all subregions except the Spring-Fed Wetland and the Upland Woodland (Fig. 10a and b). The exclusion of these two sites, which were respectively previously wetter and greener and disconnected from the meadow, depicts the effectiveness of fencing on the restoration subregions. Furthermore, this event was less extreme in the Meadow subregions compared to the Channel subregions and Expanded Wetland, perhaps due to the proximity to the flowline channel and Spring-Fed Wetland water source.

Additionally, changes in seasonal variability are observed within the time series, with many changes occurring during the Fencing

and NIDS and Maintenance (i.e., 2009 to 2024) management periods (Fig. 10a and b). For instance, a greater range in the within-year seasonality (i.e., winter to summer) was observed for several of the subregions beginning in the Fencing Period, including for the Expanded Wetland, Downstream Meadow, Downstream Channel, Upstream Meadow, and Upstream Channel. This pattern became slightly muted during the Early Restoration period (i.e., 2001 to 2008) before increasing again in intensity during the NIDS and Maintenance management period. This pattern was more substantial for NDVI compared to NDII.

Similar temporal variability was present within the ETa time series (Fig. 11a). Notably, high slope years between the subregions do not always align, highlighting variability in surface to atmospheric water fluxes between each site. For instance, between 2007 and 2011, the Wetland subregions have greater year-to-year consistency, though peak values decline slightly for the Spring-Fed Wetland and increase for the Expanded Wetland. Similarly, the Upstream Meadow and Channel have lower values in 2008 and 2010 in addition to diverging peak values in 2007 and 2009. These differences are likely driven by discrepancies in vegetation cover and surface and subsurface water flows between the subregions.

3.4. Statistical analysis of metrics influencing evapotranspiration

Pearson correlation estimates between monthly actual evapotranspiration (ETa) and monthly precipitation (Table 2a), NDII (Table 2b), and NDVI (Table 2c) for each subregion show that ETa was most highly correlated with NDVI across all subregions, except the Upland Woodland. In general, higher correlations with NDVI show that ETa was responsive to greenness over wetness and precipitation input. For NDVI, correlations were strongest for the Upstream Meadow and Channel subregions (i.e., correlation value = 0.744, 0.759, respectively) compared to the Downstream Meadow and Channel subregions (i.e., 0.711, 0.664, respectively) and Expanded Wetland (i.e., 0.593). The Spring-Fed Wetland had a higher correlation estimate (i.e., 0.667) compared to the Expanded Wetland, showing that ETa was generally more responsive to greenness conditions in the original wetland subregion while ETa was least responsive to greenness in the Expanded Wetland. Meanwhile, the Upland Woodland site had the only insignificant correlation.

Correlations between ETa and NDII were also stronger for the Upstream Meadow and Channel subregions (i.e., 0.489, 0.466, respectively) compared to the Downstream Meadow and Channel subregions (i.e., 0.396, 0.326, respectively), though lower than for NDVI. Unlike NDVI, the Spring-Fed Wetland had the highest correlation for NDII (i.e., 0.494) implying that ETa was also responsive to vegetation and soil moisture. In general, the downstream subregions had greater reductions in their correlation estimates from NDVI to NDII compared to the upstream regions, suggesting that ETa was generally more responsive to greenness than wetness below the Spring-Fed Wetland. For precipitation, correlations estimates were lowest for the Spring-Fed Wetland, Expanded Wetland, and Upland Woodland, implying that ETa was less responsive to precipitation input.

3.5. Change in monthly conditions

Monthly time series indicate changes of mean NDII (Fig. 12), NDVI (Fig. 13), and ETa (Fig. 14) across the six subregions over the 40-year period following applications of restoration. We document the notable examples here. The Expanded Wetland has significant increases for nearly all months for NDII and NDVI, only excluding December for NDII, and had significant (i.e., p -value < 0.05) increasing slopes for the spring and early summer months for ETa. Thus, following restoration applications, the Expanded Wetland became greener and wetter over the study period, with the most substantial changes occurring from July through September aligning with the monsoon-driven system. Significant increasing slopes were also documented for nearly all months for NDVI for both the Downstream and Upstream Channels (Fig. 11), only excluding March and May for the Upstream Channel, implying year-round increasing greenness at these subregions. Furthermore, significant, increasing slopes for NDII for both Channel subregions extended throughout the monsoon season, including through October for the Downstream Meadow and through September for the Upstream Meadow (Fig. 13), signifying enhanced saturation later in the year. This is likely a result of monsoon-driven flows along the channel and increased spread of groundwater.

Second, the Spring-Fed Wetland had significant decreasing slopes during the early-summer (i.e., May, June) for NDII (Fig. 12), showing that the subregion lost moisture content during the drier months as the wetland expands into the Expanded Wetland and with lateral subsurface and surface flows. Subsequently, though moisture is not significantly increasing during these months, the Spring-Fed Wetland is increasing in greenness throughout the winter months (i.e., November through February) (Fig. 13), and for December in ETa (Fig. 14). This aligns with insignificant declines in NDII during these months, where areas previously filled with water may be

Table 2

Listing Pearson correlation estimates between monthly actual evapotranspiration (ETa) and monthly (a) precipitation, (b) Normalized Difference Infrared Index (NDII), and (c) Normalized Difference Vegetation Index (NDVI) for each subregion. Significant correlations (i.e., p -value < 0.05) are identified using “*”.

Subregion	a) Precipitation Correlation Estimate	b) NDII Correlation Estimate	c) NDVI Correlation Estimate
i) Spring-Fed Wetland	0.401*	0.494*	0.667*
ii) Expanded Wetland	0.417*	0.308*	0.593*
iii) Downstream Meadow	0.588*	0.396*	0.711*
iv) Downstream Channel	0.524*	0.326*	0.664*
v) Upstream Meadow	0.564*	0.489*	0.744*
vi) Upstream Channel	0.536*	0.466*	0.759*
vii) Upland Woodland	0.425*	-0.508*	-0.081

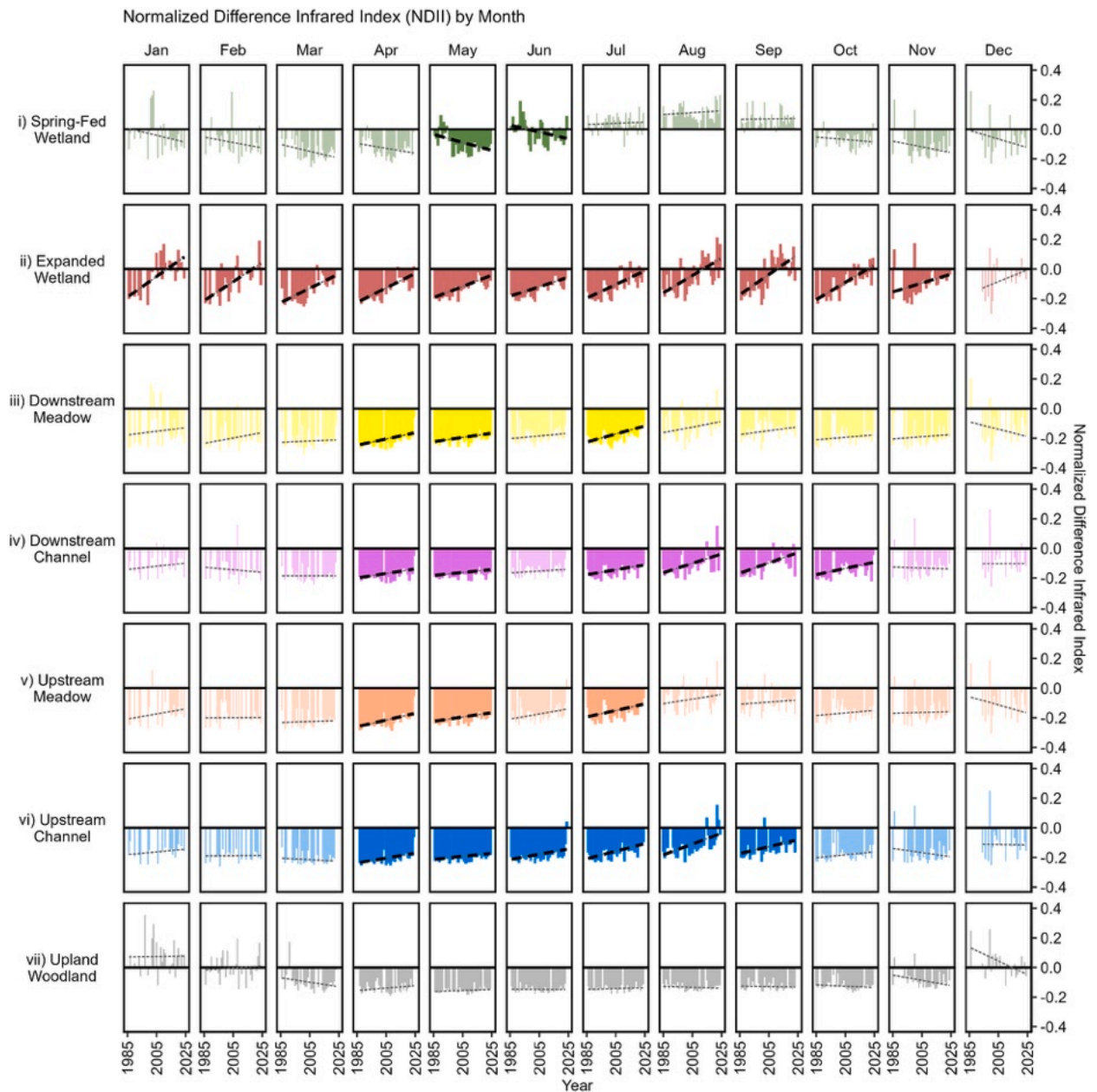


Fig. 12. Showing the monthly Normalized Difference Infrared Index (NDII) value for each subregion from 1985 to 2024. Linear regression slope lines are shown as a visual aid. Months with insignificant Sen's slope value (p -value > 0.05) are shown at 55% transparency.

filling with vegetation cover.

Other notable monthly observations show the effect of the monsoon season for the overall wetland and larger meadow. For example, (i) following restoration applications, the general wetland has more capacity to store monsoon-driven precipitation and supporting increased vegetation growth as a result, highlighted by higher slope values generally from August through October in the Expanded Wetland and both the Downstream and Upstream Channel subregions for NDII and NDVI. Furthermore, (ii) the Upland Woodland subregion shows a slight, though insignificant, decrease in NDII (i.e., getting drier) but generally stable or slightly increasing NDVI (i.e., getting greener), which implies that increased water availability within the larger meadow could be supporting increased woodland canopy cover, though surface moisture remains stable. This is evidence of increasing groundwater depth supporting woodland root systems. Lastly, (iii) ETa is increasing substantially within the Expanded Wetland and the Upstream Channel in some of the spring and summer months, aligning with increase greenness especially during those months, but also substantially for all class except the Spring-Fed Wetland in July. Thus, aligning as a monsoon-driven system, large surface-to-atmosphere water fluxes are occurring in the early monsoon season throughout the Cebolla Canyon meadow from increased vegetation cover following restoration

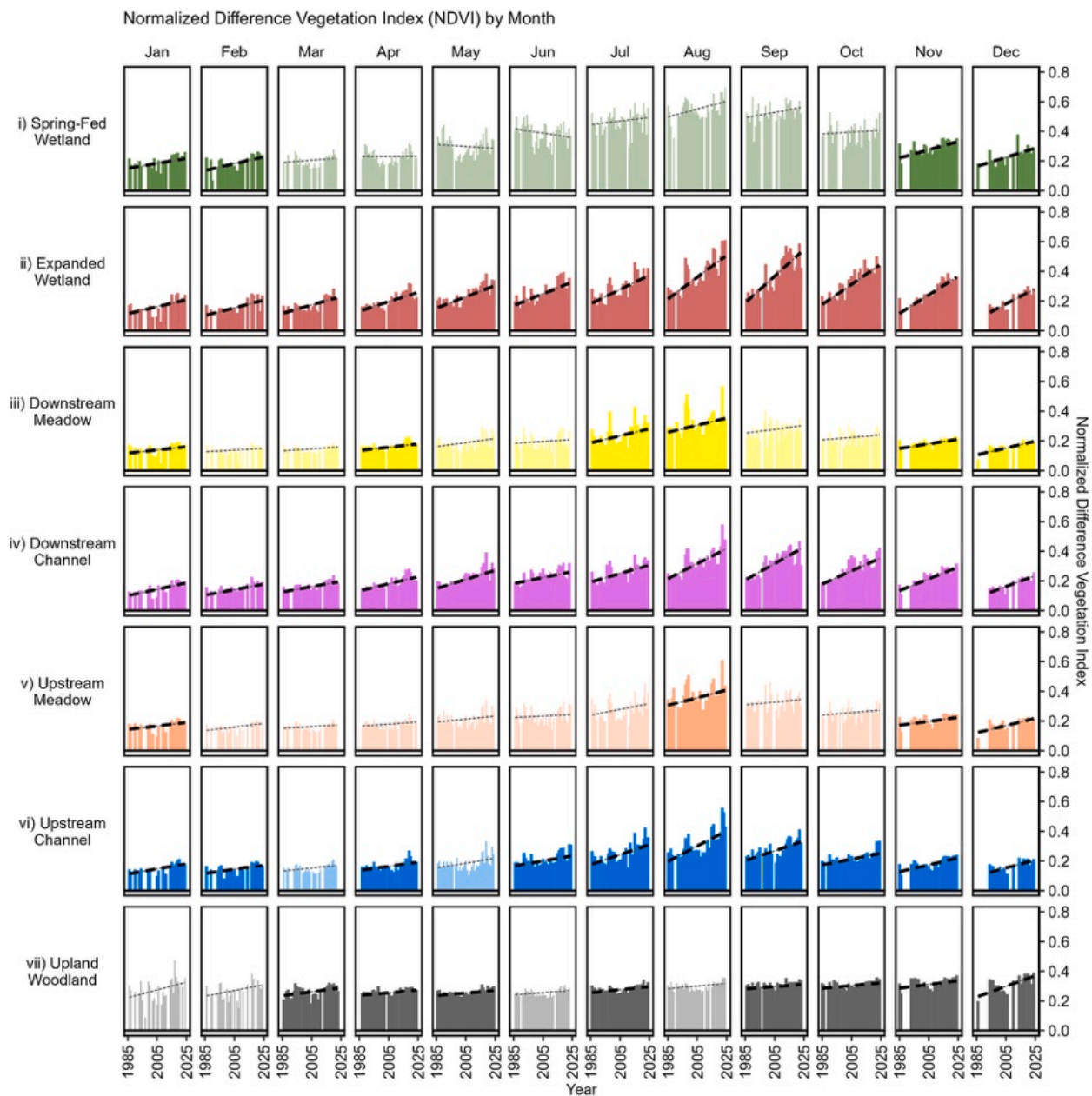


Fig. 13. Showing the monthly Normalized Difference Vegetation Index (NDVI) value for each subregion from 1985 to 2024. Linear regression slope lines are shown as a visual aid. Months with insignificant Sen's slope value (p -value > 0.05) are shown at 55% transparency.

applications, and these fluxes may help to develop a more localized water cycle and support retaining more moisture in the immediate atmosphere.

4. Discussion

This study provides a unique and innovative approach to evaluating restoration impacts in arid-region wetlands by leveraging an exceptionally long-term (89-year) aerial and satellite image archive. The integration of historical aerial photography with Landsat time series enables a rare, multi-decadal perspective on hydrological and vegetation dynamics following low-tech restoration interventions. Our methodological framework combines well-established vegetation indices with ET metrics and introduces a subregional analysis that visualizes monthly-scale trends alongside statistical significance testing. This approach not only captures spatial heterogeneity within the wetland system but also demonstrates how restoration outcomes evolve over time despite direct adjacency of treatment areas. By coupling NIDS restoration assessment with remote sensing techniques in this way, the study offers a replicable model for

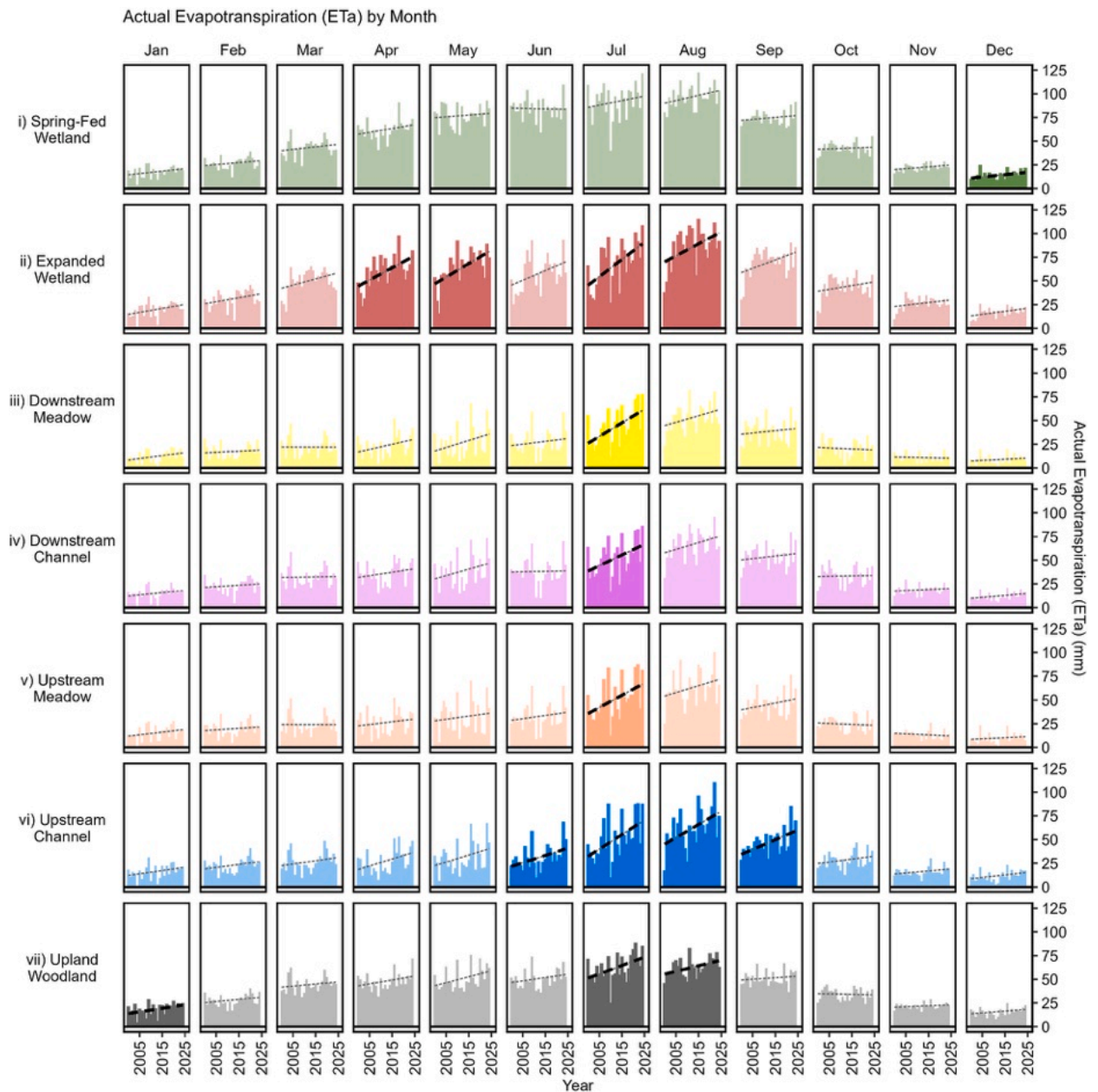


Fig. 14. Showing the monthly Actual Evapotranspiration (ETa) value for each subregion from 1985 to 2024. Linear regression slope lines are shown as a visual aid. Months with insignificant Sen's slope value (p -value >0.05) are shown at 55% transparency.

monitoring and evaluating nature-based solutions in dryland ecosystems globally, where long-term datasets and restoration evaluations are often lacking.

4.1. Restoration implications on structural design

Through the careful study of the historical and current wetland conditions, a plan was enacted to restore an abandoned agricultural homestead from the 1930s by installing simple, natural infrastructure - including rock structures - covering an area extending approximately 11.2 km along Cebolla Creek channel to slow irrigation drainage and detain water within the larger meadow for extended periods of time (McGraw, 2014). Early restoration applications began in 1994 with the placement of fencing enclosure around the spring-fed wetland, followed by periods of intensive placement of rock detention structures and Zuni bowls, and extended maintenance through present day. This study focused specifically on the spring-fed slope wetland site and the area immediately surrounding it to assess how management activities directly affected the greenness and wetness conditions of this primary water

source.

Numerous prior studies provide examples of the successful development of wetland ecosystems through restoration activities, including at prior agricultural sites, similar to the Cebolla Creek wetland (Moreno et al., 2007; Surasinghe et al., 2025). Our imagery-based analysis shows that following restoration efforts, the overall area of the Spring-Fed Wetland expanded through the Expanded Wetland and increased greenness and wetness conditions within the wetland area and within areas upstream and downstream of the Spring-Fed Wetland. As intended in the originally developed plan, following restoration application, water detention increased, water spread laterally throughout the Cebolla Canyon meadow, surface velocities were reduced, and more extensive wetland habitat and vegetation became established. Following intentional placement of structures through incised channels, flow was deviated to reconnect natural flow to the historical flow regime. We refer to this as the Cebolla Spring Restoration Feedback Loop, which applies the 'Zeedyk Approach' (Fig. 1), a four-phase feedback loop to counter negative effects of intense agriculture and irrigation-based management using natural infrastructure to re-establish the historical flow regime.

Additionally, the geomorphic and hydrologic properties of the site changed following restoration application, including flattening the gradient of the land surface and increasing water infiltration, with expectations of increased potential for emergent wetland plant species and improved bank stability (McGraw, 2014). This has resulted in potential for expansion of the wetland in the Upstream Meadow subregion. Though this subregion experienced an increase in greenness and wetness, no formal wetland expansion was observed during our study period.

Notably, sedimentation in the channel, sourced from upstream erosion, is likely impacting vegetation response, where filling the incised channel increases lateral surface and ground water spread (Norman et al., 2019). Though not directly quantified throughout this study, this result challenges the "start at the top and work down" approach that is often favored and employed by restoration practitioners (Laura M. Norman et al., 2021a; Laura M. Norman et al., 2021b), but supports results found on the Arizona-Sonora border at Cienega San Bernardino where restoration using large rock gabion NIDS occurred in downstream floodplains, trapping sediment and supporting vegetation greenness and wetness despite drought conditions (L. M. Norman et al., 2014a; L. M. Norman et al., 2014b; Wilson and Norman, 2018). The restoration of the spring-fed slope wetland and associated flow channels likely helped to retain *upstream* sediment—that would not have arrived if a "start at the top and work down" approach had been applied. This shows that starting from the bottom-up can provide benefits such as increased sediment retention (but still does not fix the upstream issues).

Results of restoration are dependent on place-based variables (i.e., soil, geology, location in watershed), but also anthropogenic impacts (e.g., NIDS and farms) and climate variables (i.e., amount and intensity of precipitation), making analysis of their success also dependent on such outside variables. We recognize that this lag and dependency sometimes dissuade critics from accepting attributed results due to the lack of immediate gratification. Our findings indicate that over time, process-based restoration using NIDS help reverse degradation and support rewetting processes.

This application of NIDS has global generalizability due to its location as a semi-arid landscape, an ecological region that cover ~15% of the global surface and is expanding in recent decades (Huang et al., 2016). Studies have shown that NIDS and other nature based solutions (NBS) have had positive societal and environmental impacts in arid and semi-arid regions, such as across sites in Africa (Okello et al., 2024), the Mulloon Creek in Australia (Hickson, 2017), the Hamedan Province in Iran (Moazeni et al., 2025), and the Loess Plateau in China (Guo et al., 2022). Lessons learned here may be applied elsewhere.

4.2. Associations with remote sensing vegetation metrics

Lateral movement of surface water and ground water was documented following restoration at the Cebolla Creek meadow by restoration managers (McGraw, 2014; McGraw and Johnson, 2013). Our remote sensing vegetation metrics and ETa estimates provide detailed information about the explicit temporal and spatial results following restoration application. For instance, we observed wetting along the Upstream Channel, beginning during the late Fencing period and extending into the Early Restoration period, followed by increased greenness later, primarily during the NIDS and Maintenance period. We also observed wetness and greenness seasonally within the Expanded Wetland and transitioning to the historical flow regime. The time series analysis shows explicit rate of change locally within the meadow but also highlights years with distinctive variability between subregions, such as 2007 with variable peaks in NDII, NDVI, and ETa. Lastly, the documentation of change in seasonality showed that NDII, NDVI, and ETa values for the Expanded Wetland temporal signature had reached or were nearing the values for the Spring-Fed Wetland, essentially resulting in the doubling of the Spring-Fed Wetland system by the end of the study periods (i.e., Spring-Fed Wetland area = 3.14 ha, Expanded Wetland area = 2.98 ha, combined area = 6.13 ha). Similar comparisons could be made across subregions. We attribute the reduction in the decline of NDII and NDVI at the Spring-Fed Wetland to increased lateral flows away from it, infiltration and percolation to the groundwater table, and declining precipitation (Fig. 4a).

Evapotranspiration is difficult to quantify but has been documented to result greater than 90% of precipitation returned to the atmosphere in arid lands (Reitz et al., 2017) through transpiration from plants and evaporation from the soil, water surfaces, and plant interception (Petrakis et al., 2024). At locations without monitoring equipment to quantify ETa, including its subparts transpiration and evaporation, estimates are dependent on satellite-based products such as OpenET, emphasizing the need for expanded capabilities of ETa. At the Brushy Mountain RAWS site, annual ETa calculated from OpenET averaged 140% of annual precipitation from 2000 through 2024, suggesting that evaporation and transpiration occur continuously despite periodic lack of rainfall. At the Spring-Fed Wetland, this comparative relationship was as high as 151.6% of precipitation to ETa. Higher precipitation to ETa ratios are seasonal, in which ETa increases during the growing season (i.e., March through June) when conditions are typically dry and warming. In areas where groundwater pumping is occurring, such as a wet meadow in an arid intermountain basin in Colorado, U.S., that could also influence water-table depth (Sanderson and Cooper, 2008), though we have no record of this in Cebolla Canyon. Thus, within a

spring-fed wetland ecosystem and monsoon driven wetland system, quantifying ETa, and furthermore its subparts, is critical for a robust understanding of water budget components.

Stronger correlations between ETa and NDVI compared to ETa with NDII and precipitation suggest that the Cebolla Creek meadow is more responsive to plant photosynthetic activity and transpiration. Though the strength of this relationship varied throughout the meadow depending on the location within it. For instance, the Expanded Wetland had the weakest correlation with both NDII and NDVI, suggesting a more independent relationship, perhaps driven by sub-monthly factors and precise timing of surface water. The Upstream Meadow and Channel subregions had higher correlations compared to the other subregions, which may be a result of location upstream of flow directionality from the Spring-Fed Wetland. Other factors such as rising temperatures (Fig. 4C), increasing potential ETa, or carbon dioxide (CO₂) fertilization tied to plant growth, driving lower ETa, may also influence these relationships (Allen, 2000; Liu et al., 2025).

4.3. Problems and challenges

Semi-arid alluvial wetland ecosystems can be challenging to restore due to factors including hydrologic characteristics, unpredictable environmental conditions, and human activity (Acreman et al., 2007; Hollis, 1990). Monitoring equipment placement, plan design, and implementation, including permitting, is essential to support restoration projects using NIDS for future generations and acceptance (Norman et al., 2022a). The full Cebolla Creek Canyon project experienced all these challenges. For instance, the Environmental Assessment for the project area took more time than anticipated to complete. Furthermore, flood events and trespassing cattle resulted in impacts on hydrologic monitoring equipment including data loggers and piezometers (Soles, 2011); the removal of cattle from the project area substantially increased project achievement (McGraw, 2014). Downstream from the spring-fed wetland study site, a huge side gully put in a head cut structure in 2009 (Fig. 2a; Reach 6), but a big flood destroyed the Zuni bowl, allowing a head cut to advance up valley, which is a high priority for treatment.

Furthermore, about 3 miles down valley from the Spring-Fed Wetland (Fig. 2a; Reach 7), the gully is about ~10 to 15 m deep, and treatments were issued there from 2006 to 2009 to build baffles using pickets (Juniper posts) driven into ground to deliberately route water into high banks, where sediment is mostly clay, for about a mile. Visual results depicted flows undercutting high banks and collapsing them allowing sediment to accumulate in new meanders and raising the bed of the channel by about 1.2 m. Land managers became concerned with this “intentional disturbance” and the project was discontinued, but this innovative methodology might be important for future project development as gullies in the arid southwest become radically entrenched.

4.4. Future remote sensing capacity for wetland monitoring

This study used a comprehensive suite of over 1200 monthly composite images covering 40 years to monitor spatial and temporal changes in the condition of the spring-fed wetland meadow in response to restoration management. Landsat is the only sensor to offer the temporal compatibility required for this study (i.e., 40+ years) with a relatively high-to-medium spatial resolution (i.e., 30-m). Other sensors such as the Sentinel-2 series provide improved spatial and temporal resolution (i.e., 10-m, 5-day) and have been widely used for land cover/use monitoring (Phiri et al., 2020), but have only collected data since 2015 (ESA, 2025). Similarly, commercial institutions are expanding capacity to monitor landscape changes with high spatial resolutions (i.e., sub-meter) using “smallsats”, but the data are not always analysis-ready (Frazier and Hemingway, 2021). Lastly, efforts such as Landsat-Sentinel-2 hybridization offer improvements in temporal resolution (Berra et al., 2024) but similarly lack the longevity of imagery available through Landsat. Thus, the Landsat suite was the most appropriate product for the objectives stated in this study.

Several products have been developed to map continuous or near-continuous wetland and small waterbody extent, including the Dynamic Surface Water Extent (DSWE) and similar derivative products (Jones, 2019; Soulard et al., 2020, 2024; Vanderhoof et al., 2020), with varied success depending on factors including environmental conditions (i.e., clouds), vegetation cover, and the size of the wetland, among others (McKenna et al., 2025; Soulard et al., 2020). A similar approach could be applied here to map more continuous areal extent of the wetland both throughout the year or in years without aerial imagery, in addition to application for similar semi-arid, spring-fed wetland ecosystems.

In this study, we effectively utilize an ensemble, satellite-based, continuous estimate of ETa to quantify relationships with greenness and wetness time series, based on a spatial division. However, varied results showing correlations and trends with the vegetation indices suggest that partitioning ETa by its subparts (i.e., transpiration, evaporation) can better inform on how water fluxes vary based on vegetation cover and water content (Booth and Lohse, 2010; Eichelmann et al., 2022). Thus, quantifying water lost to the atmosphere partitioned through evaporation and transpiration tied to restoration can better quantify direct impact of factors such as increasing lateral surface and sub-surface water flows and changing vegetation cover and type.

5. Conclusion

This study highlights the degradation of globally important wetland ecosystems—such as ciénegas and wet meadows—due to stream incision, groundwater extraction, and drought, especially in arid regions. We describe the ‘Zeedyk approach’, using investigative site descriptions to identify degradation causes, and nature-based solutions to restore landscapes, including natural infrastructure such as rock detention structures, to slow water, raise water tables, and restore wetland function. Vegetation and land use of Cebolla Canyon, New Mexico, USA, has been gradually shaped by thousands of years of human occupation. More recent agricultural and grazing activities in the 20th Century resulted in the degradation of a spring-fed wetland ecosystem, reduced in size and re-

channeled from its natural drainage through incised head cuts.

This paper describes research using a 40-year collection of satellite imagery and remote sensing analyses to derive vegetation index products and quantify efficacy of restoration efforts, paired with aerial imagery covering a period of 89 years (i.e., 1935-2024) to map wetland areal extent across four management periods. Our earliest imagery, from 1935, illustrates the original extent of the wetland and historical flow regime. We document the decrease in wetland size and disconnected floodplain incurred from homesteaders in the Dust Bowl era over ~55 years. The analysis further quantifies impacts of restoration efforts beginning in the 1990's, finding the spring-fed wetland more than doubled in spatial extent and moving surface flow towards what was believed to be the historical flow regime. Results indicate that restoration using the Zeedyk approach promotes re-wetting of valley bottoms, widening of stream banks, and aggradation of channel beds—restoring this wilderness area toward its natural condition as a perennial, functioning, and diverse wetland, highlighting increased ecosystem resilience over several decades.

A spatial analysis using remote sensing wetness (e.g., NDII) and greenness (e.g., NDVI) from indices over time show temporal shifts in vegetation greenness and wetness following restoration interventions. Specifically, the Spring-Fed Wetland subregion exhibits a reduction in wetness and greenness while areas to the south and west show increasing values, indicating lateral expansion of the wetland. Furthermore, areas beyond the primary wetland, including the Downstream and Upstream Channel subregions, also demonstrate rising wetness and greenness metrics, suggesting restoration effects extended beyond the actively managed site. These spatially explicit results highlight varied responses and a trending lateral spread of wetness and increased greenness.

Time series analyses of the vegetation metrics at each of these subregions show the comparative rate of change, depicting the significantly higher slope values (change) for the Expanded Wetland for NDII, NDVI, and ETa. Overall, the Expanded Wetland subregion experienced ~3.6x higher wetness and a ~1.5x greenness slope compared to adjacent landscapes over time. Correlations between ETa – as a response variable tied to changes in plant transpiration and soil and water evaporation – with wetness, greenness, and precipitation showed that plant growth may be more substantially driving ETa response. ETa increased significantly during July and within the Expanded Wetland and Upstream Channel throughout the spring and summer months where increased greenness was documented and when temperatures are highest.

This study applied a comprehensive monthly quantification using satellite imagery to assess monthly variability of the vegetation metrics. We found that the Expanded Wetland and areas Upstream and Downstream had year-round significant increases in greenness following implementation of the 'Zeedyk approach' to restoration using NIDS, particularly for the summer months that likely showed enhanced spread of monsoonal rainfall and associated increase in year-round vegetation growth. Declining wetness in the spring months for the Spring-Fed Wetland indicated overall loss of moisture content during the drier conditions, likely fueled by the lateral spread and redistribution of subsurface water.

This study uses cloud-based platforms like Google Earth Engine and USGS EarthExplorer to access and analyze decades of satellite and aerial imagery for monitoring effects of wetland restoration. Metrics help assess how the 'Zeedyk approach' to restoration using simple interventions influence plant health and water availability over time and offer a scalable method for evaluating restoration impacts in arid to semi-arid wetlands.

Disclaimers

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

CRedit authorship contribution statement

Roy E. Petrakis: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Laura M. Norman:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Maryann McGraw:** Writing – review & editing, Resources. **Steve Carson:** Writing – review & editing, Resources. **Craig Sponholtz:** Writing – review & editing, Resources. **Cameron Weber:** Writing – review & editing, Resources. **William D. Zeedyk:** Writing – review & editing, Resources.

Declaration of competing Interest

I have nothing to declare.

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Data availability

The data is published in the U.S. Geological Survey ScienceBase Data Repository and a link to the data release is included in the manuscript.

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