Central Valley Landscape Conservation Project

Climate Change Vulnerability Assessment (January 2017 version)

Vernal Pools and Swales

Vulnerability Assessment Summary

Overall Vulnerability Score and Components:

Vulnerability Component	Score
Sensitivity	Moderate-high
Exposure	Moderate-high
Adaptive Capacity	Moderate
Vulnerability	**Moderate-high**

Overall vulnerability of vernal pools and swales was scored as moderate-high. The score is the result of moderate-high sensitivity, moderate-high future exposure, and moderate adaptive capacity scores.

Key climate factors for this system include those that can alter vernal pool hydrology, including precipitation timing and amount, drought, and soil moisture.

Key non-climate factors include urban/suburban development, dams, levees, and water diversions, agricultural and rangeland practices, land use change, pollutions and poisons, nutrient loading, invasive and problematic species, and roads, highways, and trails. These factors can fragment and destroy habitat, alter hydrology, and can affect gene flow.

Key disturbance mechanisms are grazing, wildfire, and flooding; all of these factors influence invasive species pressure, and flooding also influences vegetative composition and distribution of native species.

Vernal pools and swales are patchily distributed in the Central Valley, and a majority of historical vernal pool habitat has been lost to agricultural and urban development. Many of the non-climate factors listed above, in addition to energy production and mining, act as landscape barriers, affecting gene flow and dispersal of vernal pool species.

High spatial and topographical diversity amongst vernal pools drives high species diversity, endemism and specialization. Hydrological and ecological diversity between vernal pools and high specialization of component organisms enhances overall habitat resilience to climate change. Vernal pools and swales support a diversity of plant, invertebrate, vertebrate and bird species, but high levels of endemism and increasing habitat fragmentation make component populations vulnerable to extirpation.

Management potential for vernal pools was scored as moderate, and is likely influenced by different agricultural and rangeland modifications (e.g., grazing, wetland mitigation) and regulatory mechanisms (e.g., Endangered Species Act, Clean Water Act).

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Introduction

Description of Priority Natural Resource

Vernal pools and swales are ephemeral wetlands that form in landscape depressions where soil characteristics limit water infiltration. Vernal pools are characterized by a wet period in winter, drying during spring, and complete desiccation during late spring and summer (Marty 2005). Swales connect or feed vernal pools, but typically experience less extensive inundation (U.S. Fish and Wildlife Service 2005).

As part of the Central Valley Landscape Conservation Project, workshop participants identified the vernal pools habitat as a Priority Natural Resource for the Central Valley Landscape Conservation Project in a process that involved two steps: 1) gathering information about the habitat's management importance as indicated by its priority in existing conservation plans and lists, and 2) a workshop with stakeholders to identify the final list of Priority Natural Resources, which includes habitats, species groups, and species.

The rationale for choosing vernal pools and swales as a Priority Natural Resource included the following: the habitat has high management importance, and because vernal pools harbor high endemism, because restoration efforts often fail, and because there is a high threat of conversion. Please see Appendix A: "Priority Natural Resource Selection Methodology" for more information.

Vulnerability Assessment Methodology

During a two-day workshop in October of 2015, 30 experts representing 16 Central Valley resource management organizations assessed the vulnerability of priority natural resources to changes in climate and non-climate factors, and identified the likely resulting pressures, stresses, and benefits (see Appendix B: "Glossary" for terms used in this report). The expert opinions provided by these participants are referenced throughout this document with an endnote indicating its source[1]. To the extent possible, scientific literature was sought out to support expert opinion garnered at the workshop. Literature searches were conducted for factors and resulting pressures that were rated as high or moderate-high, and all pressures, stresses, and benefits identified in the workshop are included in this report. For more information about the vulnerability assessment methodology, please see Appendix C: "Vulnerability Assessment Methods and Application." Projections of climate and non-climate change for the region were researched and are summarized in Appendix D: "Overview of Projected Future Changes in the California Central Valley".

Vulnerability Assessment Details

Climate Factors

Workshop participants scored the resource's sensitivity to climate factors and this score was used to calculate overall sensitivity. Future exposure to climate factors was scored and the overall exposure score used to calculate climate change vulnerability.

Climate Factor	Sensitivity	Future Exposure
Air temperature	Moderate	High
Extreme events: drought	High	High
Increased flooding	-	Moderate
Increased wildfire	-	Moderate
Precipitation (amount)	High	Moderate-high
Precipitation (timing)	High	Moderate
Soil moisture	High	-
Water temperature	Moderate	-
Overall Scores	**Moderate-high**	**Moderate-high**

Drought

Sensitivity: *High (high confidence)*
Future exposure: *High (high confidence)*
Potential refugia: *Large complexes of vernal pools distributed across north-south gradient with diversity in pool depth.*

Compared to the preceding century (1896-1994), drought years in California have occurred twice as often in the last 20 years (1995-2014; Diffenbaugh et al. 2015). The recent drought (2012-2014) has been the most severe drought on record in the Central Valley (Williams et al. 2015), with record accumulated moisture deficits driven by high temperatures and reduced, but not unprecedented, precipitation (Griffin & Anchukaitis 2014; Williams et al. 2015).

Over the coming century, the frequency and severity of drought is expected to increase due to climate change (Hayhoe et al. 2004; Cook et al. 2015; Diffenbaugh et al. 2015; Williams et al. 2015), as warming temperatures exacerbate dry conditions in years with low precipitation, causing more severe droughts than have previously been observed (Cook et al. 2015; Diffenbaugh et al. 2015). Recent studies have found that anthropogenic warming has substantially increased the overall likelihood of extreme California droughts, including decadal and multi-decadal events (Cook et al. 2015; Diffenbaugh et al. 2015; Williams et al. 2015).

Vernal pool species are typically adapted to seasonal drought (Zedler 2003), but drought periods can completely prevent vernal pool ponding, and many pools experience minimal ponding duration in years with below-average precipitation (Bauder 2005). Even small hydroperiod reductions can affect community diversity and habitat suitability for plant and animal species, particularly those with longer aquatic life stages (e.g., California tiger salamanders, western spadefoot toads; Marty 2005).

Precipitation (amount)

Sensitivity: *High (high confidence)*
Future exposure: *Moderate-high (low confidence)*
Potential refugia: *The North Valley.*

Annual rainfall volume increases on a south-north gradient, with higher annual rainfall in the Sacramento Valley than the San Joaquin Valley (Pyke 2005).Although precipitation models for California are highly uncertain, some projections suggest that annual precipitation will remain quite variable over the next century, and may increase slightly in the Sacramento River Basin and decrease slightly in the San Joaquin River Basin by 2050 (Bureau of Reclamation 2015), and precipitation extremes may increase (Toreti et al. 2013).

Total annual rainfall and total seasonal precipitation are positively correlated with the length of pool inundation (Bauder 2005; Pyke & Marty 2005). Precipitation and hydroperiod changes, particularly drying, may alter habitat suitability for a variety of vernal pool obligate species (Pyke & Marty 2005), and may make vernal pools more vulnerable to exotic invasion (Marty 2005). Many common invasive grasses are likely to benefit from drying because they are intolerant of extended inundation and decline with increasing vernal pool water depth (Gerhardt & Collinge 2003). Some invasive species also experience increased growth during high precipitation years (e.g., El Niño; Bauder 2005).

Precipitation (timing)

Sensitivity: *High (high confidence)*
Future exposure: *Moderate (moderate confidence)*

Fall and winter rains drive the “wet” period of the vernal pool hydrologic cycle. Initial rains stimulate plant germination and invertebrate hatching (Zedler 1987), and continued rains result in ponding. As precipitation declines in spring, vernal pools experience slow drying of surface water and substrate, with significant desiccation common by late summer (Zedler 2003).

In conjunction with total annual rainfall, shifts in seasonal precipitation patterns will influence ponding frequency and duration, affecting habitat suitability. For example, in several southern California study sites, high rainfall delivered in discrete periods yielded longer ponding time than the same rainfall volume distributed equally throughout the season in years with average precipitation; however, at the same study sites during years with low annual precipitation, consistent rain favored longer ponding times than discrete, intense rainfall events (Bauder 2005).

Winter precipitation is likely to be a key driver in causing slightly shorter or substantially longer vernal pool inundation periods (Pyke 2004). However, high variability in future precipitation projections for the Central Valley and greater California region will likely result in variable impacts on vernal pool hydrology (Lawler et al. 2010), with impacts fluctuating depending on current pool characteristics and geographical location within the Central Valley (Pyke 2005). For example, larger, deeper pools may show less of a response to precipitation shifts than shallow pools that currently provide marginal habitat; with shifts in precipitation, these latter pools could experience significant increases or decreases in habitat suitability for obligate wildlife (Pyke 2005). Similarly, pools in the southern (severely water-limited) and northern (water-rich) end of the study region may show less response to climate than pools in the central part of the study region, where pools currently provide variable habitat suitability from year to year (Pyke 2005). In addition, precipitation shifts are likely to interact with land use practices and habitat loss to cause variable impacts on pool hydrology at the individual and landscape level (Pyke 2004; Pyke & Marty 2005).

Soil moisture

Sensitivity: *High (high confidence)*

Vernal pool ponding creates a soil moisture gradient from the lowest point in the pool basin to the upper upland habitat edge, creating unique microsites that support a variety of vegetation. This gradient contracts and sometimes disappears in drier years, which can alter micro-distribution of component plant species (Bauder 2005).

Air temperature

Sensitivity: *Moderate (high confidence)*
Future exposure: *High (high confidence)*

Temperature is projected to increase over the next century (Bureau of Reclamation 2015). Regardless of changes in precipitation, warmer temperatures are expected to increase evapotranspiration and cause drier conditions (Cook et al. 2015).

Projected air temperature increases in the Central Valley will drive increased evaporation, and will likely interact with precipitation shifts and land use changes to alter the hydroperiods and persistence of vernal pools in the region (Lawler et al. 2010). However, in multiple modeling studies, shifts in air temperature were found to have less of an impact on pool hydrology than shifts in precipitation (Pyke 2004, 2005; Pyke & Marty 2005).

Water temperature

Sensitivity: *Moderate (high confidence)*
Future exposure: *High (high confidence)*

Water temperature controls vernal pool crustacean hatching (Eriksen & Belk 1999) and development rates, and influences immature and adult crustacean mortality (Helm 1998; U.S. Fish and Wildlife Service 2005; for more information, see Vernal Pool Crustacean Vulnerability Assessment). Vernal pool plants are not as sensitive to water temperature[1].

Non-Climate Factors

Workshop participants scored the resource's sensitivity and current exposure to non-climate factors, and these scores were then used to assess their impact on climate change sensitivity.

Non-Climate Factor	Sensitivity	Current Exposure
Agriculture & rangeland practices	High	High
Dams, levees, & water diversions	High	Moderate-high
Invasive & other problematic species	High	Moderate-high
Land use change	High	High
Nutrient loading	High	Moderate-high
Pollution & poisons	High	Moderate-high
Roads, highways, & trails	High	Moderate-high
Urban/suburban development	High	Moderate-high
Overall Scores	**High**	**Moderate-high**

Habitat fragmentation is an increasing problem for the remaining vernal pool landscapes. Off-site induced problems such as pollution and OHV activities will become inevitable. Human-related disturbance decreases wildlife use, especially waterfowl and waterbirds, which in turn reduces transport of cysts and seeds over the long-term. Isolated rangelands are difficult for livestock operations and so habitat quality at fragmented sites declines. Central Valley vernal pools and vernal pool landscapes survived the last mega-drought, in part because of cyst/seed adaptations, and while fragmentation reduces habitat quantity in its wake, it also reduces the quality of the remaining habitat[1].

Agricultural & rangeland practices

Sensitivity: *High (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Consistent across the landscape.*

Along with suburban/urban development, agricultural development has destroyed large portions of historical Central Valley vernal pool habitat (Holland 1998, 2000; Witham et al.

2014). Agricultural conversion, particularly orchards and vineyard establishment, contributed to 81% (110,000 acres) of vernal pool habitat loss from 1997-2005, with losses concentrated in the northern San Joaquin Valley and southern Sacramento Valley (Holland 2009). Agriculture was also the key driver in habitat loss from 2005-2012, accounting for 95% of vernal pool habitat lost, with losses occurring most heavily in Madera County (Witham et al. 2014). Current crops of concern include high value walnut orchards, almond orchards, and to lesser extent olives and grapes[1].

Aside from directly destroying and fragmenting habitat, agricultural & rangeland practices can alter hydrology and increase erosion and sedimentation, potentially affecting vernal pool persistence, animal and plant recruitment, and vegetative composition. For example, conversion of lands adjacent to the Hickman Vernal Pools to almond farming in Stanislaus County caused vernal pool conversion to freshwater marsh by increasing summer runoff (Witham et al. 2014). Ground-disturbance activities (e.g., plowing, trenching, grading, deep ripping) can increase siltation, suffocate larvae, bury eggs and cysts, and reduce plant germination (U.S. Fish and Wildlife Service 2005).

Land use change

Sensitivity: *High (high confidence)*
Current exposure: *High (high confidence)*
Pattern of exposure: *Localized; at energy development sites.*

Land use conversion is the leading cause of vernal pool habitat loss in the Central Valley (Holland 2009). Rates of habitat loss accelerated from 1997 through 2005 (Holland 2009), and 42,951 acres were lost from 2005-2012. Vernal pools have been replaced by a variety of different land uses, including irrigated cropland, solar fields, agricultural facilities such as walnut/almond shelling plants, poultry operations, bio-power generation plants, and prisons[1]. Mapping efforts have identified that roughly 19% (144,683 acres) of remaining vernal pool habitat is likely vulnerable to future conversion due to high disturbance/human activity on adjacent land parcels (Witham et al. 2014). In general, land use change contributes to vernal pool habitat destruction and fragmentation, ultimately affecting gene flow, dispersal, and persistence of vernal pools and many of their rare species (U.S. Fish and Wildlife Service 2005).

Urban/suburban development

Sensitivity: *High (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Consistent across the landscape.*

Urban and suburban development have destroyed significant portions of historical vernal pool habitat in California (Bartolome et al. 2014). Urban development contributed to 19% (26,000 acres) of vernal pool habitat loss from 1997-2005, and 5% of habitat loss from 2005-2012. Early century losses were concentrated largely in Placer and Sacramento Counties (Holland 2009); currently, few counties have long-term conservation planning to protect vernal pools from development[1]. Urban development contributes to increased nutrient loading via urban runoff (Carpenter et al. 1998), fragments habitat, impedes gene flow, contributes to altered vernal pool hydrology by altering runoff patterns, and can eliminate critical pollinator habitat (U.S. Fish and Wildlife Service 2005).

Dams, levees, & water diversions

Sensitivity: *High (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Localized, including near the Merced City and County streams project, Sites Reservoir (proposed), and other possible future water storage projects.*

Dams, levees and water diversions for agriculture and other human needs can lower regional groundwater tables, affecting vernal pool development. In some cases, these activities contribute to the creation of new vernal pools in areas that were previously marshland (Holland 1978), but typically, these water structures contribute to de-watering of vernal pool systems (U.S. Fish and Wildlife Service 2005). Dams, levees, and water diversions, including water supply projects, can also fragment and destroy vernal pool habitat, and/or lead to hydrological alterations by impacting surface flows (U.S. Fish and Wildlife Service 2005).

Invasive & other problematic species

Sensitivity: *High (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Consistent across the landscape.*

Exotic annual species commonly invade and compete with native vegetation at pool edges and in shallow pool areas (Bartolome et al. 2014). Invasive annuals can outcompete native vernal pool plants for soil moisture and light, reducing native germination and recruitment. Invasive grasses also reduce pool hydroperiods by increasing system evapotranspiration (Marty 2005). Common invaders include *Bromus hordeaceus*, *Convolvulus arvensis*, *Hordeum marinum*, *Lolium multiflorum*, *Lythrum hyssopifolium* (Gerhardt and Collinge 2003). The annual grasses *H. marinum* and *L. multiflorum* are particularly threatening for vernal pools because they appear to be the least affected and excluded by inundation (Gerhardt & Collinge 2007). Invasive grasses in adjacent upland habitat are also problematic, as accumulated thatch can reduce nesting habitat for key vernal pool pollinators, impacting reproductive success and genetic variability in vernal pool plants (U.S. Fish and Wildlife Service 2005). Additional non-natives include *Crypsis shoenoides* and *C. vaginiflora*[1].

Roads, highways, & trails

Sensitivity: *High (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Localized; proposed high-speed rail will fragment last of the largest intact vernal pool landscapes in Merced and Madera Counties.*

Road, highway, and trail construction within basins containing vernal pools can alter basin hydrology, potentially impacting biodiversity and species composition within and amongst regional vernal pools (U.S. Fish and Wildlife Service 2005). Off-road vehicle traffic through vernal pools directly affects hydrology by increasing soil loss and enhancing ponding frequency and duration by reducing soil between the hardpan and the soil surface. Rutting can also change pool elevation and the associated distribution of vernal pool species due to shifts in soil moisture gradients (Bauder 2005). Trails and roads can also contribute to vernal pool siltation, affecting both animal and plant recruitment (U.S. Fish and Wildlife Service 2005).

Nutrient loading

Sensitivity: *High (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Localized; around orchards.*

Many vernal pools in the Central Valley are exposed to urban or agricultural runoff that can increase nutrient loading, particularly phosphorous and nitrogen (Carpenter et al. 1998). Runoff commonly stems from orchard and vineyard operations, but other agriculture industries have also historically contributed, such as poultry ranches in Merced County in early 1990s[1]. Experiments have shown that increased nutrient loading increases green algal crust cover (mainly *Cladophora* sp.) in drying vernal pool systems, which reduces native annual plant percent cover and species richness (Kneitel & Lessin 2009). Higher phosphorous and organic matter levels have also been tied with increased invasive species abundance (Gerhardt & Collinge 2003).

Pollution & poisons

Sensitivity: *High (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Localized; around point sources.*

Pesticide and herbicide use on adjacent farmland (orchards and vineyards) may negatively impact water quality in vernal pools, potentially restricting vernal pool plant growth (U.S. Fish and Wildlife Service 2005) and causing mortality of vernal pool invertebrates and higher-level consumers (Ryan et al. 2013). Roadway contaminants and mosquito-control pesticides can also reach and impact vernal pool systems, with similar effects (U.S. Fish and Wildlife Service 2005).

Disturbance Regimes

Workshop participants scored the resource's sensitivity to disturbance regimes, and these scores were used to calculate climate change sensitivity.

Overall sensitivity to disturbance regimes: *Moderate-high (high confidence)*

Flooding

Sensitivity: *Low-moderate, but depends on flood timing (confidence score not assessed)*
Future exposure: *Moderate (high confidence)*
Potential refugia: *Higher elevations.*

Vernal pools experience seasonal winter flooding (December-March). There is a gradient from the center of the pool to the surrounding upland edge, with flooding frequency, depth, duration, and timing varying considerably. This gradient drives differences in vegetation assemblages, vulnerability to invasion, and crustacean predator presence. Greater inundation depth and duration typically reduces invasive species establishment success, and inundation has been found to reduce the survival, growth and reproduction of many invasive species (Gerhardt & Collinge 2007).

Although vernal pools are adapted to seasonal flooding, prolonged flooding (usually a result of human modifications) can cause seed rot and trigger novel germination patterns, potentially facilitating vegetation shifts, including shifts to more permanent wetland-affiliated vegetation. Prolonged inundation can also increase habitat suitability for key crustacean predators, including fish and bullfrogs (U.S. Fish and Wildlife Service 2005).

Wildfire

> ***Sensitivity:*** *Moderate (confidence score not assessed)*
> ***Future exposure:*** *Moderate (moderate confidence)*
> ***Potential refugia:*** *Large complexes of vernal pools distributed across north-south gradient with diversity in pool depth.*

Wildfire may increase invasive species pressure by reducing native species cover and minimizing biotic interactions that limit invasive establishment. In a Central Valley study, burned plots had higher exotic species richness and increased abundance of six invasive plants compared to unburned plots (Gerhardt & Collinge 2003).

Grazing

> ***Sensitivity:*** *Moderate (confidence score not assessed)*

Cattle grazing may help maintain water in vernal pool systems (Pyke & Marty 2005) and mitigate invasive species (Marty 2005). In a modeling study by Pyke and Marty (2005), removal of cattle grazing contributed to a significant reduction in maximum ponding days per year. Marty (2005) found similar results in a 3-year experimental grazing study, with grazing elimination contributing to a 50-80% reduction in pool inundation period. Declines in pool hydroperiod under reduced or no grazing treatments was likely due to elevated evapotranspiration resulting from higher vegetation cover, particularly exotic grasses (Marty 2005).

The experimental grazing study by Marty (2005) also found significant grazing benefits for native vernal pool species. Ungrazed vernal pools in this study featured higher invasive species cover, lower relative cover of native species, and lower species richness in both native plants and aquatic invertebrates than pools experiencing continuous grazing year-round (Marty 2005). Cattle preferentially select taller grasses, which may encourage removal of exotic grasses rather than native forbs (Bartolome et al. 2014; Marty 2005). However, site-specific tailored grazing practices are likely required to avoid negative impacts on vernal pool vegetation and soils (U.S. Fish and Wildlife Service 2005).

Adaptive Capacity

Workshop participants scored the resource's adaptive capacity and the overall score was used to calculate climate change vulnerability.

Adaptive Capacity Component	Score
Extent, Integrity, & Continuity	Low-moderate
Landscape Permeability	Low
Resistance & Recovery	Moderate-high
Habitat Diversity	High
Overall Score	**Moderate**

Extent, integrity, and continuity

Overall degree of habitat extent, integrity, and continuity: *Low-moderate (high confidence)*
Geographic extent of habitat: *Endemic to a particular area (high confidence)*
Structural and functional integrity of habitat: *Altered but not degraded (high confidence)*
Continuity of habitat: *Patches with connectivity between them (high confidence)*

Vernal pool habitats (defined to include the wetland and surrounding grassland matrix) occupied 764,868 acres in the Central Valley as of 2012 (Witham et al. 2014). This extent is greatly reduced relative to historical distribution, as extensive vernal pool and other wetland habitat has been lost and altered over time due to human land use change, development, and agriculture (Holland 1998, 2009).

Vernal pool systems occur across various biomes and on other continents, and in California, tend to occur in clusters in areas with suitable topography and underlying impermeable soils (U.S. Fish and Wildlife Service 2005). Individual vernal pools can be fairly isolated and/or connected or supplied by swales, which are differentiated from vernal pool habitats by lower inundation rates (U.S. Fish and Wildlife Service 2005). Hydrological connectivity to other aquatic systems (e.g., through groundwater movement or surface flow) can occur during high precipitation periods (Zedler 2003).

Landscape permeability

Overall landscape permeability: *Low (high confidence)*
Impact of various factors on landscape permeability:

Urban/suburban development: *High (high confidence)*
Agricultural & rangeland practices: *High (high confidence)*
Land use change: *High (high confidence)*
Energy production & mining: *Moderate-high (high confidence)*
Roads, highways, & trails: *Moderate-high (high confidence)*
Invasive & problematic species: *Low-moderate (high confidence)*

Landscape barriers listed above fragment vernal pool habitats and populations, impacting local gene flow and genetic diversity amongst these naturally isolated communities. These barriers can also directly or indirectly affect the dispersal of some vernal pool species. For example, habitat fragmentation may reduce avian vernal pool use and avian-mediated branchiopod dispersal to smaller habitat patches (U.S. Fish and Wildlife Service 2005 and citations therein).

The high-speed rail will be a new barrier[1]. Agricultural and rangeland practices that act as barriers include deep ripping and conversions. Land use change can include many conversion types, but mostly refers to agricultural and urban/suburban development (Holland 2009).

Resistance and recovery

Overall ability to resist and recover from stresses: *Moderate-high (high confidence)*
Resistance to stresses/maladaptive human responses: *Moderate-high (high confidence)*
Ability to recover from stresses/maladaptive human response impacts: *Moderate (high confidence)*

Vernal pools support a variety of specialized species that are adapted to the unique hydrological cycle of each pool, and have evolved to capitalize on short aquatic growing phases and tolerate extended seasonal drought periods (Zedler 2003). For example, vernal pool wildlife has evolved to finish aquatic life stages quickly, and cysts and eggs can withstand heat and desiccation; further, many species exhibit prolonged dormancy in the cyst and egg stage (U.S. Fish and Wildlife Service 2005). Similarly, many plant species typically have long-lived seed banks and growth forms that facilitate transitions from wet to dry environments (Zedler 1990). In addition, the high abundance of annual species facilitates adaptation to annual fluctuations in environmental conditions (Zedler 1990) and may allow rapid adaptation to shifting environmental pressures in the future (Rice & Emery 2003). In general, evolutionary adaptations to deal with large intra- and inter-annual hydrological variability in this system may allow vernal pool species to accommodate future climate shifts (Rice & Emery 2003). However, vernal pool vegetation typically has low dispersal capacity (Zedler 1990).

Vernal pool habitat recovery depends on the stresses and climate change issues that are present. Recovery can be high after some non-climate factors, while this habitat will not recover from other activities, such as deep ripping[1].

Habitat diversity

Overall habitat diversity: *High (high confidence)*

Physical and topographical diversity of the habitat: *High (high confidence)*
Diversity of component species within the habitat: *High (high confidence)*
Diversity of functional groups within the habitat: *High (high confidence)*

Component species or functional groups particularly sensitive to climate change:

- Brachiopods and aquatic invertebrates: *Downingia*, *Lasthenia*, *Navarretia*
- Hybrid tiger salamander alleles

Keystone or foundational species within the habitat:

- Livestock (cattle grazing)

High physical and topographical diversity amongst vernal pool habitats in the Central Valley and broader California region drive highly diverse responses to regional climatic factors (e.g., total annual rainfall; Hanes & Stromberg 1998). Individual pool hydroperiod and ecology is influenced by nearby mounds, connecting swales, depression depth, width, and shape, presence of inlets or outlets, topographic position, connectivity with other systems, and land use (Hanes & Stromberg 1998). Diverse hydrological functions amongst regional pools enhances the overall landscape resilience of this habitat, because not all pools will respond identically to the same regional climate or non-climate signal (Bauder 2005).

Vernal pools support both ephemeral wetland specialist species and a mix of species from wetland and upland habitats that are tolerant of fluctuating environmental conditions (Zedler 2003). California vernal pools support at least 200 vascular plant species and 34 crustacean species (Keeley & Zedler 1998), as well as numerous insects and migratory and resident birds (U.S. Fish and Wildlife Service 2005). In addition, many vernal pool species depend on animals from other habitats for persistence; for example, native ground-dwelling bees from adjacent grasslands are key vernal pool pollinators (U.S. Fish and Wildlife Service 2005).

The extreme hydrological conditions of this habitat, paired with the unique hydrology of each individual pool, contributes to high endemism and specialization amongst vernal pool associates (Zedler 2003). However, endemism and small and isolated populations may increase vulnerability to extirpation (e.g., from stochastic events), particularly as habitat fragmentation and loss increases (U.S. Fish and Wildlife Service 2005).

Brachiopods and aquatic invertebrates have a narrow range of tolerance to dryness[1]. Hybrid tiger salamander alleles may be favored by climate changes such as warmer temperatures or climate-related migration opportunities (Johnson et al. 2010).

Management potential

Workshop participants scored the resource's management potential.

Management Potential Component	Score
Habitat value	Moderate
Societal support	Moderate-high
Agriculture & rangeland practices	High
Extreme events	Low-moderate
Converting retired land	Low
Managing climate change impacts	Moderate-high
Overall Score	**Moderate**

Value to people

Value of habitat to people: *Moderate (high confidence)*
Description of value: *Aesthetics.*

Support for conservation

Degree of societal support for managing and conserving habitat: *Moderate-high (high confidence)*

Degree to which agriculture and/or rangelands can benefit/support/increase the resilience of this habitat: *High (high confidence)*
Description of support: *Rangelands only. Proper grazing regimes limit the ability of invasive plants to inhabit vernal pools.*

Degree to which extreme events (e.g., flooding, drought) influence societal support for taking action: *Low-moderate (high confidence)*
Description of events: *Possibly during extreme flooding events vernal pools and other wetlands receive increased support for conservation.*

Likelihood of converting land to habitat

Likelihood of (or support for) converting retired agriculture land to habitat: *Low (high confidence)*
Description of likelihood: *Issues with fractured durapan; if durapan is deep ripped, and it usually is, then conversion is not possible.*

Likelihood of managing or alleviating climate change impacts on habitat: *Moderate-high (high confidence)*

Habitat management opportunities, particularly managing for climate impacts, will vary amongst vernal pool systems in the Central Valley (e.g., see Pyke and Marty 2005), and require monitoring and adaptive management as conditions change (Lawler et al. 2010). For example, grazing has been shown to benefit some vernal pool systems (Marty 2005), but stocking rates will likely require adjustment depending on precipitation and other climate changes (Lawler et al. 2010).

There is some regulatory support for managing vernal pool systems, mainly through Endangered Species Act listings of several plant, vertebrate, and invertebrate species (U.S. Fish and Wildlife Service 2003, 2005), the Clean Water Act, and the Central Valley Project Improvement Act (Vendlinski 2000). In addition, as of 2012, 30% of existing vernal pool habitat in the Central Valley was under some sort of protective land management agreement (Witham et al. 2014).

Agricultural conversion is the largest driver of vernal pool habitat loss in the Central Valley, and wetland mitigation requirements for agricultural development are not as clear as in other sectors (e.g., industrial development; Holland 2009). However, some mitigation activities have occurred, including vernal pool "banks" constructed on formerly irrigated agricultural fields (Witham et al. 2014), although the ecosystem value of these systems is likely different than that of those lost pools (De Weese 1998), and climate change may affect restoration and mitigation activities by influencing water supply (Ferren Jr. & Pritchett 1988).

Literature Cited

Bartolome JW, Allen-Diaz BH, Barry S, Ford LD, Hammond M, Hopkinson P, Ratcliff F, Spiegal S, White MD. 2014. Grazing for biodiversity in Californian Mediterranean grasslands. Rangelands **36**:36–43.

Bauder ET. 2005. The effects of an unpredictable precipitation regime on vernal pool hydrology. Freshwater Biology **50**:2129–2135.

Bureau of Reclamation. 2015. Sacramento and San Joaquin Basins study, report to Congress 2015. U.S. Department of the Interior, Bureau of Reclamation, Mid Pacific Region. Prepared by CH2M Hill. Available from http://www.usbr.gov/watersmart/bsp/.

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications **8**:559–568.

Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Science Advances **1**:e1400082.

De Weese JM. 1998. Vernal pool construction monitoring methods and habitat replacement evaluation. Pages 217–223 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA. Available from http://ww.vernalpools.net/proceedings/deweese.pdf.

Diffenbaugh NS, Swain DL, Touma D. 2015. Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences **112**:3931–3936.

Eriksen CH, Belk D. 1999. Fairy shrimps of California's puddles, pools, and playas. Mad River Press.

Ferren Jr. WR, Pritchett DA. 1988. Enhancement, restoration, and creation of vernal pools at Del Sol Open Space and Vernal Pool Reserve, Santa Barbara County, California. Environmental Report No. 13. University of California, Santa Barbara. Available from https://archive.org/stream/enhancementresto00ferr/enhancementresto00ferr_djvu.txt.

Gerhardt F, Collinge SK. 2003. Exotic plant invasions of vernal pools in the Central Valley of California, USA. Journal of Biogeography **30**:1043–1052.

Gerhardt F, Collinge SK. 2007. Abiotic constraints eclipse biotic resistance in determining invasibility along experimental vernal pool gradients. Ecological Applications **17**:922–933.

Griffin D, Anchukaitis KJ. 2014. How unusual is the 2012–2014 California drought? Geophysical Research Letters **41**:9017–9023.

Hanes WT, Stromberg LT. 1998. Hydrology of vernal pools on non-volcanic soils in the Sacramento Valley. Pages 38–49 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA. Available from http://libra.msra.cn/Publication/10615960/hydrology-of-vernal-pools-on-non-volcanic-soils-in-the-sacramento-valley.

Hayhoe K et al. 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences **101**:12422–12427.

Helm BP. 1998. Biogeography of eight large branchiopods endemic to California. Pages 124–139 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA.

Holland RF. 1978. The geographic and edaphic distribution of vernal pools in the Great Central Valley, California. Special Publication No. 4. California Native Plant Society, Fair Oaks, CA. Available from http://www.calwater.ca.gov/Admin_Record/C-053529.pdf.

Holland RF. 1998. Great Valley vernal pool distribution, photorevised 1996. Pages 71–75 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA. Available from http://www.elkhornsloughctp.org/uploads/files/1401303246Holland.%201998.%20Great%20Valley%20vernal%20pool%20distribution,%20photorevised..pdf.

Holland RF. 2009. California's Great Valley vernal pool habitat status and loss: rephotorevised 2005. Auburn, CA. Available from http://www.vernalpools.org/vpreports/Great%20Valley%20Vernal%20Pool%20Distribution_Final.pdf.

Johnson JR, Johnson BB, Bradley Shaffer H. 2010. Genotype and temperature affect locomotor performance in a tiger salamander hybrid swarm. Functional Ecology **24**:1073–1080.

Keeley JE, Zedler PH. 1998. Characterization and global distribution of vernal pools. Pages 1–14 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA. Available from http://vernalpools.org/proceedings/keeley.pdf.

Kneitel JM, Lessin CL. 2009. Ecosystem-phase interactions: aquatic eutrophication decreases terrestrial plant diversity in California vernal pools. Oecologia **163**:461–469.

Lawler JJ et al. 2010. Resource management in a changing and uncertain climate. Frontiers in Ecology and the Environment **8**:35–43.

Marty JT. 2005. Effects of cattle grazing on diversity in ephemeral wetlands. Conservation Biology **19**:1626–1632.

Pyke CR. 2004. Habitat loss confounds climate change impacts. Frontiers in Ecology and the Environment **2**:178–182.

Pyke CR. 2005. Assessing climate change impacts on vernal pool ecosystems and endemic branchiopods. Ecosystems **8**:95–105.

Pyke CR, Marty J. 2005. Cattle grazing mediates climate change impacts on ephemeral wetlands. Conservation Biology **19**:1619–1625.

Rice KJ, Emery NC. 2003. Managing microevolution: restoration in the face of global change. Frontiers in Ecology and the Environment **1**:469–478.

Ryan ME, Johnson JR, Fitzpatrick BM, Lowenstine LJ, Picco AM, Shaffer HB. 2013. Lethal effects of water quality on threatened California salamanders but not on co-occurring hybrid salamanders. Conservation Biology **27**:95–102.

Toreti A, Naveau P, Zampieri M, Schindler A, Scoccimarro E, Xoplaki E, Dijkstra HA, Gualdi S, Luterbacher J. 2013. Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. Geophysical Research Letters **40**:4887–4892.

U.S. Fish and Wildlife Service. 2003. Endangered and Threatened wildlife and plants; Final designation of critical habitat for four vernal pool crustaceans and eleven vernal pool plants in California and southern Oregon: Final Rule. Federal Register **68**:46684–46762.

U.S. Fish and Wildlife Service. 2005. Recovery plan for vernal pool ecosystems of California and southern Oregon. U.S. Fish and Wildlife Service, Region 1, Portland, OR. Available from http://www.fws.gov/sacramento/ES/Recovery-Planning/Vernal-Pool/es_recovery_vernal-pool-recovery.htm.

Vendlinski T. 2000. California's vernal pools: accomplishments and conservation strategies. Fremontia **27**:19–27.

Williams AP, Seager R, Abatzoglou JT, Cook BI, Smerdon JE, Cook ER. 2015. Contribution of anthropogenic warming to California drought during 2012-2014. Geophysical Research Letters **in press**:1–10.

Witham CW, Holland RF, Vollmar JE. 2014. Changes in the distribution of Great Valley vernal pool habitats from 2005 to 2012. Available from http://www.vernalpools.org/2012CVPIA/20141914_Final_2012_Remapping_Report.pdf.

Zedler PH. 1987. The ecology of southern California vernal pools: a community profile. Biological Report 85 (7.11). U.S. Fish and Wildlife Service. Available from http://www.nwrc.usgs.gov/techrpt/85-7-11.pdf.

Zedler PH. 1990. Life histories of vernal pool vascular plants. Pages 123–146 in D. Ikeda and R. Schlising, editors. Vernal pool plants– their habitat and biology. Studies from the Herbarium Number 8. California State University-Chico, Chico, CA.

Zedler PH. 2003. Vernal pools and the concept of "isolated wetlands." Wetlands **23**:597–607.

[1] Expert opinion, Central Valley Landscape Conservation Project Vulnerability Assessment