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Mapping indicators of groundwater dependent ecosystems in Nevada: Important resources for a water-limited state

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ABSTRACT

Groundwater dependent ecosystems (GDEs) rely on groundwater for all or part of their water needs, and provide benefits to plants, wildlife and people. Almost half of endemic species in Nevada are associated with GDEs. To increase our understanding of groundwater needs for GDEs we 1) created a spatial database to identify the location and extent of GDEs in Nevada; 2) developed a story map to share data from the database to increase awareness about GDEs among the general public; and 3) conducted an assessment of GDE condition for areas previously mapped at high resolution. We found that at least 10% of Nevada is classified as having an indicator of groundwater dependence, and over two-thirds of Nevada's hydrographic areas contained all 5 types of indicators of GDEs (i.e., phreatophyte communities; wetlands; springs; lakes and playas; and rivers and streams). Of the GDEs in 11 landscapes in Nevada, GDEs in montane riparian systems were the most ecologically departed from reference, mostly due to non-native plant species. Our next steps involve using the database to assess stressors and threats to GDEs to help us develop and prioritize strategies for protecting GDEs for people and nature.

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INTRODUCTION

Groundwater is a critical resource for people and nature throughout the world, providing basic water needs to over 2 billion people (IWRA, 2017), comprising almost half of global irrigation water (Siebert et al., 2010), and sustaining healthy ecosystems (Brown et al., 2011). Groundwater provides valuable water resources to supplement surface water supplies, can serve as emergency reserves during drought, and can moderate temperature and water quality (Brown et al., 2011; Eamus et al., 2006; Gleeson and Richter, 2017; Womble et al., 2018). In addition, groundwater dependent ecosystems (GDEs) rely on groundwater for all or part of their water needs, and encompass natural communities including plants, animals, and microbes. These GDEs assist human well-being by supplying forage for livestock, providing water storage and purification, preserving soils, storing carbon, reducing flood risk, and providing recreational and economic benefits (Brown et al., 2011; Kath et al., 2018).

While technically a renewable resource, replenishment of groundwater by precipitation occurs at much slower rates than most anthropogenic withdrawal rates (Alley et al., 1999). Groundwater depletion and contamination can take a long time to be detected, and even longer to remedy (Barlow and Leake, 2012; Gleeson et al., 2012). Thus, sustainable use of groundwater for the long term requires consideration of many factors, including the relationships between groundwater dynamics and GDEs (Kath et al., 2018; Rohde et al., 2017).

As the driest state in the United States, Nevada has benefitted from having groundwater aquifers that can provide additional water to limited surface water supplies. In 2015, almost half of Nevada's water withdrawals came from groundwater, with about 67% of groundwater withdrawals for irrigation, 14% for mining, and 11% for domestic and municipal use (Dieter et al., 2015). However, over a third of Nevada's hydrographic areas (administrative groundwater units) are fully- or over-appropriated (i.e., committed water rights equal or exceed estimated available groundwater, which is defined in Nevada as "perennial yield"). Furthermore, actual groundwater withdrawals exceed perennial yield in over 18% of hydrographic areas (King, 2019). Overuse of the groundwater resource is a pressing issue as the state considers how to provide water sustainably for future generations.

Nevada ranks 11th in biodiversity among US states, 6th among all states in number of endemic species (i.e., species found nowhere else in the world), and 3rd among all states in number of species at risk (NNHP, 2019). Almost half of the over 300 endemic species in Nevada are associated with GDEs. As Nevada receives less than 250 mm of precipitation per year on average, understanding groundwater needs for GDEs is an important aspect of addressing sustainable groundwater management in Nevada. We sought to increase our understanding of groundwater needs for GDEs by achieving three overarching goals: 1) create a spatial database that inventories the location and extent of indicators of GDEs in Nevada; 2) increase awareness about what GDEs are and their importance among the general public; and 3) conduct an assessment of GDE condition for areas previously mapped at fine resolution. For goal 1, we gathered the best available data about GDEs in Nevada and assembled them into a publicly available database. We then used the database to construct a story map to raise public awareness of GDEs in Nevada to address the second goal. Finally, we addressed the third goal by conducting an assessment of localized GDEs in 11 areas previously mapped by The Nature Conservancy (TNC) in Nevada. The assessment 1) described the condition of GDEs across the 11 areas, 2) identified possible causes of degradations among the landscapes and GDE types, and 3) identified management actions that may be used to improve GDE condition. Together, these efforts can support strategic planning for groundwater sustainability in Nevada.

METHODS

Nevada indicators of groundwater dependent ecosystems (iGDE) database and story map development

Identifying where GDEs are located requires detailed, local data about the land use, hydrology, and geology of a location. Because detailed local data are not available in all Nevada basins, the database incorporates existing datasets to identify and map ecosystems that potentially rely on groundwater, or indicators of GDEs (hereafter, iGDEs; Klausmeyer et al. (2018)). We organized the iGDEs into 5 categories of ecosystem types and included information regarding species associated with GDEs (Figure 1).

We developed a geographic information system (GIS) using the Arcpy module under Python 3.6 (ESRI, 2018; Python Software Foundation, 2018) to integrate the spatial and non-spatial datasets. Data from the original datasets were selected, prioritized, combined, and summarized in the GIS to create both the Nevada iGDE Database and story map products (Figure 1). The database is organized in spatial layers for 1) phreatophyte communities; 2) wetlands; 3) springs; 4) lakes and playas; 5) rivers and streams; and 6) species (Figure 1). Data in each layer were aggregated for summary by hydrographic area or 2.59 km^2 (1 mi^2) hexagons. The latter units were chosen because they are the uniform units used in the Nevada Crucial Habitat Assessment tool (NDOW 2019); they were readily available and would represent the data at a useful spatial scale without compromising sensitive data.

We held meetings with data providers and potential users to determine how to organize the database to ensure data integrity and ease-of-use for spatially displaying different types of GDEs. We decided that a public story map would be useful for achieving the secondary goal of educating users about what GDEs are and where they are. We released a beta version of the draft story map in March 2019 to get feedback from potential users, and this feedback was incorporated into the final version released in July 2019.

Phreatophyte Communities

The Phreatophyte Communities layer is a polygon feature class showing where forest and shrubland phreatophyte communities are located throughout Nevada. Three data sources were used to create this statewide layer as some data sources did not cover the entire state of Nevada: 1) remotely sensed coverages of ecological systems and vegetation classes provided by TNC for over 1.6 million ha (over 4 million ac) in Nevada at 1.5 m to 10 m resolution (Abele et al., 2010; Low et al., 2010; Provencher, 2008; Provencher et al., 2008, 2009a,b, 2010, 2013, 2016, 2017);

2) phreatophyte communities mapped by LANDFIRE (2014) at 30 m resolution; and 3) phreatophyte boundary polygons mapped by Minor et al. (2019).

Land cover data provided by TNC were derived from high resolution satellite imagery with substantial ground-truthed data collected to validate land cover classifications. The TNC data products contain more land cover classes beyond phreatophyte vegetation, but only forest and shrubland phreatophyte communities (i.e., Aspen-Mixed Conifer, Aspen Woodland, Greasewood, Jeffrey Pine Riparian, Lodgepole Pine-Wet, and Mesquite) were added to the Phreatophyte Communities layer in the database (Table 1; see Byer et al. (2019) for more detailed descriptions of the ecological systems in the Phreatophyte Communities layer). The TNC data products were converted from their original raster format to polygon features, then aggregated by their vegetation types and data sources.

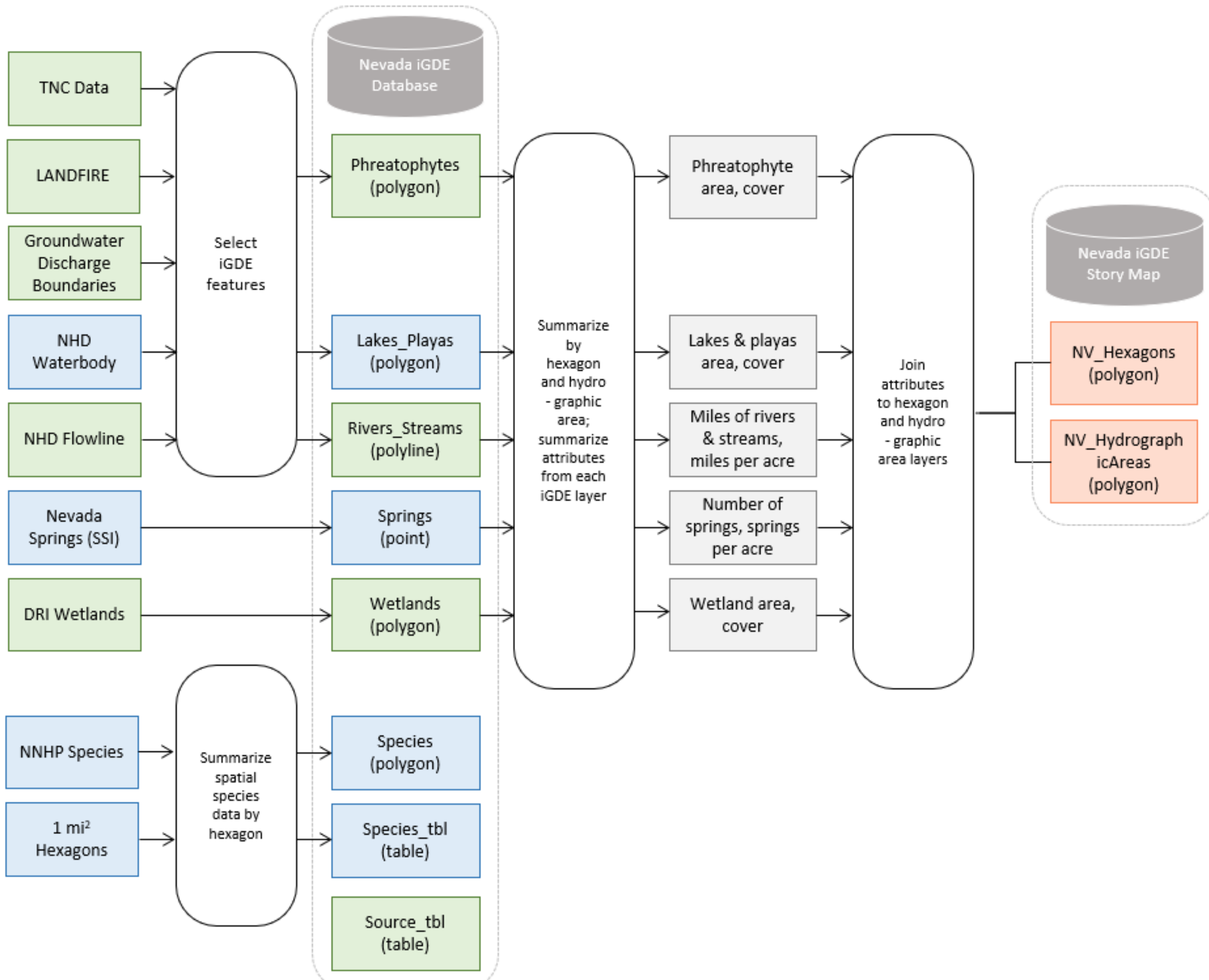

Figure 1: Overview of the datasets and processes used to create the Nevada iGDE database layers and story map layers.

Table 1. Ecological systems from TNC included in the NV iGDE database and story map and the ecological departure analysis of GDEs. PCF = Phreatophyte Communities layer forests. PCS = Phreatophyte Communities layer shrublands. W = Wetlands layer.

Ecological system	**NV iGDE layer**	**General site conditions**	**Dominant vegetation**	**Disturbance considerations**
Aspen-Mixed Conifer (AMC)	PCF	Elevations 1700-2800 m; soils are highly variable but generally cool	Quaking aspen (*Populus tremuloides*); white fir (*Abies concolor*) and limber pine (*Pinus flexis*) subdominant	Fire is a key disturbance, but prolonged fire exclusion and ungulate herbivory allow dominance by conifers
Aspen Woodland (AW)	PCF	Elevations 1981-2743 m where precipitation is ≥36 cm	Quaking aspen (*P. tremuloides*)	Frequent fires historically maintained dynamics; grazing by non-native and native ungulates and fire suppression are causes of degradation
Greasewood (GW)	PCS	Valley bottoms on alluvial flats or adjacent to playas; saline or sodic soils	Greasewood (*Sarcobatus vermiculatus*)	Flooding regimes important to dynamics. Increased fire (largely absent prior to 1980s), and declining water tables threaten these systems
Jeffrey Pine Riparian (JPR)	PCF	Along channels with intermittent flow above 1220 m in western NV	Jeffrey pine (*Pinus jeffreyi*)	Relatively frequent fires and flooding are important ecological processes
Lodgepole Pine-Wet (LPW)	PCF	Elevations 2000-3200 m on gentle slopes or drainage bottoms	Sierran lodgepole pine (*Pinus contorta* spp. *murrayana*)	Natural wet and dry climate cycles and infrequent fire are important factors in forest dynamics
Mesquite (Mes)	PCF	Warm desert drainages of southern NV	Screwbean mesquite (*Prosopis pubescens* Benth.) and honey mesquite (*Prosopis glandulosa* Torr.)	Infrequent fire, ≥100-year flood events, severe drought, and hard freezes can limit growth; wood cutting and off-road vehicle driving are current threats
Montane Riparian (MR)	W	Elevations above 1220 m with gravel	Willow (*Salix* spp.) on steeper slopes; cottonwoods (*Populus* spp.) on shallower slopes and below 2,750 m	Flooding is main ecological driver of system dynamics; drought, fire, and grazing can also play roles
Ponderosa Pine Riparian (PPR)	W	Along channels with intermittent flow (1980-2900 m) in eastern NV	Ponderosa pine (*Pinus ponderosa*)	Relatively frequent fires and flooding are important ecological processes
Saline Meadow (SM)	W	Valley bottoms or alluvial flats; saline or sodic soils	Alkali sacaton (*Sporobolus airoides*), alkali muhly (*Muhlenbergia asperifolia*), and inland saltgrass (*Distichlis spicata*)	Cyclical patterns of above and below average precipitation governs plant composition; grazing and non-native plant invasion are current threats
Wet Meadow-Bottomland (WMB)	W	Elevations below 1524 m in valley bottoms	Tufted hairgrass (*Deschampsia cespitosa*), Nevada bluegrass (*Poa nevadensis*), inland saltgrass, Baltic or mountain rush (*Juncus arcticus*), and various sedges (*Carex* spp.)	Wet and dry climate cycles affect relative cover of woody species with less constant wetting; channel incision can shift plant community to more upland species; hummocking caused by non-native grazing and non-native plants are threats; some meadows may depend on flows from thermal springs
Wet Meadow-Montane (WMM)	W	Elevations above 1524 m on a wide range of slopes	Graminoids (see Wet Meadow-Bottomland)	See Wet Meadow-Bottomland; infrequent fires also important
Wetland (Wet)	W	Lacustrine sites or those with inundation or slow flows most of the year	Helophytes like cattail (*Typha* spp.), bulrush (*Scirpus* spp.), and tule (*Schoenoplectus* spp.)	Non-native ungulate grazing, non-native plants, and water diversions are causes of degradation

The 2014 LANDFIRE Biophysical Setting (BpS) product "represents the vegetation that may have been dominant on the landscape prior to Euro-American settlement and is based on both the current biophysical environment and an approximation of the historical disturbance regime" (https://www.landfire.gov/bps.php). LANDFIRE data were converted from the original raster format into polygons and dissolved by vegetation type. Only ecological systems with phreatophyte vegetation were included from the BpS product and were assigned phreatophyte community names and groups (i.e., forest or shrubland) to match those in the TNC data products (Table 1).

Groundwater discharge boundary data for 160 of the 256 hydrographic areas (i.e., groundwater administrative units defined by the Nevada Division of Water Resources) in Nevada were provided by the Desert Research Institute (DRI; Minor et al., 2019). Phreatophyte boundaries from this dataset encompassed areas where shallow groundwater (i.e., groundwater within 3 to 15 m below the ground surface) is available for consumption by phreatophyte species according to previously published groundwater studies in Nevada (Minor et al., 2019) and these areas cover about 9.5% of the state. Because the phreatophyte boundaries did not identify the vegetation communities within them, the DRI vegetation polygons were assigned to an "unknown phreatophyte" group for the story map.

To combine the three data sources, data were prioritized by resolution and accuracy, with higher priority given to more accurate and higher resolution data. Because they had the highest resolution and had been ground-truthed, TNC data were highest priority. LANDFIRE data were used wherever TNC data were not available in Nevada (i.e., at locations where both TNC and LANDFIRE data were present, only TNC data were used and all underlying LANDFIRE data were removed; Figure 2). TNC and LANDFIRE data took priority where they overlapped with the DRI boundary dataset. All phreatophyte communities in the Phreatophyte Communities layer were then masked by a high- and medium-density development layer from the 2016 National Land Cover Database (NLCD; https://www.mrlc.gov/data/nlcd-2016-land-cover-conus), a 30-m land cover dataset derived from Landsat imagery. This mask was applied to remove mapped phreatophyte communities in cities and developed areas to better represent the current extent.

Percent phreatophyte cover was calculated by intersecting the Phreatophyte Community layer's polygons with the summarizing feature class (i.e., hexagons or hydrographic areas), creating phreatophyte sections in each feature class (Figure 3). The area covered by phreatophyte communities in a feature class was divided by the total area of that feature to get a statistic of percent phreatophyte community cover (e.g., the Carson Desert hydrographic area had 163,450 ha of phreatophyte community cover out of 521,490 ha total area for a percent phreatophyte community cover of 31%). Phreatophyte types were classified into phreatophyte community groups (i.e., forest, shrubland, or unknown) in each summarizing feature for the story map. The percentage areas of these groups were also calculated for each feature class.

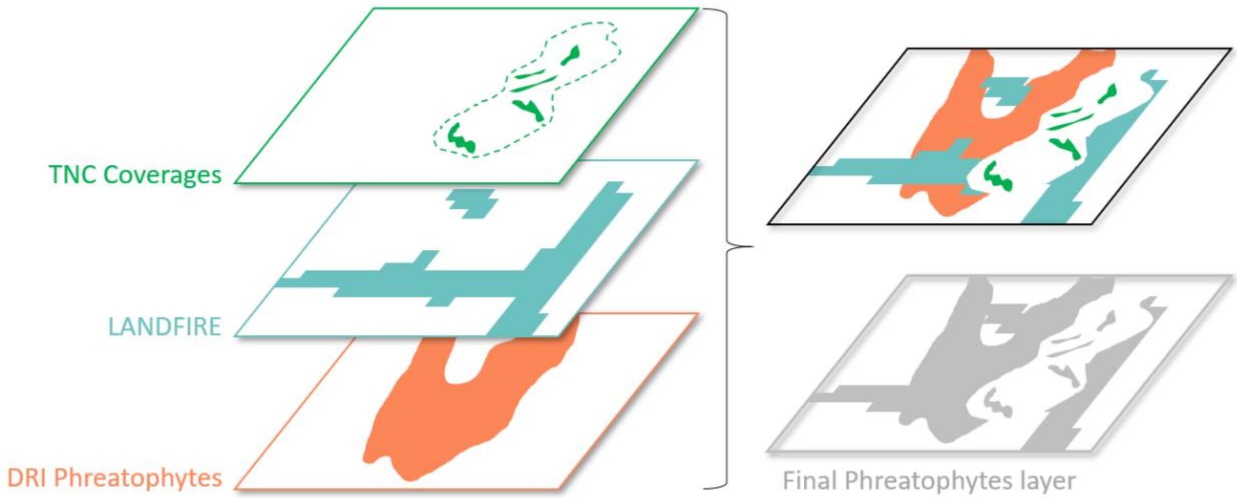

Figure 2: Representation of priority combination of datasets from different sources to create the Phreatophyte Communities layer in the Nevada iGDE database.

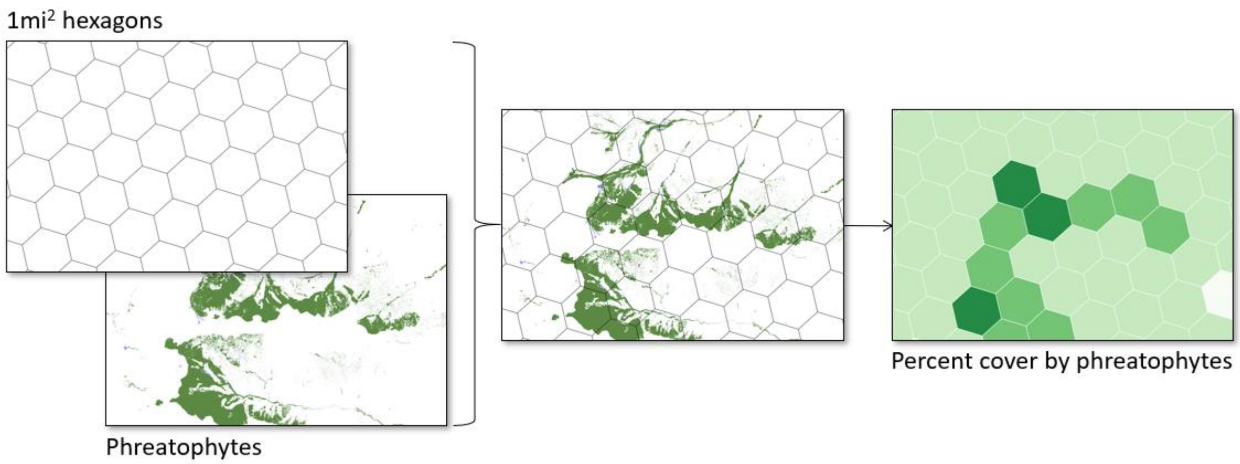

Figure 3: Illustration of how the Phreatophyte Community layer is summarized by 2.59 km^2 (1 mi^2) hexagons. Darker hexagons indicate higher percentages of phreatophyte community cover.

Wetlands

The Wetlands layer utilized a map of wetlands for Nevada that was developed by the DRI (http://www.dri.edu/wetland-mapnv). This product was a composite of multiple input sources, including the U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI). NWI data for the state of Nevada is a patchwork of different completion dates, and the portion of NWI completed before the 1990s was largely eliminated and replaced with other data sources due to extremely poor data quality. Lakes, playas, and areas mapped as palustrine in U.S. Geological Survey's National Hydrography Dataset (NHD; https://www.usgs.gov/core-science-systems/ngp/national-hydrography/about-national-hydrography-products) were incorporated in the statewide wetland map. The wetland map also incorporated the map of riparian vegetation in

Nevada (MRVN; www.dri.edu/mrvn; McGwire, 2019) that was developed using normalized difference vegetation index (NDVI) data derived from Landsat satellites. Perennial stream features from the enhanced NHDPlus product (version 2; https://www.epa.gov/waterdata/get-nhdplus-national-hydrography-dataset-plus-data) also were used in the development of the MRVN product.

The coordinates of spring locations from Springs Stewardship Institute (SSI), described in the next section on the Springs layer, were converted to polygons indicating wetland areas when they were associated with anomalously vigorous vegetation in midsummer satellite imagery. The gridded SSURGO soils map product from the U.S. Natural Resources Conservation Service includes an attribute called potential wetland soil landscapes (PWSL) that is a statistically modeled estimate of the probability of wetland presence. Based on comparisons of PWSL to satellite imagery, field observations, and other sources, areas where PWSL was 50% or higher were included. The U.S. Forest Service, Rocky Mountain Research Station (RMRS) and collaborators have performed extensive mapping of wet meadows in the mountains of central Nevada (Trowbridge et al., 2011). These meadows are typically detected in the MRVN product, but mapped polygons from the RMRS team's effort were used to improve the identification and geometry of these wetland features. The wetland map also included high resolution maps of wetland classes that were derived from high-resolution satellite imagery by TNC, as described in section on the Phreatophyte Communities layer. In order to maintain a more consistent mapping scale throughout the product, TNC data were aggregated to a 15-m resolution based on a class majority rule. Finally, a normalized difference wetness index (NDWI) that indicates inundated or icy areas based on a ratio of shortwave infrared and green wavelengths was calculated from midsummer Landsat data from 1985-2017 in order to indicate the extent of inundated areas across the state. NDWI values can range from -1.0 to 1.0, with values greater than zero indicating an increasing signal of wetness. Histograms of NDWI values from open water and land surfaces were compared, and NDWI values greater than 0.2884 reliably separated waterbodies from land. This threshold value was used to map waterbodies in each year. Some geological formations created false positives with this method, particularly in shadowed areas, and these errors were manually removed. The resulting map of waterbody extent by year was used to refine lake boundaries in the other map products and to assign wetland attributes related to inundation frequency.

A python program compiled these various data sources into a single product. Wetland attribute data from NWI were retained. The program also used relationships between different map inputs to assign attributes to the wetland polygons without NWI attributes. For example, if an area was mapped as lake in NHD, but was inundated less than 1/3 of the time based on the Landsat NDWI timeseries, it was changed to "Palustrine, shoreline." However, if Landsat NDVI indicated the presence of vegetation (NDVI >= 0.2), it was labelled "Palustrine, vegetated shoreline." If the region was inundated more frequently, it was labeled "Littoral" or "Littoral, emergent," respectively. Other database fields in the wetland map product include binary flags that indicate which combination of source datasets identified each wetland polygon.

Similar to the Phreatophyte Communities layer, a percent wetland statistic for each feature class was calculated by intersecting the Wetland layer's polygons with the summarizing feature class. This statistic is accessible in the story map for each hydrographic basin and hexagon.

Springs

Springs data were provided by SSI, a non-profit organization of the Museum of Northern Arizona. SSI extracted data on Nevada springs from the Springs Online database and delivered this dataset in a point feature class along with summarized survey data at spring. The unique Site ID of each spring can be used to seek more information about a spring in the Springs Online database (https://springstewardshipinstitute.org/). The high- and medium-density development layer from the 2016 NLCD was used to remove springs that were mapped in cities and developed areas that are now likely covered by roads or buildings or dried up.

A spatial join between the summarizing feature layers and the Springs layer's point feature class identified all springs that intersect each summarizing feature. For hydrographic areas, an additional attribute was calculated because larger hydrographic areas could appear to have more springs because of their larger areas, but the density of springs might actually be smaller than for smaller hydrographic areas. Thus, the number of springs was divided by the total hydrographic area and multiplied by 10,000 ac to represent the number of springs per 10,000 ac (Figure 4).

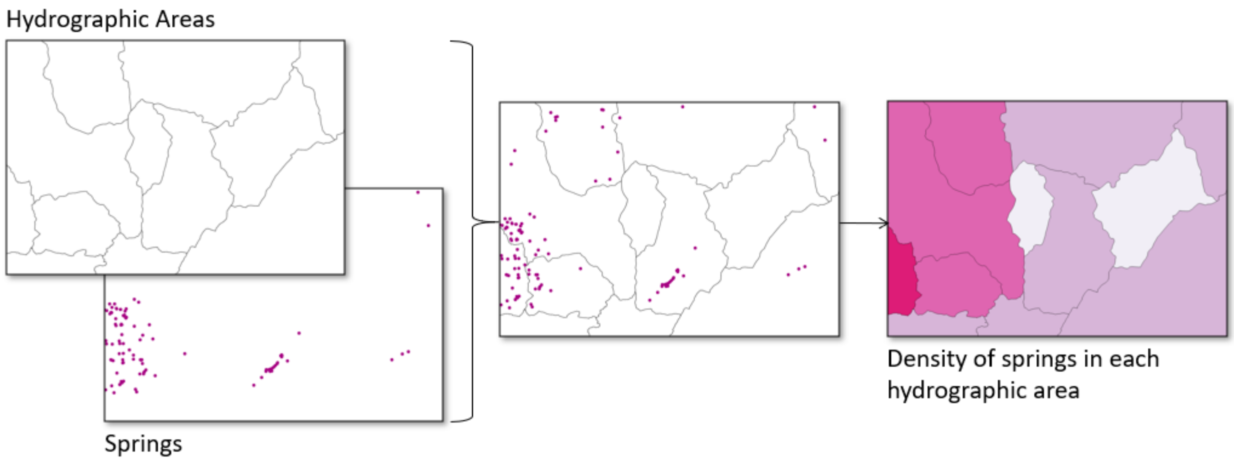

Figure 4: Illustration of how the Springs layer is summarized by hydrographic area. Darker regions indicate higher densities of springs per 10,000 ac.

Lakes and Playas

NHD Waterbody data were used to create the Lakes and Playas layer. The NHD Waterbody feature class contains surface water features across the continental U.S. It was assumed that all playas in Nevada were iGDEs based on the definition of playas by Rosen (1994). All natural perennial lakes were also assumed to be iGDEs because most rivers and creeks feeding Nevada's natural lakes have groundwater contributions (Mifflin 1988), and lakes can also receive groundwater inflow and seepage loss through their bed (Winter et al. 1998). Lake and playa features were clipped to the extent of Nevada and added to the iGDE database.

The percentage of lakes and playas for each summarizing feature class in the story map was calculated by intersecting the Lakes and Playas polygons with the summarizing feature class. In addition, attributes representing the percent and area of only lakes or only playas were calculated.

Rivers and Streams

NHD Flowline data were used to create the Rivers and Streams layer by filtering for perennial streams in rivers from the NHD dataset. Because of the low precipitation across Nevada, streams and rivers that rely solely on precipitation are likely be dry periodically. Streams that contain water year-round (i.e., perennial reaches) were assumed to be iGDEs because groundwater was likely to supply the consistent water source (Winter et al. 1998).

All river and stream polylines were dissolved to create a single feature class, then intersected with the summarizing feature layer. The miles of rivers and streams per summarizing feature were calculated. An additional attribute was calculated for the hydrographic areas to scale the rivers and streams to the size of each summarizing feature. Larger hydrographic areas could have more miles of rivers and streams, so the miles of river and streams were divided by the total hydrographic area and multiplied by 10,000 ac to represent the miles of iGDE rivers and streams per 10,000 ac.

Species

Species data were provided by the Nevada Natural Heritage Program (NNHP). Because of the inclusion of sensitive species, species data were generalized to protect location information. We created the Species layer as a polygon feature class of uniform 2.59 km^2 (1 mi^2) hexagons. Wetland-dependent species in Nevada were exported as points, lines, and polygons on April 23, 2019. Points and lines were buffered by 5 m on all sides and combined with the original species polygon data to create a combined polygon feature class of wetland species occurrences (Figure 5). TNC received generalized (within about 10 km) locations of sensitive species represented by polygons.

A spatial join combined all NNHP species polygons with the hexagon feature class to identify species recorded in each hexagon. Because the ‘Intersect’ method was used in the spatial join, a species occurrence that spans multiple hexagons would be counted in all hexagons it touches.

A unique list of species was generated from the combined NNHP species polygon layer (Figure 5). Although not spatial, these data provide information to users about wetland-dependent species that have been mapped by NNHP.

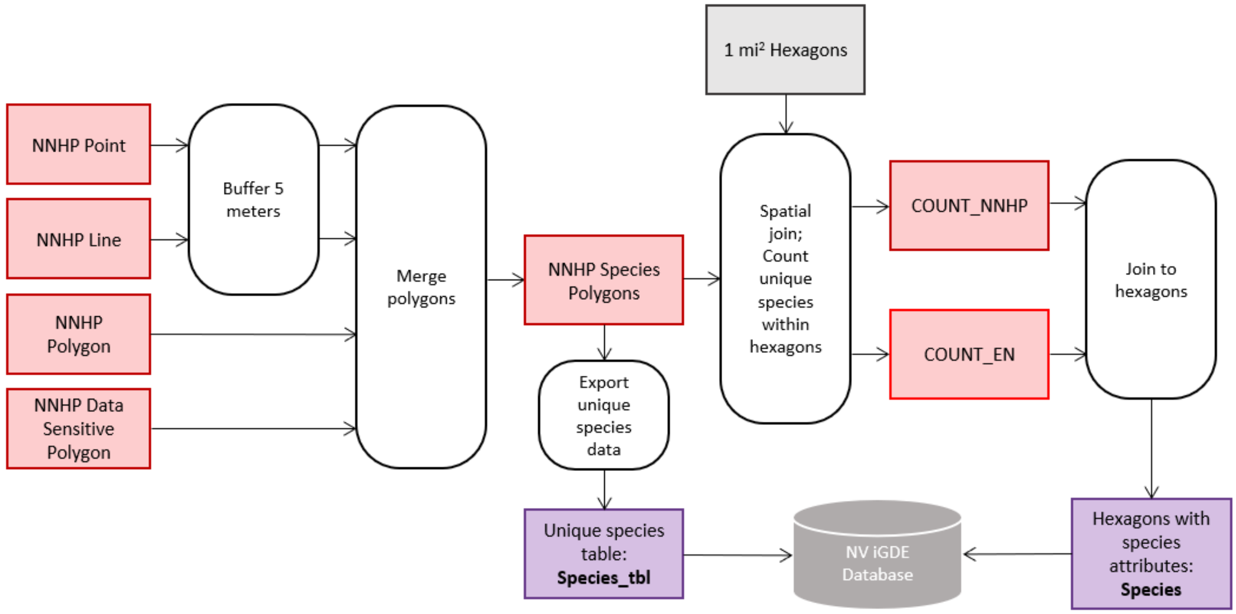

Figure 5: Processing steps for creating the 2.59 km^2 (1 mi^2) hexagon Species layer and species table from NNHP species data.

Spatial species data were not displayed in the story map to prevent misinterpretations of where groundwater dependent species are present or absent. Visualizing such data might show an absence of species in an area because someone has not yet surveyed there, not because the species cannot or does not exist there. Because of this, the Species layer did not have full statewide coverage, unlike the other data layers that consisted of at least one national or state-wide dataset (e.g., LANDFIRE, NHD, and DRI wetland data).

Summary iGDE count

The five iGDE types (phreatophyte communities, wetlands, springs, lakes and playas, and rivers and streams) were summarized for the story map by counting how many data layers were represented in each feature class, with a value of "0" indicating that no iGDE types were present, and "5" indicating that all five GDE types were present.

Ecological departure analysis

The vegetation cover provided by TNC for the phreatophyte communities layer was used to assess ecological departure of iGDEs at those locations. Ecological departure (ED) is a measure of how different a natural community is from some baseline. TNC mapped over 1.6 million ha (4 million ac) across Nevada between 2003 and 2016 (Figure 6). The goals of the original mapping were related to natural resource planning in the surrounding upland systems to assess fire risk or improve habitat for species of concern. In addition to mapping, state-and-transition models (STSMs) were created for each ecological system observed in the landscape. By running multiple simulations over 700 simulated years without anthropogenic inputs with the STSMs, the natural range of variation (NRV) can be defined for vegetation communities (Low et al., 2010;

Rollins, 2009). NRV is the pre-settlement or natural distribution of successional vegetation class percentages obtained from pre-settlement equilibrium simulations.

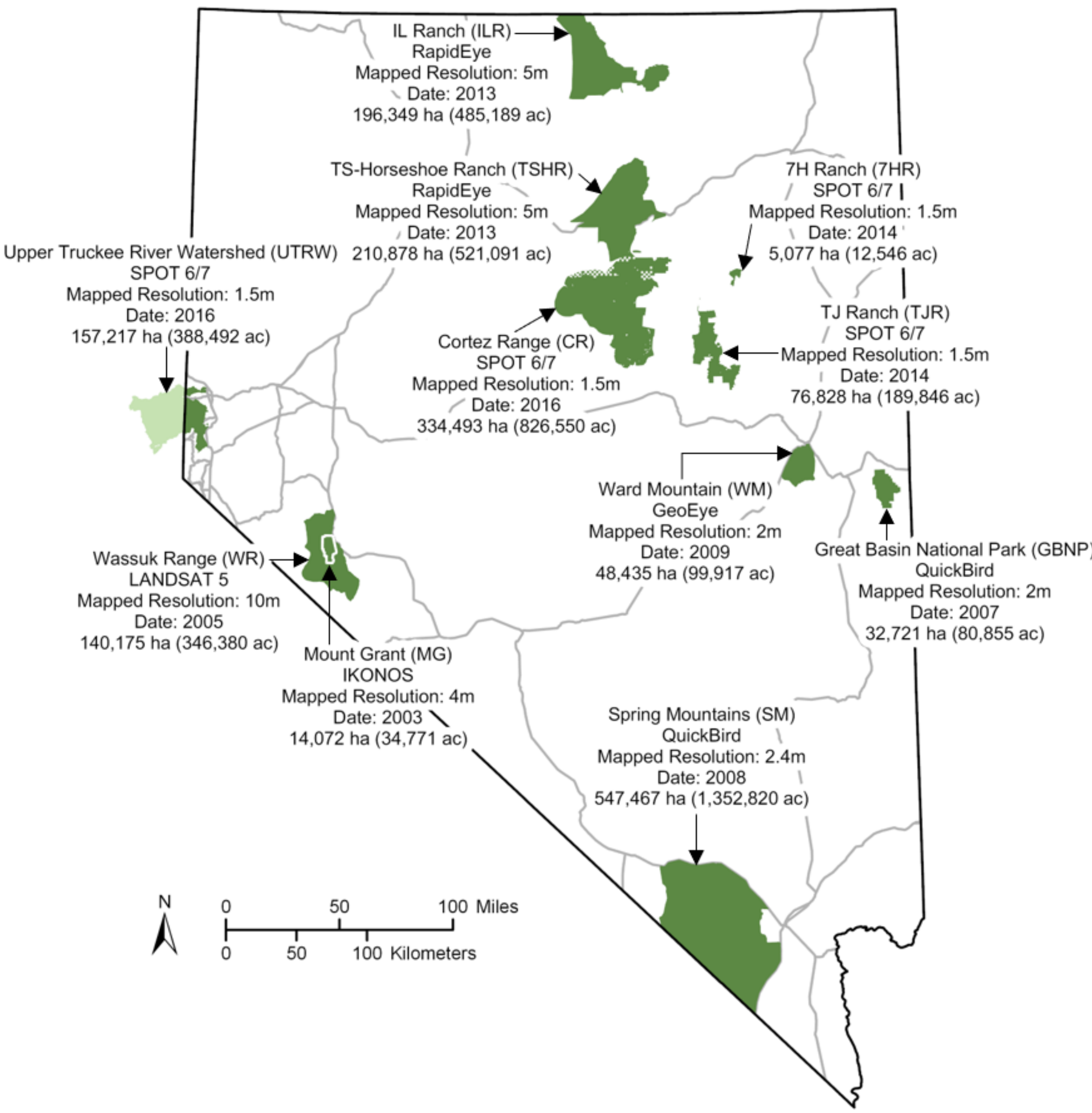

Figure 6. TNC-mapped landscapes for ecological departure analysis, including source of remote sensing, mapped spatial resolution, date of capture, and area of landscape.

Two types of raster maps were created for each of our study landscapes from the satellite imagery. The first map describes the *ecological system* for each pixel. The ecological system describes the site potential based on dominant vegetation type and abiotic factors. The second map type is the *vegetation class,* which describes the current composition and structure of the vegetation. Vegetation classes describe the various states possible within an ecological system. Vegetation classes that do not reflect composition or structure expected under NRV are called "uncharacteristic classes."

If current conditions are known for a landscape, the NRV can be a helpful standard to understand where the landscape deviates from historical condition and what actions may be taken to improve degraded areas (Keane et al., 2009). ED was developed as a standardized departure metric to measure how much a system varies from the expected NRV conditions (Barrett et al., 2006), with lower scores indicating systems that are closer to NRV. Mathematically, ED is calculated as (Low et al., 2010):

$$ED\ (\%) = 100\% - \sum_{i=1}^{n} \min\{Current_i, NRV_i\} \quad (1)$$

where

$Current_i$ = current percentage of landscape in a given vegetation class

NRV_i = expected percentage of the landscape in a given vegetation class

We categorized ED into three tiers: low departure (< 34 %), moderate departure (34-66 %), and high departure (>66 %). For a given landscape, ED is calculated for each vegetation system (not across them).

Twelve ecological systems were identified as being iGDE systems (Table 1) where the site potential suggests phreatophytes would dominate, whether the site is currently occupied by a phreatophyte or not. For example, a site currently dominated by non-native cheatgrass (*Bromus tectorum* L.), a non-phreatophyte, is still considered an iGDE if the system is classified as a phreatophytic shrubland, such as black greasewood (*Sarcobatus vermiculatus* (Hook.) Torr.*)*. As the predicted causes of uncharacteristic classes are explicitly listed in the STSMs, we can make assumptions about the causes of degradation and actions to reverse the impacted sites.

We used a weighted average to assess overall condition of each iGDE *across* landscapes to account for the variation in each iGDE system's area in different landscapes. The weighted average was based on the relative area of a given ecological system within a landscape compared to the total area for that ecological system. We used a similar weighted average approach to assess iGDE condition *within* landscapes where ED scores were weighted by the area of each iGDE type relative to the total iGDE areas for that landscape.

RESULTS

Nevada iGDE database and story map development

Of the 28.6 million ha (70.8 million acres) of Nevada, we classified at least 10% of Nevada as having an iGDE as of May 2019. Black greasewood shrublands covered more than 800,000 ha (over 2 million ac), making them the most extensive groundwater dependent vegetation type in Nevada. There are more than 300,000 ha (800,000 ac) of groundwater dependent meadows, and over 360,000 ha (900,000 ac) of groundwater dependent forests in Nevada. More than 25,000 springs were documented in the database. 175 of Nevada's 256 hydrographic areas had all 5 iGDE types represented in the story map and database (i.e., phreatophytic communities, wetlands, springs, lakes and playas, and rivers and streams; Figure 7).

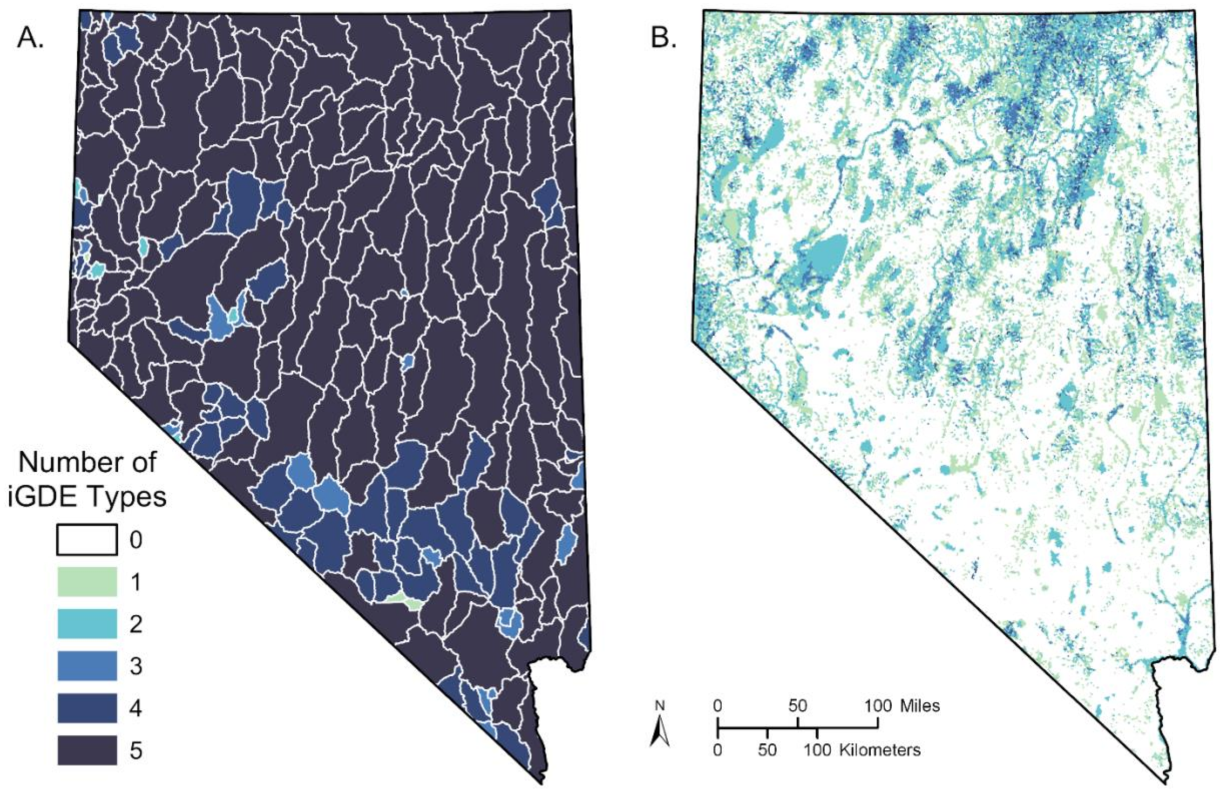

Figure 7: Summary map of iGDEs that quantifies the number of story map layers (i.e., Phreatophyte Communities, Wetlands, Springs, Lakes and Playas, or Rivers and Streams) in each a) hydrographic area and b) 2.59 km^2 (1 mi^2) hexagon.

Ecological departure analysis

Across landscapes, the montane riparian system had, on average, the highest ED (i.e., it was less similar to NRV conditions), was the only system classified in the highest departure category (i.e., greater than an ED of 67, Table 2), and was moderately to highly departed in each landscape. Wet meadow-montane, the only other system found on all the landscapes, varied greatly in its ED. While the weighted average indicated low departure across all landscapes, the ED scores ranged from 7.5 (low departure) to 98.4 (high departure). Among the rest of the GDEs, 5 were in low departure (i.e., less than an ED of 33) and 6 were in moderate departure (i.e., ED between 33 and 66, Table 2).

iGDE condition within landscapes varied from ED values as low as 16.7 (low departure) to a high of 78.1 (high departure) at Cortez Range and Mt. Grant, respectively (Table 2). Greasewood, which was largely intact at Cortez Range, accounted for approximately 80% of the GDEs in that landscape (data not shown). The landscape with the highest ED, Mt. Grant, only had a total of 116 ha of iGDE, suggesting potential skew due to low sampling size. Two of the 11 landscapes were highly departed, and 6 were moderately departed.

Table 2. Ecological departure (ED) for the iGDEs found across the 11 mapped landscapes. Lower ED values indicate the system is closer to the estimated natural range of variation for that system. Green, yellow, and red colors indicate the categories of "low departure" (0-33), "moderate departure" (34-66), and "high departure (67-100), respectively. An asterisk (*) indicates ecological systems with small total areas (i.e., less than 100 ha) that have more uncertain system weighted average ED estimates due to the low sample size. See Figure 6 for landscape abbreviations and Table 1 for iGDE system abbreviations.

	iGDE System												
Landscape	AW	AMC	GW	JPR	LPW	Mes	MR	PPR	SM	WMB	WMM	Wet	Landscape Weighted Avg.
MG	--	--	--	--	--	--	91.4	--	--	--	18.1	--	78.1
WR	34.6	--	10.8	--	--	--	73.4	--	--	--	98.4	--	68.2
GBNP	37.6	63.2	--	--	--	--	70.0	34.2	--	--	12.0	--	61.0
SM	--	39.9	--	--	--	58.3	81.4	--	--	--	88.7	--	58.0
WM	57.1	47.4	--	--	--	--	77.7	--	--	--	7.5	--	50.8
ILR	21.4	53.7	--	--	--	--	59.1	--	--	--	27.1	--	34.7
TSHR	37.6	--	38.9	--	--	--	66.3	--	61.8	24.3	25.1	59.5	41.8
7HR	27.7	--	100.0	--	--	--	68.9	--	17.2	--	76.0	27.4	40.1
CR	25.1	--	10.9	--	--	--	75.3	--	39.3	--	37.5	4.1	16.7
TJR	21.5	--	10.9	--	--	--	82.7	--	27.5	--	9.1	20.1	16.8
UTR	--	18.0	--	26.7	53.5	--	55.1	--	--	--	22.0	0.7	30.6
System Weighted Average	**30.9**	**48.5**	**26.1**	**26.7***	**53.5**	**58.3**	**67.9**	**34.2***	**42.8**	**24.3***	**29.2**	**47.3**	

At the time that these landscapes were mapped, the majority of the iGDEs were classified in a reference class (Table 3). This indicates that the ED scores were mostly driven by the differences in the distribution of reference classes compared to NRV, as opposed to high occurrence of uncharacteristic classes. Among the ecological systems, mesquite had the highest percentage of uncharacteristic classes (Table 3); this was due to the high amounts of bare ground that were caused, in part, by excessive off-highway vehicle use. Higher elevation systems (e.g., aspen woodland, aspen-mixed conifer, Jeffrey pine riparian, ponderosa pine riparian, and lodgepole pine-wet) tended to have lower proportions of uncharacteristic classes. Non-native plant species were the most common cause of departure, being found in 6 of the ecological systems (Table 3).

Table 3. Distribution of vegetation across the iGDE systems based on state-and-transition degradation processes. "Reference classes" are those expected in the natural range of variation. The other categories reflect a suite of vegetation classes. "Fire suppression" indicates where the natural fire regime has been interrupted. "Inappropriate grazing" is the historic or contemporary degradation due to non-native ungulates. "Lowered water table" indicates where changes to hydrogeomorphology have caused the water table to drop. "Non-native plants" is the presence or dominance of exotic plant species. "Misc." are unknown or hard to identify causes of degradation.

iGDE System	Reference classes	Fire Suppression	Inappropriate Grazing	Lowered water table	Non-native plants	Misc.
AW	93%	7%	0%	0%	0%	0%
AMC	96%	4%	0%	0%	0%	0%
GW	74%	0%	0%	0%	24%	2%
JPR	100%	0%	0%	0%	0%	0%
LPW	100%	0%	0%	0%	0%	0%
Mes	68%	0%	0%	0%	0%	32%
MR	79%	0%	1%	11%	1%	7%
PPR	100%	0%	0%	0%	0%	0%
SM	78%	0%	17%	0%	5%	0%
WMB	76%	0%	0%	0%	24%	0%
WMM	81%	0%	8%	6%	1%	5%
Wet	76%	0%	0%	0%	24%	0%
Average	**79%**	**1%**	**2%**	**1%**	**15%**	**3%**

DISCUSSION

Nevada iGDE database and story map

The effort to map iGDEs throughout Nevada revealed the extent of different types of ecological systems that rely on groundwater for their structure and function. Many of Nevada's GDEs are typical of arid areas by being isolated wet spots with endemic species while also providing critical habitat and water sources for plants and wildlife (Davis et al., 2017; Glazer and Likens, 2012). Sustainable groundwater management involves development and use of groundwater such that it does not cause unacceptable environmental, economic or social consequences over the long term (Alley et al., 1999). With almost all types of iGDEs in every hydrographic basin in Nevada, consideration of groundwater needs for these systems is important for groundwater sustainability for the long-term. We are currently using the database to assess stressors and threats to GDEs in Nevada to help us identify strategies to address groundwater sustainability that includes ecological systems.

The database has some limitations that are important to consider. We used the best available data and methods to develop this database, but it is possible that useful datasets were not made available to the project team during this study. All data in the database are static although the data sources and GDEs themselves will change over time. As data sources like Springs Online or the NNHP Biotics database are updated, their data will be more representative of particular GDEs and species. Springs may become dry during drought cycles, waterways may be altered by people for different purposes, or other changes may occur on the ground that will not be reflected in the database or story map unless it is updated.

Given that much of the NWI data from the 1980s was not used in the wetlands layer due to poor data quality, there may be some undercounting in those areas for features that were also not mapped by the other data sources. While the Landsat-based MRVN product detected most wetland features, it does not carry attributes indicating wetland type like NWI does. USFWS NWI map data for Nevada is being progressively updated in selected project subareas on a semi-annual basis, and any future work to update the iGDE database should incorporate the latest NWI release. A benefit of compositing multiple data sources for the wetlands map layer is that the metadata indicating the different sources associated with each mapped polygon also provides an indication of confidence in that mapped feature.

We also note that iGDEs like wet meadows and aspen woodlands are often relatively small in size and may not be detected with 30-m spatial resolution datasets like LANDFIRE and Landsat. Multiple (commonly 5-7) pixels are required for analysis software to detect a coherent spectral signature correlated to vegetation (Lillesand and Kiefer, 2000); therefore, small wet systems will be undetected when the majority of adjacent pixels covering and surrounding a wet system are dominated by upland vegetation. Thus, the actual land area covered by iGDEs in Nevada may be greater and more dissected than shown in the iGDE database.

Another consideration in the mapping is that while we are mapping iGDEs as community types, individual species are what respond to changes in water availability. For example, pine species such as Jeffrey and ponderosa pine are not considered phreatophytic. However, the riparian areas that support these species get varying amounts of groundwater inputs. We chose to include these types of communities because of the uncertainty about how much groundwater is being used by these types.

NHD data were used in the iGDE database as the best available data for rivers, streams, lakes and playas. The NHD provides comprehensive information about hydrographic features nationwide. At this scale, many features are outdated or may have become inaccurate as the lakes, playas, rivers, and streams mapped in the NHD are dynamic landscape features. The sizes and shores of lakes may change with drought cycles, rivers may form new channels, and streams may be diverted into different channels. The USGS is working on the NHDPlus HR dataset (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution), an updated, quality-controlled version of the NHD, but at this time we do not have plans to incorporate the updated NHDPlus HR dataset into the NV iGDE database.

In general, we did not do an explicit assessment of error for the datasets used in the NV iGDE database. There are positional accuracy assessments for the NHD (https://www.usgs.gov/faqs/what-positional-accuracy-national-hydrography-dataset-nhd?qt-news_science_products=0#qt-news_science_products) and vegetation classification error assessments for the LANDFIRE datasets (https://www.landfire.gov/dp_quality_assessment.php).

Furthermore, TNC conducted an accuracy assessment of LANDFIRE data for a large landscape in western Nevada where accuracy was at best 50% for ecological systems (Provencher et al. 2009a). Remote sensing products for TNC datasets were ground-truthed and a limited mapping accuracy assessment done for one of the projects had ≥90% accuracy. For the DRI phreatophyte dataset, field investigations were used to confirm the presence of phreatophyte indicator species when remote sensing, water level data, and other ancillary datasets were scarce. No formal accuracy assessment of the potential groundwater discharge boundary dataset was conducted because the data are a compilation of previous delineations that used various methods of data collection and development. Metadata for the DRI wetland map of Nevada provides an estimated statewide accuracy for binary wetland/non-wetland distinctions to be 90% based on 300 photo-interpreted test points.

We also acknowledge the existence of overlapping data between some of the database layers. In particular, the Phreatophyte Communities and Wetlands layers have overlap because although not all wetlands have phreatophytes, many wetland communities are composed of both phreatophytes and non-phreatophytic vegetation. The scale of mapping for statewide data products can dictate a minimum mapping unit dimension that will preclude delineations between vegetation communities in upland versus lowland positions within a wetland complex. Further, the high interannual variability and very seasonal pattern of inundation in arid environments like Nevada can make the distinction of boundaries between perennial wetland and nearby phreatophytes difficult to determine from single date imagery. Therefore, it is difficult to separate wetlands from phreatophyte communities. Aspen Woodland polygons from the Phreatophyte Communities layer and Riparian polygons from the Wetlands layer commonly overlap. Some phreatophytic plants do not live in wetlands, and these are easier to classify as Phreatophyte Communities. Greasewood, for example, composes phreatophyte-dominated communities in drier areas and would not usually be considered “wetland,” but due to differences in mapping methods between the input datasets to the Phreatophyte Communities and Wetlands layers and the inundation status at the time of mapping, some phreatophytes like greasewood communities may be represented by both layers (Figure 8).

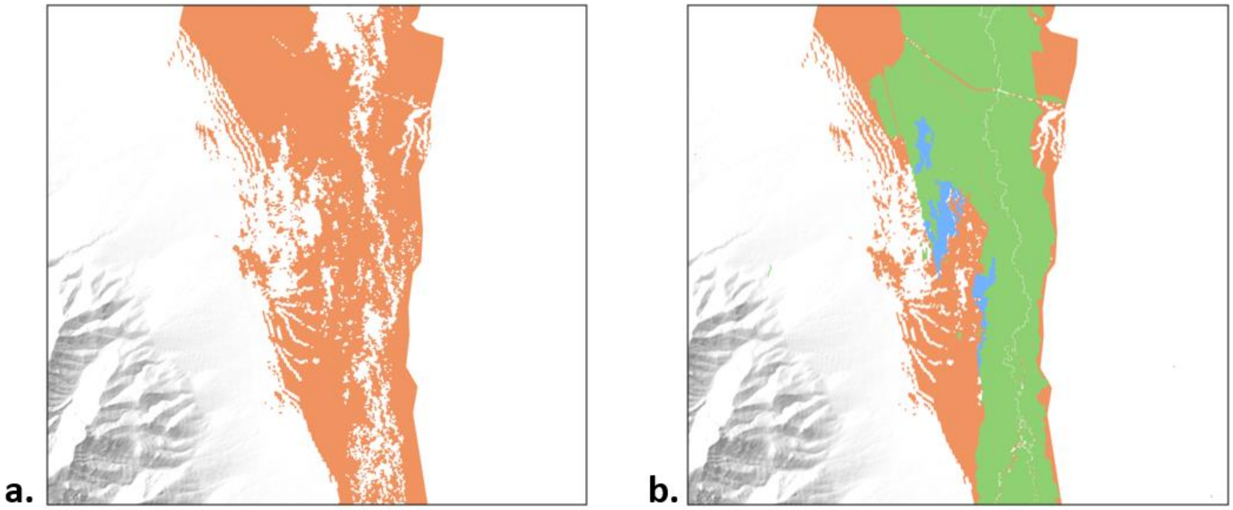

Figure 8: Illustration of overlap between Phreatophyte Communities and Wetlands layers of the NV iGDE database. (a) Greasewood mapped in orange in the Phreatophytes Communities layer in Steptoe Valley in eastern Nevada. (b) Features from the Wetlands layer mapped over the greasewood. According to the Wetlands layer, some of the area mapped as greasewood may also be considered palustrine (green) or playa (blue) wetland.

Ecological departure analysis

The detailed look at ecological departure for the 11 landscapes across Nevada revealed that montane riparian systems were most departed across all TNC mapped landscapes, whereas higher elevation systems were less departed and had lower proportions of uncharacteristic classes. The most widespread type of degradation was the presence of non-native species, with lower elevation systems tending to have more non-native species. This result follows hypotheses regarding higher elevation systems being more resistant to invasion (Guo et al., 2018) and areas with greater human access having higher rates of invasion (Hudgins et al., 2017) because higher elevation iGDEs are often less accessible than lower elevation ones.

We also note that types of degradation can interact and such interactions are not represented in Table 3. For example, while inappropriate grazing was listed as the main type of degradation in only 3 ecological systems, grazing interacts with many of the other issues (e.g., lowered water table, non-native plants, and fire suppression). Additionally, degradation such as non-native presence may be an indicator of an underlying process, rather than the main perturbation. The relative distribution of reference classes can also be sufficiently departed from NRV, causing high ecological departure (e.g., the entire system is mostly found in one of many possible successional vegetation classes) due to past land management (e.g., fire exclusion, grazing management, etc.). In addition, changes in ecological processes do not uniformly impact a species across stages of its life history (e.g., seeding, juvenile, mature, etc.). If a perturbation causes mortality in the juvenile stage more dramatically than the mature stage, one might expect a shift away from the NRV as the ratio of juvenile to mature stages become more skewed.

While use of remote sensing and STSMs can be a powerful tool, all impacts to GDEs are not captured by a single remote sensing capture. Moreover, remote-sensed spectral variation in plant productivity due to consecutive wet and dry years can be greater in the short term than any slow ecological community change. The conversion of phreatophytic communities such as greasewood due to lowered water tables may be a slow process that is not effectively captured in a remote sensing snapshot. For example, a drop of the groundwater table below maximum rooting depth (2.5-3 m) could progressively thin greasewood community shrub cover and open up exposed soil to non-native annual species invasion much before a shift to an upland community type (Devitt and Bird, 2016; Donovan et al., 1996; Elmore et al., 2006; Ganskopp, 1986; Harr and Price, 1972; Provencher et al. *in review*). Thus, repeated measures (whether they are remote sensing or field-based) and trend analysis are needed to truly detect a shift away from NRV in such cases.

CONCLUSION

Over 10% of Nevada's land area includes iGDEs, highlighting the importance of groundwater for sustaining plants and wildlife in the state. iGDEs in montane riparian systems were the most ecologically departed from reference classes across 11 landscapes in Nevada that total over 1.6 million ha (4 million ac). Current condition of iGDEs indicate that these systems do not reflect historic vegetation composition or structure. Future work involves using the database to examine potential stressors and threats to GDEs, and development of strategies and priorities for sustaining GDEs and their ecosystem services for people, plants, and wildlife.

DATA AVAILABILITY

The story map is found at https://arcg.is/qyj0v and the database is available for download at http://heritage.nv.gov/wetlands. Scripts to integrate the spatial and non-spatial datasets of the GIS can be found on Github at https://github.com/sbyer-tnc/Nevada-iGDE.

REFERENCES

Abele SL, Low G, Provencher L. 2010. Ward Mountain Restoration Project: An ecological assessment and landscape strategy for native ecosystems in the Ward Mountain landscape. Report to the Bureau of Land Management and U.S. Forest Service, Ely, Nevada.

Alley WM, Reilly TE, Franke OL. 1999. Sustainability of ground-water resources. US Geological Survey Circular 1186. Reston: US Geological Survey. https://pubs.usgs.gov/circ/1999/circ1186/pdf/circ1186.pdf (accessed 12/31/19)

Barlow PM, Leake SA. 2012. Streamflow depletion by wells: understanding and managing the effects of groundwater pumping on streamflow. US Geological Survey Circular 1376. Reston: US Geological Survey. https://pubs.usgs.gov/circ/1376/ (accessed 12/31/19)

Barrett SW, DeMeo T, Jones JL, Zeiler JD, Hutter LC. 2006. Assessing ecological departure from reference conditions with the Fire Regime Condition Class (FRCC) mapping tool.

In: Andrews, P.L., Butler, B.W. (Eds.), Fuels Management – How to Measure Success. Portland (OR): USDA Forest Service Rocky Mountain Research Station, pp. 575–585.

Brown J, Bach L, Aldous A, Wyers A, DeGagné J. 2011. Groundwater-dependent ecosystems in Oregon: an assessment of their distribution and associated threats. Frontiers in Ecology and the Environment 9(2):97-102. doi: 10.1890/090108.

Byer S, Saito L, Badik K, Provencher L, Anderson T, Larkin J, McGwire K. 2019. Indicators of Groundwater Dependent Ecosystems in Nevada: Methods Report. Reno: The Nature Conservancy. Available at https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/nevada/water/Pages/database-collaboration.aspx (accessed 4/20/20).

Davis JA, Kerezsy A, Nicol S. 2017. Springs: Conserving perennial water is critical in arid landscapes. Biological Conservation 211:30-35. http://dx.doi.org/10.1016/j.biocon.2016.12.036.

Devitt DA, Bird B. 2016. Changes in groundwater oscillations, soil water content and evapotranspiration as the water table declined in an area with deep rooted phreatophytes. Ecohydrology 9:1082-1093. https://doi.org/10.1002/eco.1704

Dieter CA, Maupin MA, Caldwell RR, Harris MA, IVahnenko TI, Lovelace JK, Barber NL, Linsey KS. 2017. Estimated Use of Water in the United States in 2015. US Geological Survey Circular 1441. Reston: US Geological Survey, 65 pp. https://pubs.usgs.gov/circ/1441/circ1441.pdf (accessed 11/27/19)

Donovan LA, Richards JH, Muller MW. 1996. Water relations and leaf chemistry of *Chrysothamnus nauseosus* spp. *consimilis* (Asteraceae) and Sarcobatus vermiculatus (Chenopodiaceae). American Journal of Botany. 83:1637-1646.

Eamus D, Froend R, Loomes R, Hose G, Murray B. 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. Australian Journal of Botany 54(2): 97-114.

Elmore AJ, Manning SJ, Mustard JF, Craine JM. 2006. Decline in alkali meadow vegetation cover in California: the effects of groundwater extraction and drought. Journal of Applied Ecology 43:770-779. http://dx.doi.org/10.1111/j.1365-2664.2006.01197.

[ESRI] Environmental Systems Research Institute. 2018. ArcGIS Pro Version 2.2 and ArcPy module. Windows, Redlands, CA.

Ganskopp DC. 1986. Tolerances of sagebrush, rabbitbrush, and greasewood to elevated water tables. Journal of Range Management 39:334-337.

Glazer AN, Likens GE. 2012. The water table: the shifting foundation of life on land. Ambio 41:657-669. DOI.10.1007/s13280-012-0328-8.

Gleeson T, Alley WM, Allen DM, Sophocleous MA, Zhou Y, Taniguchi M, VanderSteen J. 2012. Towards sustainable groundwater use: setting long-term goals, backcasting, and managing adaptively. Groundwater 50(1): 19-26.

Gleeson T, Richter B. 2017. How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. River Research and Applications 34(1): 83-92. DOI: 10.1002/rra.3185

Guo Q, Fei S, Shen Z, Iannone BV, Knott J, Chown SL. 2018. A global analysis of elevational distribution of non-native versus native plants. Journal of Biogeography 45:793-803.

Harr RD, Price KR. 1972. Evapotranspiration from a greasewood-cheatgrass community. Water Resources Research 8:1199-1203

Hudgins EJ, Liebhold AM, Leung B. 2017. Predicting the spread of all invasive forest pests in the United States. Ecology letters 20(4): 426-435.

[IWRA] International Water Resources Association. 2017. Policy Brief: Groundwater and Climate Change: Multi-level Law and Policy Perspectives. Water International, No. 8. 4 p. https://www.iwra.org/wp-content/uploads/2017/10/PB-N8-web.pdf (accessed 12/31/19).

Kath J, Boulton AJ, Harrison ET, Dyer FJ. 2018. A conceptual framework for ecological responses to groundwater regime alteration (FERGRA). Ecohydrology 11:e2010. https://doi.org/10.1002/eco.2010.

Keane RE, Hessburg PF, Landres, Swanson FJ. 2009. The use of historical range and variability (HRV) in landscape management. Forest Ecology and Management 258: 1025-1037.

King J. 2019. Groundwater management in Nevada. Presentation to American Water Resources Association Summer Specialty Conference. Reno, NV. https://www.waterwired.org/2019/06/jason-king-awra-presentation-groundwater-management-in-nevada-the-good-the-bad-and-the-ugly-1.html (accessed 12/31/19).

Klausmeyer K, Howard J, Keeler-Wolf T, Davis-Fadtke K, Hull R, Lyons A. 2018. Mapping Indicators of Groundwater Dependent Ecosystems in California: Methods Report. San Francisco, CA: The Nature Conservancy.

LANDFIRE. 2014. Biophysical Settings, LANDFIRE 1.4.0. U.S. Department of Interior, Geological Survey. Website: www.landfire.gov (accessed 6/20/18)

Lillesand TM, Kiefer RW. 2000. Remote sensing and image interpretation. Fourth Edition, New York: John Wiley & Sons Inc. 763 p.

Low G, Provencher L, Abele S. 2010. Enhanced conservation action planning: assessing landscape condition and predicting benefits of conservation strategies. Journal of Conservation Planning 6:36-60.

McGwire K. 2019. Optimized stratification for mapping riparian vegetation in arid and semiarid environments. Remote Sensing 11(14):1638. DOI:10.3390/rs11141638

Mifflin MD. 1988. Chapter 8: Region 5, Great Basin. Pp. 69-78 in Back w, Rosenshein JS, Seaber PR. The Geology of North America, Volume O-2: Hydrogeology. Boulder: The Geological Society of America.

Minor BA, Huntington JL, Bromley M. 2019. Potential Groundwater Discharge Boundaries and Evapotranspiration Units in Nevada. Vers. 1.0. Reno: Desert Research Institute. Available at https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/nevada/water/Pages/database-collaboration.aspx (accessed 4/20/20)

[NDOW] Nevada Department of Wildlife. 2019. Nevada Crucial Habitat Assessment Tool. http://www.ndow.org/Nevada_Wildlife/Maps_and_Data/NVCHAT/ (accessed 1/2/20).

[NNHP] Nevada Natural Heritage Program. 2019. Biodiversity and At-Risk Species. http://heritage.nv.gov/species_info (accessed 12/31/19).

Provencher L. 2008. Fire Regime Condition Class Mapping for the Spring Mountains Southern Nevada. Final Report to the U.S. Forest Service Spring Mountains National Recreation Area USDA Forest Service Solicitation AG-9360-S-08-0004. The Nature Conservancy, Reno, Nevada.

Provencher L, Anderson T, Badik K, Cameron M, Munn L, Welch N. 2016. Sage-grouse conservation forecasting for Newmont Mining's IL and TS-Horseshoe Ranches. Final report by The Nature Conservancy in Nevada to Newmont Mining Corp., Elko, NV. The Nature Conservancy, Reno, NV.

Provencher L, Anderson T, Low G, Hamilton B, Williams T, Roberts B. 2013. Landscape Conservation Forecasting™ for Great Basin National Park. Park Science 30: 56-67.

Provencher L, Badik K, Anderson T, Munn L, Cameron M. 2017. Sage-Grouse conservation forecasting for Barrick's Bank Study Area and Deep South Expansion Projects Plan of Operations Study Area. Report by The Nature Conservancy in Nevada to Barrick Gold Corp., Elko, NV, Version 1.0. The Nature Conservancy, Reno, NV

Provencher L, Blankenship K, Smith J, Campbell J, Polly M. 2009a. Comparing Locally Derived BpS and LANDFIRE Geo-Layers in the Wassuk Range, NV. Fire Ecology 5:98-104.

Provencher L, Campbell J, Nachlinger J. 2008. Implementation of mid-scale fire regime condition class mapping. International Journal of Wildland Fire 17:390-406.

Provencher L, Low G, Anderson T. 2010. Landscape Conservation Forecasting™ report to Great Basin National Park. The Nature Conservancy, Reno, NV.

Provencher L, Low G, Abele SL. 2009b. Bodie Hills conservation action planning: final report to the Bureau of Land Management Bishop field office. The Nature Conservancy, Reno, NV.

Provencher L, Saito L, Badik KJ, Byer S. *In review*. All systems are equal: In defense of undervalued phreatophytes. Submitted to Rangelands.

Python Software Foundation. 2018. Python Language Reference, Version 3.6. Available at https://www.python.org/

Rohde MM, Froend R, Howard J. 2017. A global synthesis of managing groundwater dependent ecosystems under sustainable groundwater policy. Groundwater 55(3):293-301.

Rollins MG. 2009. LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. International Journal of Wildland Fire 18:235-249.

Rosen MR. 1994. The importance of groundwater in playas: A review of playa classifications and the sedimentology and hydrology of playas. Geological Society of America Special Papers 289:1-18. Doi: 10.1130/SPE289-p1

Siebert S, Burke J, Faures JM, Frenken K, Hoogeveen J, Döll P, Portmann FT. 2010. Groundwater use for irrigation – a global inventory. Hydrol. Earth Syst. Sci. 14:1863-1880. doi:10.5194/hess-14-1863-2010.

Trowbridge W, Chambers JC, Germanoski D, Lord ML, Miller JR, Jewett DW. 2011. Classification of meadow ecosystems based on watershed and valley segment/reach characteristics. Pp. 95-112 in: Chambers JC, Miller JR, eds. Geomorphology, Hydrology and Ecology of Great Basin Meadow Complexes: Implications for Management and Restoration. Gen. Tech. Rep. RMRS-GTR-258 Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Winter TC, Harvey JW, Franke OL, Alley WM. 1998. Ground Water and Surface Water: A Single Resource. US Geological Survey Circular 1139. Denver: US Geological Survey.

Womble P, Perrone D, Jasechko S, Nelson RL, Szeptychi LF, Anderson RT, Gorelick SM. 2018. Indigenous communities, groundwater opportunities. Science 361(6401): 453-455. DOI 10.1126/science.aat6041.

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