Stressor and Threat Assessment of Nevada Groundwater Dependent Ecosystems

Torrance Ranch (S. Williams/TNC)

Laurel Saito, Sarah Byer, Kevin Badik, Louis Provencher
The Nature Conservancy

Dan McEvoy
Desert Research Institute

April 2022 (rev. May 2022)

This page intentionally left blank.

Stressor and Threat Assessment of Nevada Groundwater Dependent Ecosystems

EXECUTIVE SUMMARY

Groundwater dependent ecosystems (GDEs) are those ecosystems that rely on groundwater for all or part of their water needs. GDEs are extremely important to plants and wildlife in Nevada, the driest state in the United States, and they are also important resources for human uses, including drinking water, agriculture, water quality improvements, and recreation. However, the future viability of GDEs can be impacted directly or indirectly from human uses and activities.

In 2019, The Nature Conservancy (TNC) produced a database and maps of indicators of GDEs (iGDEs) to assist with identifying where GDEs occur across the state. The purpose of the assessment presented here was to identify and evaluate stressors and threats to GDEs in Nevada by using the TNC Nevada iGDE database along with additional best available data. For the purposes of this report, we define a **GDE stressor** as *any physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that reduces the viability of an individual, population, or a species or the viability of its habitat*, and a **GDE threat** as *a potential (or impending) physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that is reasonably likely to negatively affect an organism, population, species or its habitat.*

The authors focused on five themes of stressor and threat risk factors that are critical for the sustainability of GDEs (Table ES-1): a) groundwater withdrawals; b) climate; c) ungulates; d) non-native species; and e) additional impacts due to human development. Risk factors due to stressors and threats were assessed on a scale of 0.00 (negligible risk) to 1.00 (high risk). To assess overall risk for each iGDE in the Nevada iGDE database, the five themes of risk factors were combined using a weighted approach that assigned the highest weight to groundwater withdrawal stressors and threats, followed by climate stressors and threats, with stressor and threats due to ungulates, non-native species, and additional impacts from human development equally assigned the lowest weight. This resulted in mean risk factor values by GDE types that ranged between 0.00 and 8.00 (Figures ES-1 through ES-5).

Results were focused on highlighting the amount of five GDE types at high risk for stressor and threat risk factors: 1) springs; 2) wetlands; 3) phreatophyte communities; 4) lakes and playas; and 5) rivers and streams. Figures ES-6 and ES-7 show the amount of iGDEs at high risk for each of the stressor and threat risk factors assessed, and Figure ES-8 and Tables ES-2 and ES-3 summarize stressor and threat risks in each risk factor theme by GDE type.

Key takeaways from this assessment include:

- Overall, more than 2,000 springs, over 16,000 hectares (>40,000 acres) of wetlands, over 300,000 hectares (>700,000 acres) of phreatophyte communities, over 16,000 hectares (>40,000 acres) of lakes and playas, and over 1,300 kilometers (>1,000 miles) of rivers and streams are at moderate to high risk for combined stressor risk factors.

- Over 800 springs, over 60,000 hectares (>160,000 acres) of wetlands, almost 175,000 hectares (>425,000 acres) of phreatophyte communities, over 160,000 hectares (>400,000 acres) of lakes and playas, and over 1,000 kilometers (>650 miles) of rivers and streams are at moderate to high risk for overall combined threat risk factors.

- Among stressors overall, phreatophyte communities had the largest percentage at moderate to high risk, followed by springs and GDE rivers and streams.

- For threats overall, lakes and playas had the highest percentage at moderate to high risk, mostly due to threats for the groundwater withdrawals and climate themes.

- The stressor and threat risk factors that pose the highest risk for springs and rivers and streams are the ungulate stressor and threat risk factors, with over 22,000 springs at high risk, and over 13,000 km (over 8,000 miles) at high risk.

- More than 370,000 hectares (> 900,000 acres) of wetlands, 1.3 million hectares (3.3 million acres) of phreatophyte communities, and over 320,000 hectares (>800,000 acres) of lakes and playas are at high risk for the surface water diversions stressor risk factor.

- The proximity of potential groundwater withdrawals in areas with shallow groundwater was the threat risk factor that had the largest areas at high risk for wetlands (>850,000 hectares [>2.1 million acres]), phreatophyte communities (>1.7 million hectares [almost 4.3 million acres]), and lakes and playas (>430,000 hectares [>1 million acres]).

- On average, about one-fifth of all GDEs, regardless of type, are in hydrographic areas that had groundwater withdrawals greater than the perennial yield, which can put them at risk of having groundwater they use captured by excessive groundwater withdrawals.

- At least 40% of all GDE types are at high or moderate risk for the appropriation status threat risk factor.

- Over 70% of wetlands, phreatophyte communities, and lakes and playas are at high risk for the threat of potential groundwater withdrawals within 800 m (0.5 mile) when shallow groundwater is present.

- Out of 6,536 wells analyzed for groundwater level trends, 39% had significantly falling trends,15% had significantly rising trends, and the remainder did not have significant trends.

- Over half of the hydrographic areas in Nevada had at least one well site with significantly falling water level trends, but only 8 had most of the wells in their basins with significant falling trends.

- Over 40% of phreatophyte communities (over 800,000 hectares [~2 million acres]) are within 800 m (0.5 mile) of a well with a significantly falling water level trend, which could affect their sustainability and lead them to transition to a community with less ecological value.

- The small percentage of springs and GDE rivers and streams that were within 800 m (0.5) miles of a well with a significantly falling water level trend could reflect decisions by the Nevada State Engineer in evaluating water right applications for groundwater use near surface waters, indicate that groundwater development has been more prevalent where surface water resources are unavailable, or occur because of capture of surface water from springs, rivers, or other water bodies.

- Because they are often located in recharge areas with local flow paths at higher elevations, more springs and GDE rivers and streams are at high risk for the current climate stressor risk factor than other GDE types, and this high risk will continue into the future.

- Between 2022 and 2060 and across all Localized Constructed Analogs (LOCA) models, all hydrographic areas in Nevada had mean Standardized Precipitation and Evapotranspiration Index (SPEI) values that indicated more droughty conditions than current conditions are expected throughout the state.

- Over 20% of all GDE types were at moderate to high risk for the climate threat risk factor, with almost 50% of lakes at playas at moderate to high risk, which are important locations for endemic fish, migratory bird species, and aquatic invertebrates.

- Almost 90% of springs and over 70% of GDE rivers and streams are at high risk for ungulate stressor and threat risk factors.

- Over 60% of lakes and playas are at high risk from the non-native species presence stressor risk factor.

- Springs had the lowest percentage at high risk from the non-native species presence risk factor, which may reflect a lower rate of reporting of non-native species at springs in the databases used for this report.

- Over 60% of phreatophyte communities and GDE lakes and playas are at high risk for the surface water points of diversion stressor risk factor.

Table ES-1. Risk factors to groundwater-dependent ecosystems assessed in this report.

Theme	Risk factor	Stressor	Threat
Groundwater withdrawals			
	Water right appropriation status of hydrographic area		X
	Pumping status of hydrographic area	X	
	Proximity of GDE to potential groundwater withdrawals		X
	Nearby lowering of water tables	X	
Climate			
	Current climate	X	
	Future climate		X
Ungulates			
	Herd management areas, elk distribution areas, grazing allotments	X	X
Non-native species			
	Known presence	X	
	Road density		X
Other human development			
	Housing density	X	
	Nearby surface water diversion	X	
	Future housing density		X

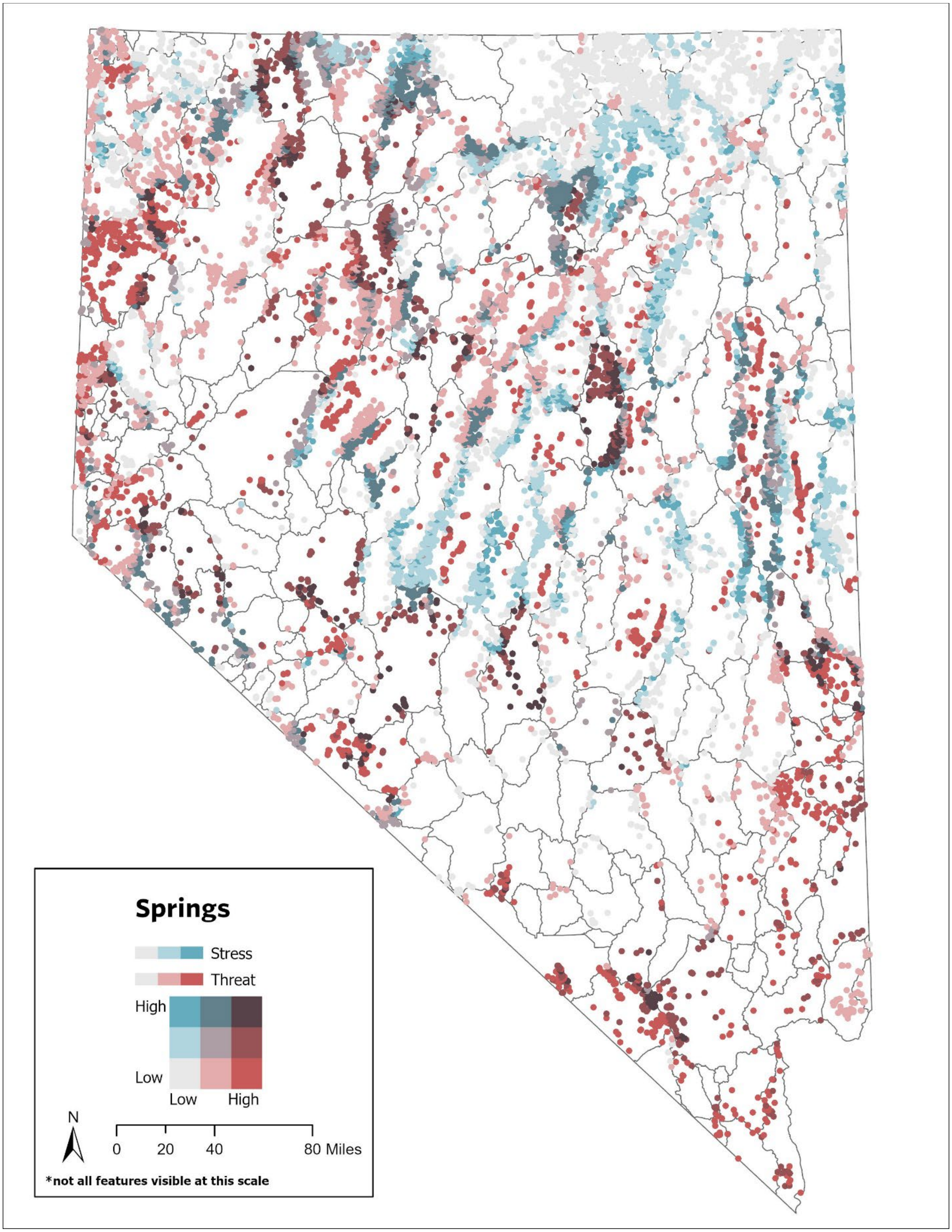


Figure ES-1. Overall stressor and threat risk factor values for GDE springs. Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

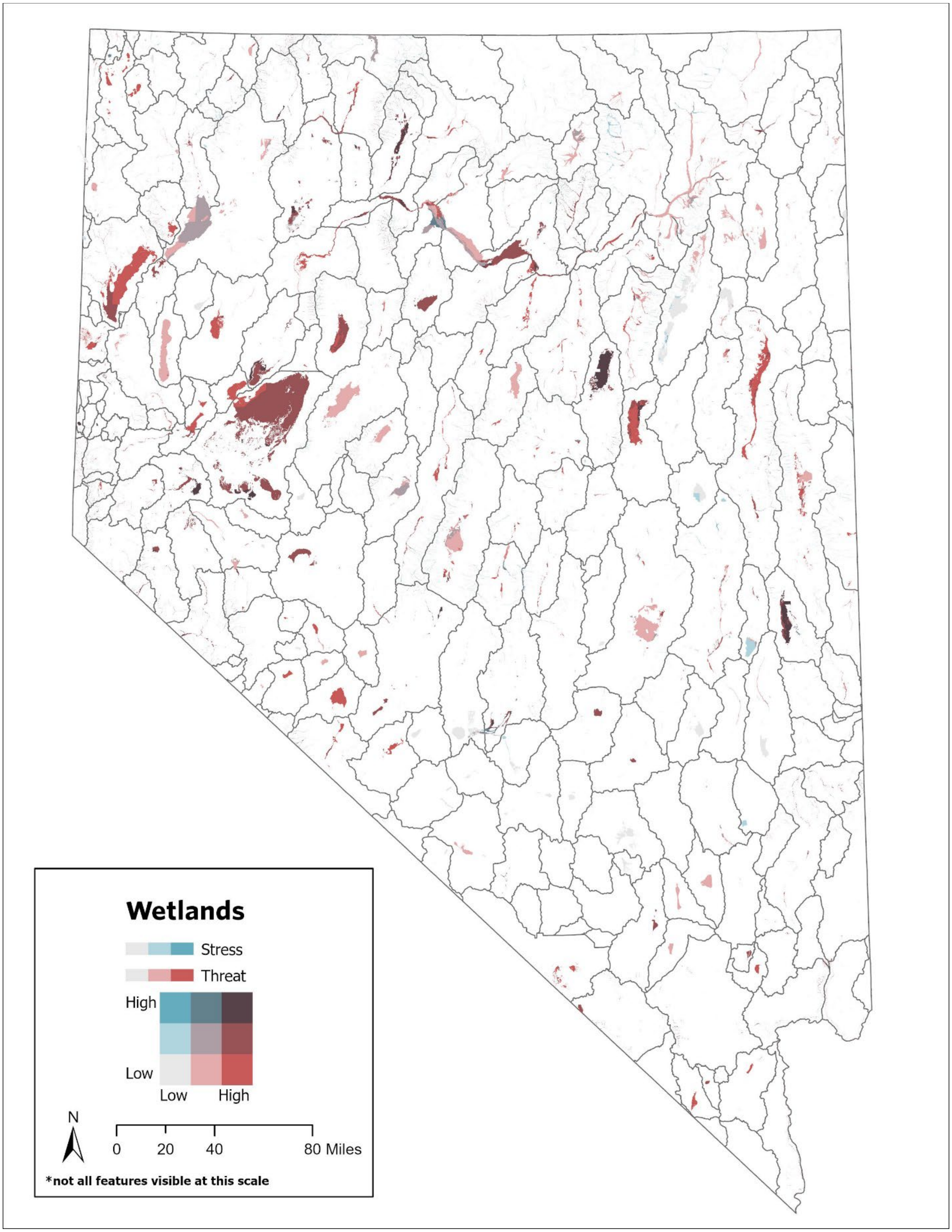


Figure ES-2. Overall stressor and threat risk factor values for GDE wetlands. Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

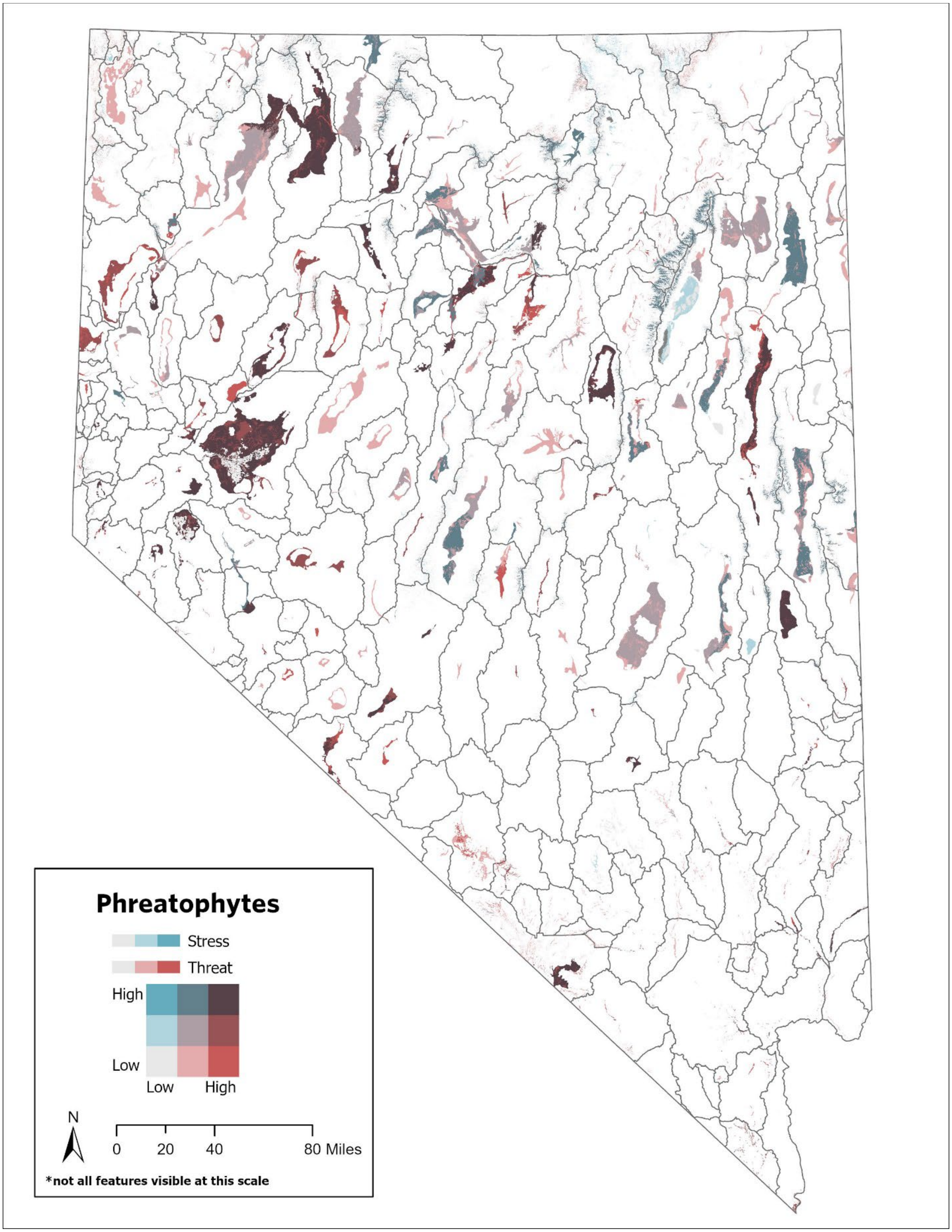


Figure ES-3. Overall stressor and threat risk factor values for GDE phreatophyte communities. Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

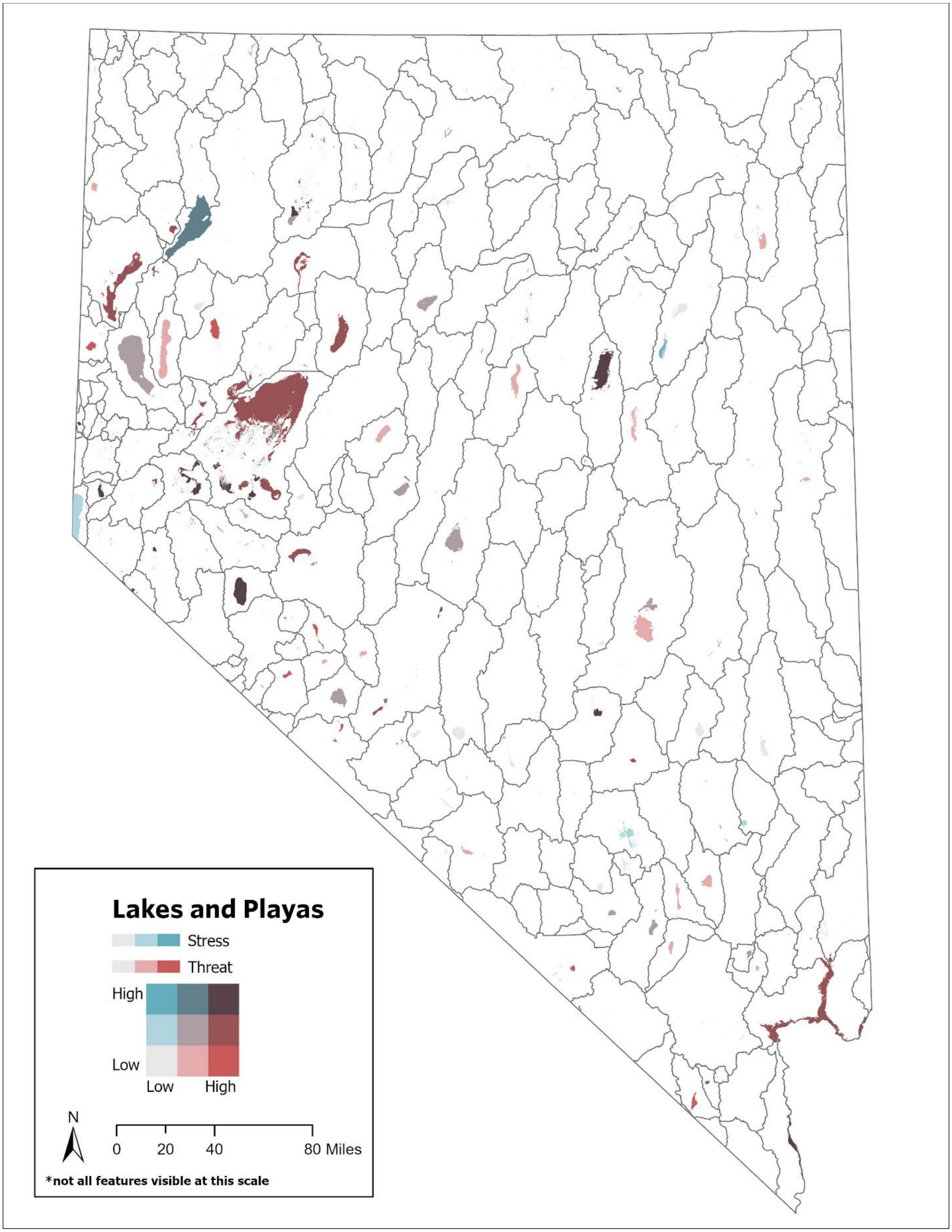


Figure ES-4. Overall stressor and threat risk factor values for GDE lakes and playas. Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

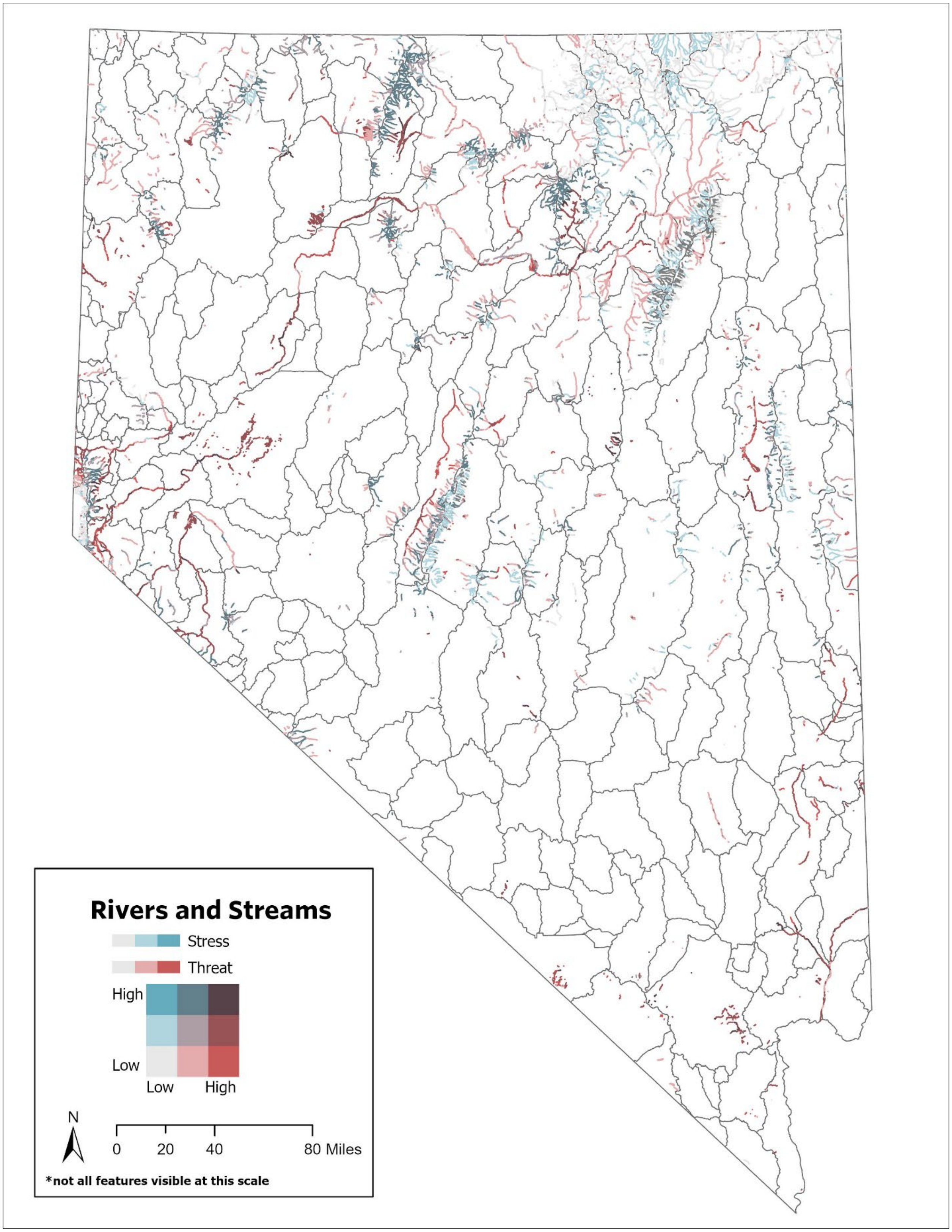


Figure ES-5. Overall stressor and threat risk factor values for GDE rivers and streams. Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

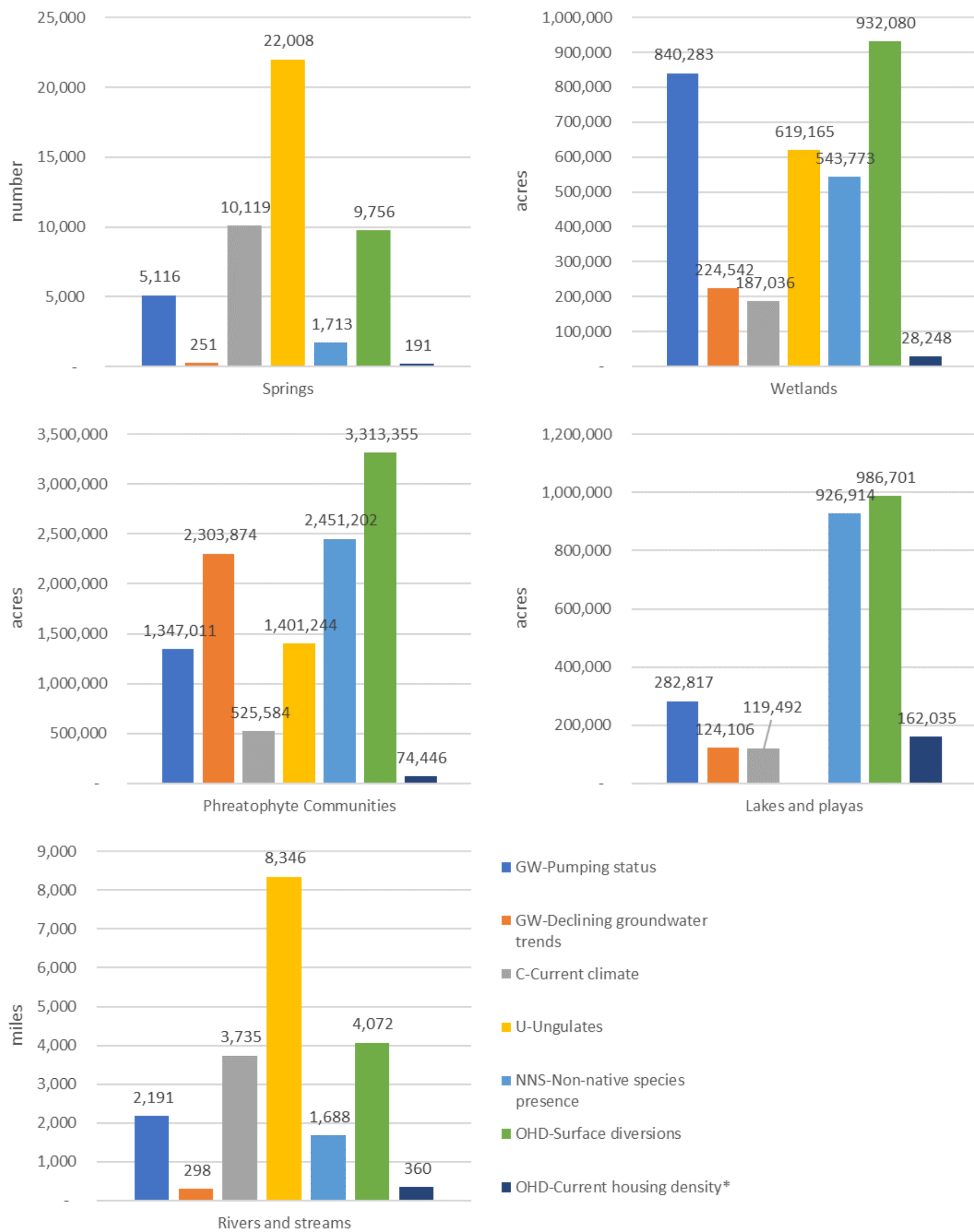


Figure ES-6. Amount of iGDEs in Nevada at high risk for stressor risk factors (asterisk [*] indicates amount of iGDEs at moderate to high risk for current housing density). Legend abbreviations for stressor risk factor themes: GW = groundwater withdrawal; C = climate; U = ungulates; NNS = non-native species; OHD = other human development

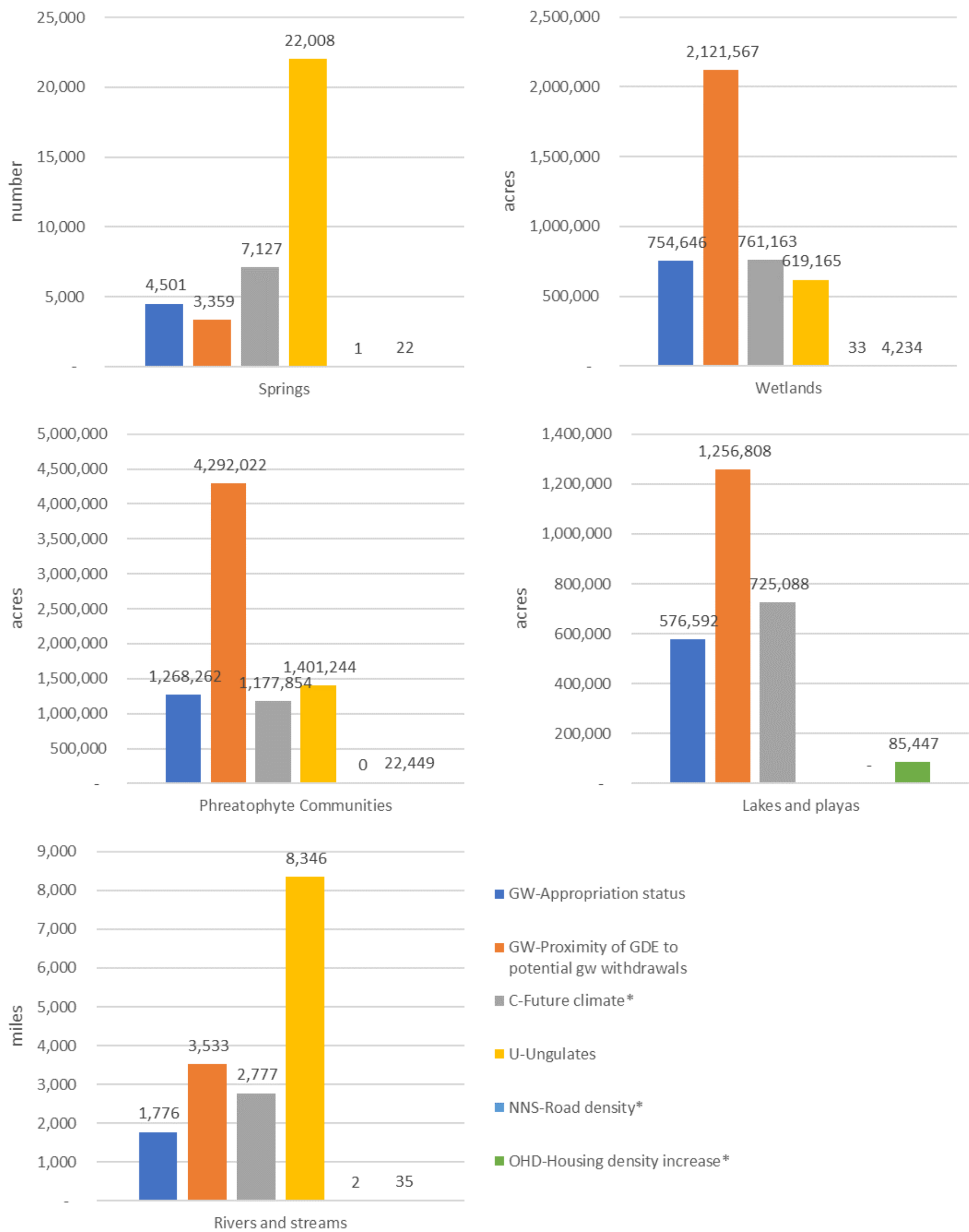


Figure ES-7. Amount of iGDEs in Nevada at high risk for threat risk factors (asterisk [*] indicates amount of iGDEs at moderate to high risk for future climate, road density and housing density increase threat risk factors). Legend abbreviations for threat risk factor themes: GW = groundwater withdrawal; C = climate; U = ungulates; NNS = non-native species; OHD = other human development

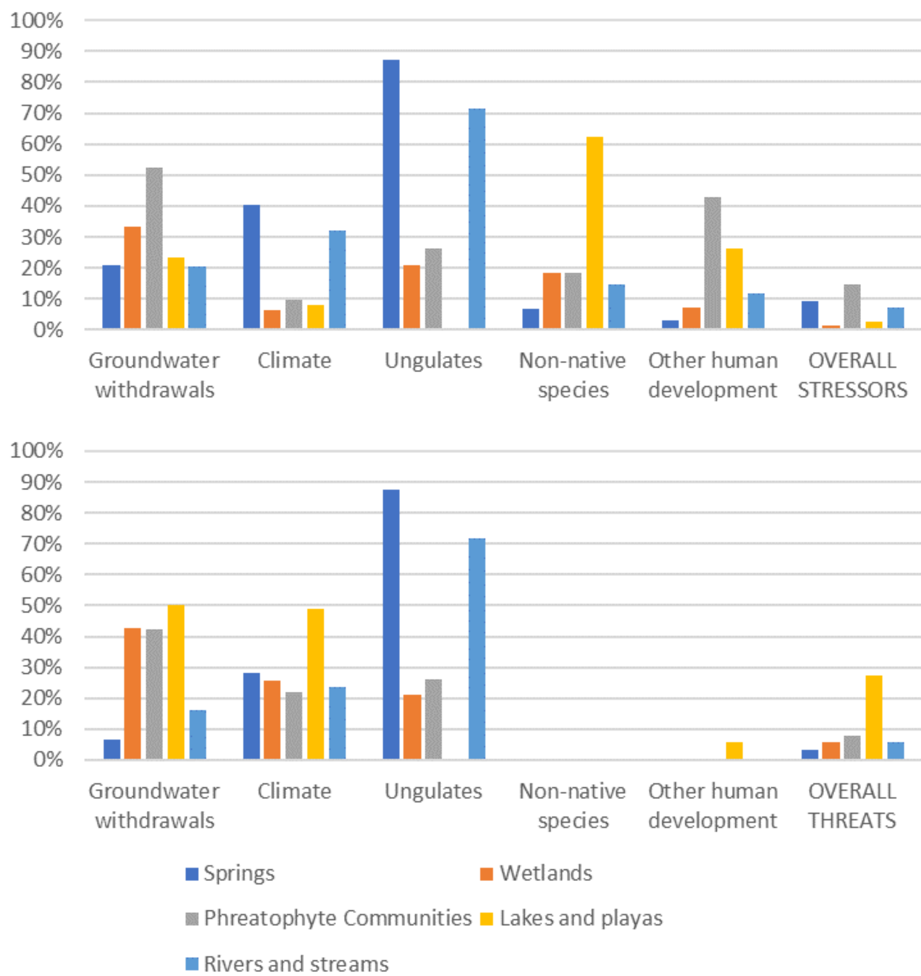


Figure ES-7. Percentages of GDE types at moderate to high risk by stressor theme (top) and threat theme (bottom). Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. PY = perennial yield.

Table ES-2. Amount of GDE types at moderate to high risk for stressor risk factors by theme and overall.

Theme	Springs (number)	Wetlands (ha / ac)	Phreatophyte communities (ha/ac)	Lakes and playas (ha/ac)	Rivers and streams (km / mi)
Groundwater withdrawals	5,299	397,464 / 982,155	1,135,113 / 2,804,922	140,523 / 347,241	3,806 / 2,365
Climate	10,119	75,691 / 187,036	212,697 / 525,584	48,357 / 119,492	6,011 / 3735
Ungulates	22,008	250,567 / 619,165	567,064 / 1,401,244	-- / --	13,431 / 8,346
Non-native species	1,713	220,057 / 543.773	991,967 / 2,541,202	375,109 / 926,914	2,716 / 1,688
Other human development	735	86,828 / 214,557	931,567 / 2,301,951	157,794 / 389,916	2,241 / 1,393
Overall stressors	2,284	16,284 / 40,238	314,650 / 777,517	16,678 / 41,212	1,322 / 821

Table ES-3. Amount of GDE types at moderate to high risk for threat risk factors by theme and overall.

Theme	Springs (number)	Wetlands (ha / ac)	Phreatophyte communities (ha/ac)	Lakes and playas (ha/ac)	Rivers and streams (km / mi)
Groundwater withdrawals	1,621	507,914 / 1,255,081	921,375 / 2,276,765	302,348 / 747,118	3,036 / 1,886
Climate	7,127	308,032 / 761,163	476,661 / 1,177,854	293,433 / 725,088	4,470 / 2,777
Ungulates	22,008	250,567 / 619,165	567,064 / 1,401,244	-- / --	13,431 / 8,346
Non-native species	1	13 / 33	0 / 0	0 / 0	4 / 2
Other human development	22	1,713 / 4,234	9,085 / 22,449	34,579 / 85,447	56 / 35
Overall stressors	807	66,746 / 164,933	173,488 / 428, 698	163,705 / 404,523	1,053 / 654

Stressor and Threat Assessment of Nevada Groundwater Dependent Ecosystems

Groundwater dependent ecosystems (GDEs) are those ecosystems that rely on groundwater for all or part of their water needs. GDEs include species and ecological communities such as wetlands, seeps, springs, lakes, playas, rivers, and streams. Although it is the driest state in the United States, Nevada ranks 6th among US states in the number of endemic species (i.e., species found nowhere else in the world), with almost half of those endemic species associated with GDEs. Many GDEs have relatively small footprints on the landscape but groundwater can provide constant environments that support the persistence and evolution of endemic species that may only be found in one or a few locations (Cantonati et al. 2020; Ostoja et al. 2013).Thus, GDEs are extremely important to plants and wildlife in Nevada, and they are also important resources for human uses, including drinking water, agriculture, water quality improvements, and recreation (Brown et al. 2011; Saito et al 2020). However, the future viability of GDEs can be impacted directly or indirectly from human uses and activities. For example, Sada and Lutz (2016) found that 83 percent of the 2,256 springs that were inventoried between the late 1980s to 2013 in the Great Basin and Mojave Desert had evidence of human disturbance, and that 27 populations of rare aquatic springs taxa had been extirpated from these springs over that time period.

In 2019, The Nature Conservancy (TNC) produced a database and maps of indicators of GDEs[1] (iGDEs; Byer et al. 2019) to assist with identifying where GDEs occur across the state. The database revealed that out of Nevada's 28.6 million hectares (70.8 million acres), over 10% is within or associated with iGDEs (Saito et al. 2020). The database includes maps of 6 types of iGDEs: phreatophytic communities, wetlands, springs, lakes and playas, rivers and streams, and species. The maps can be viewed on a story map (https://arcg.is/qyj0v) and can be downloaded from the Nevada Division of Natural Heritage (NDNH; https://heritage.nv.gov/programs/wetland-program). Saito et al. (2020) and the story map provide background on the types of GDEs in Nevada and where they are.

This report identifies and evaluates stressors and threats to GDEs in Nevada by using the TNC Nevada iGDE database along with additional best available data. For the purposes of this report, we define a **GDE stressor** as *any physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that reduces the viability of an individual, population, or a species or the viability of its habitat*, and a **GDE threat** as *a potential (or impending) physical, chemical, or biological alteration of the GDE directly or indirectly caused by humans that is reasonably likely to negatively affect an organism, population, species or its habitat*[2]. Thus, a stressor is something that currently impacts GDEs, and a threat is something that potentially can impact them in the future (Box 1). The results of this assessment will be used in future work to consider strategies for sustaining and improving freshwater resilience in Nevada.

TNC Nevada staff met with other TNC colleagues working on GDEs, scientists, and tribal and agency staff while doing this assessment. A list of entities who met with us and in some cases provided data and expertise are listed in Appendix A. As a result of these conversations, TNC staff focused on five themes of stressor and threat risk factors that are critical for the sustainability of GDEs (Box 1; Table 1):

---

[1] Detailed local data on land use, hydrology and geology were not available throughout Nevada, so the database incorporates existing datasets to identify and map ecosystems that potentially rely on groundwater, which we called iGDEs. See Byer et al. (2019) and Saito et al. (2020) for more details. Throughout this report we will use the abbreviation GDE unless we are specifically referring to the Nevada iGDE database.

[2] The definitions of stressor and threat are similar to definitions used in Springsnail Conservation Team (2020).

1. groundwater withdrawals
2. climate
3. ungulates
4. non-native species
5. additional impacts due to human development

As with the Nevada iGDE mapping, we used the best available data for this assessment (i.e., we did not collect any new data). Risks due to stressors and threats were assessed on a scale of 0.00 (negligible risk) to 1.00 (high risk). Many of the risk factor ratings were qualitative based on judgment of TNC staff and reviewers. The assessment was intended to assist with determining iGDEs at high risk for stressors and threats, so results were focused on highlighting the amount of iGDEs at high risk. In the next sections we describe the stressors and threats in the five themes, the methods we used to assess them, and the combined assessment of all these themes.

Box 1: Stressor and threat risk factor rating approach

Stressors are due to the legacy of past management and impacts and are affecting GDEs now, whereas threats could potentially impact GDEs in the future. While it is true that all stressors are also threats because they could continue into the future, we chose to assess them separately, and in most cases assessed threats as risks that were not included in the stressor assessment. The exception was ungulates where the stress is due to the legacy of past management, and we assumed there were no different threats for the future from ungulates because we had no data to estimate that.

We rated all risk factors on a scale of 0.00 (negligible risk) to 1.00 (high risk). Most of the stressor and risk factors were assessed qualitatively and given discrete values of 1.0, 0.5, 0.1 and 0.0. The intermediate values of 0.5 and 0.1 were intended to indicate uncertainty in the data used in evaluation of the respective risk factors. The future climate threat risk factor was based on the most quantitative evaluation. Road density and housing density risk factors were also based on more quantitative methods. Thus, the future climate threat risk factor and the road density and housing density risk factors were scored using continuous values ranging from 0.00 to 1.00.

We chose this risk factor approach to provide a high-level (generalized) assessment of the risks with the available data across Nevada. This approach did require assumptions as outlined in the "Assumptions" section of the report, and the thresholds used (e.g., 800 m distance, 50 m depth to water, etc.) are not absolute. For example, it is possible that GDEs may be more impacted in an area with groundwater deeper than 50 m as compared to another site where the groundwater is less than 50 m deep depending on the distribution of the hydraulic properties of the aquifer. Thus, readers are encouraged to consider this assessment as a first-cut approach of where stressors and threats are likely for GDEs, and to perform site-specific regional and localized studies of potential impacts to GDEs, which may require additional data collection and the development, calibration, and use of numerical groundwater models. The assessment is non-regulatory, which means that no information presented is intended to imply whether a project can or should be approved or denied and the assessment is not legally binding in any way.

Table 1. Risk factors to groundwater-dependent ecosystems assessed in this report.

Theme	Risk factor	Stressor	Threat
Groundwater withdrawals			
	Water right appropriation status of hydrographic area		X
	Pumping status of hydrographic area	X	
	Proximity of GDE to potential groundwater withdrawals		X
	Nearby lowering of water tables	X	
Climate			
	Current climate	X	
	Future climate		X
Ungulates			
	Herd management areas, elk distribution areas, grazing allotments	X	X
Non-native species			
	Known presence	X	
	Road density		X
Other human development			
	Housing density	X	
	Nearby surface water diversion	X	
	Future housing density		X

GROUNDWATER WITHDRAWALS

As Theis (1940) noted, water withdrawn by wells from a groundwater aquifer is balanced by a change in the amount of water somewhere, which could be from one or more of three sources: 1) more water entering the aquifer through precipitation or seepage from another water source like rivers, lakes or wetlands (an increase in recharge), 2) removal of water stored in the aquifer, or 3) less water leaving the aquifer through natural discharge. Natural discharge of groundwater is the release of water from the aquifer in the absence of pumping, which can be through water uptake by phreatophytic[3] or riparian vegetation or discharge to surface waters such as springs, rivers or lakes (Bredehoeft 2002). All of these are considered GDEs. The combination of decrease in discharge and increase in recharge as a result of groundwater pumping is referred to as "capture" (see Box 2).

Box 2: Capture concept for groundwater management

Lohman (1972) published the following definition of capture:

> *Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in the recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed "capture."*

In other words:

$$\text{Pumpage} = \underbrace{\text{increased recharge} + \text{decreased discharge}}_{\text{capture}} + \text{water removed from storage}$$

If groundwater pumping exceeds the capture (the combined decrease in the natural discharge and the increase in recharge), then the system will continue to be depleted and water levels will never stabilize (Bredehoeft and Durbin 2009). Two additional capture terms that are important for this report are:

- **Stream (or surface water) capture** is a reduction in streamflow or surface water resources because of groundwater pumping. This can occur because of *reduced discharge* from the groundwater system to the river or surface water body as illustrated by comparing conditions in Figures 1a and 1b. This can also occur because of *increased recharge* because there is more water going from the river or surface water body to the groundwater system as illustrated by comparing conditions in Figures 1a and 1c. This type of capture can occur from any surface water resource, including rivers, springs, lakes and reservoirs. Stream capture can also be referred to as streamflow depletion.
- **Evapotranspiration capture** is a reduction in evapotranspiration by vegetation that was sourced by groundwater. This occurs as a result of water level declines due to groundwater pumping as illustrated by comparing conditions depicted in Figures 1a or 1b and Figure 1c, noting that the water table has declined beneath the phreatophytic vegetation.

The upper elevation of water in the aquifer is called the water table, which naturally fluctuates over time. Figures 1 and 2 illustrate how GDEs like streams, vegetation, and springs, seeps and wetlands

[3] Phreatophytic vegetation are plants, trees, and shrubs that have roots that tap into groundwater or can draw water from groundwater to their roots

interact with groundwater. These GDEs could be affected if water withdrawals cause the water table to drop because of a loss of water stored in the aquifer or if pumped water is replenished through induced recharge from surface waters. For example, streams or lakes that usually receive inputs from groundwater (Figure 1a) can experience reduced inflows from groundwater (reduced discharge; Figure 1b) or can have their water captured by the groundwater aquifer (induced recharge; Figure 1c) if water tables drop too low. Some of these streams may completely dry. Figure 1 also illustrates that trees and shrubs with roots that tap into groundwater (i.e., phreatophytes) can lose their access to the groundwater source through capture of natural discharge if the water table drops below their root zones.

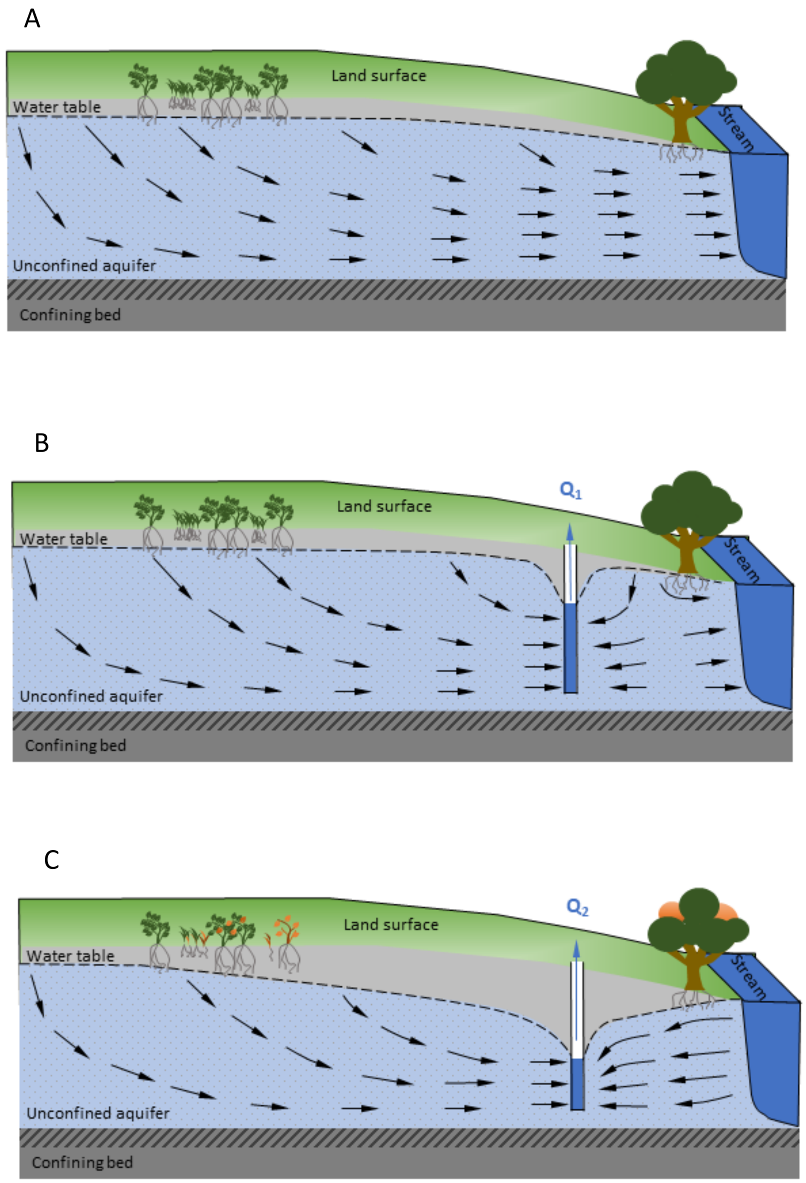


Figure 1. Illustration of how lowered water tables due to groundwater withdrawals can affect GDEs in cases where groundwater naturally contributes to streamflow (i.e., "gaining" stream. (A) Groundwater naturally discharges to a stream and vegetation. (B) A well placed near the stream pumping at a rate Q_1 will intercept part of the groundwater that would have discharged to the stream and lowers water tables near the well. (C) With continued or greater pumping (Q_2) the well can draw water from the stream and lower water tables enough to affect vegetation, causing mortality of riparian and upland vegetation. Illustration adapted from Winter et al. (1998).

When pumping from a well begins, initial withdrawals remove groundwater stored in the aquifer, and groundwater eventually will also come from surface water or other sources that use natural discharge such as vegetation (Theis 1940). Furthermore, water levels will continue to drop until the withdrawal is balanced by capture (Box 2; Bredehoeft and Durbin 2009). In a global assessment of environmentally critical streamflow, deGraaf et al. (2019) estimated that by 2050, environmental flow limits could be reached in as much as two-thirds of watersheds where groundwater pumping occurs because in many cases pumping would decrease groundwater inputs to streams such that streamflows would be reduced before large losses in groundwater storage would occur.

Stressors and threats to GDEs from groundwater withdrawals were estimated by assessing the following:

- Stressor risk factors associated with Nevada water right appropriation status of hydrographic areas containing GDEs
- Threat risk factors associated with amount of water being pumped relative to perennial yield in hydrographic areas containing GDEs
- Threat risk factors to GDEs due to proximity of groundwater withdrawals where water tables are near the ground surface
- Stressor risk factors to GDEs because of nearby lowering of water tables.

Surface water diversions also impact GDEs (Sada and Lutz 2016) and are accounted for in the "Additional impacts to human developments" theme.

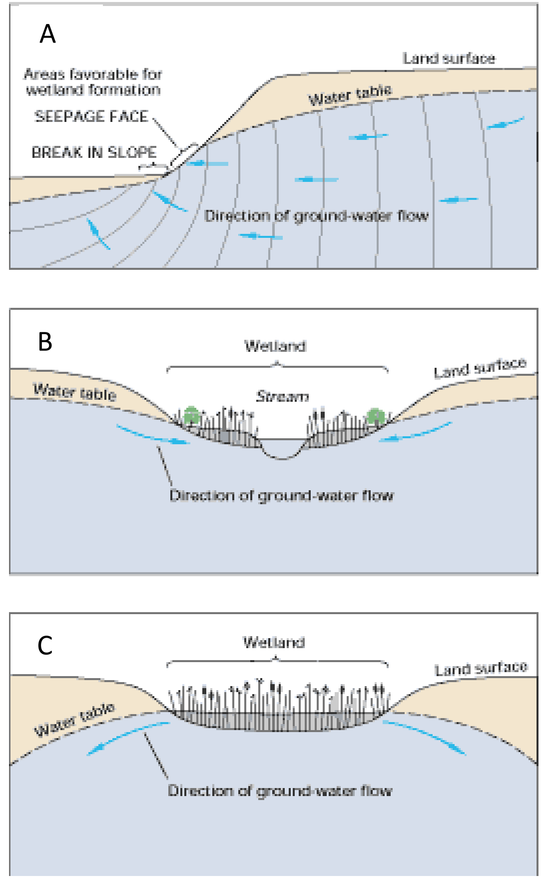


Figure 2. Water table interactions with (A) springs and seeps at breaks in the slope of the water table, (B) riparian wetlands where streams interact with groundwater, and (C) wetlands fed by precipitation and groundwater gradients slope away from the wetland, which is most likely to occur in upland locally sourced systems. Source: Winter et al. (1998).

Hydrographic area stressor and threat risk factors

Administration of groundwater in Nevada is the responsibility of the Nevada Division of Water Resources (NDWR) and is managed by hydrographic area, with each of the 256 hydrographic areas across the state having an assigned "perennial yield" that is used as general guidance for evaluating the amount of water available for use in each hydrographic area (Nevada State Engineer Order 1308). Perennial yield is defined by as "*the maximum amount of groundwater that can be withdrawn each year over the long term without depleting the groundwater reservoir. Perennial yield is ultimately limited to the maximum amount of natural discharge that can be utilized for beneficial use. The perennial yield cannot be more than the natural recharge to a groundwater basin and in some cases is less*" (Nevada State Engineer Order 1308). Another term for perennial yield is "safe yield" (http://water.nv.gov/WaterPlanDictionary.aspx). Most perennial yields were established in the 1950s to 1970s (Sullivan 2021).

Total perennial yield for Nevada is about 2.5×10^9 m^3 (2 million acre-feet (af)), of which about 2.0×10^9 m^3 (1.6 million af) were being used for human purposes in 2015 (Dieter et al. 2018). According to Wilson (2019), 128 of the hydrographic areas (50%) were fully- or over-appropriated (overcommitted), which means that water rights were committed at or above the perennial yield in those hydrographic areas (Figure 3). Of these, 62 were over-appropriated by more than 200%, and 49 (19%) of the hydrographic areas had more groundwater withdrawn than the perennial yield (Wilson 2019).

For GDEs, there are several considerations related to application of perennial yield to hydrographic areas in Nevada. First is the concept of perennial yield and its calculation. As Theis (1940) described and Bredehoeft et al. (1982) also explained, under natural conditions (i.e., no withdrawal of groundwater

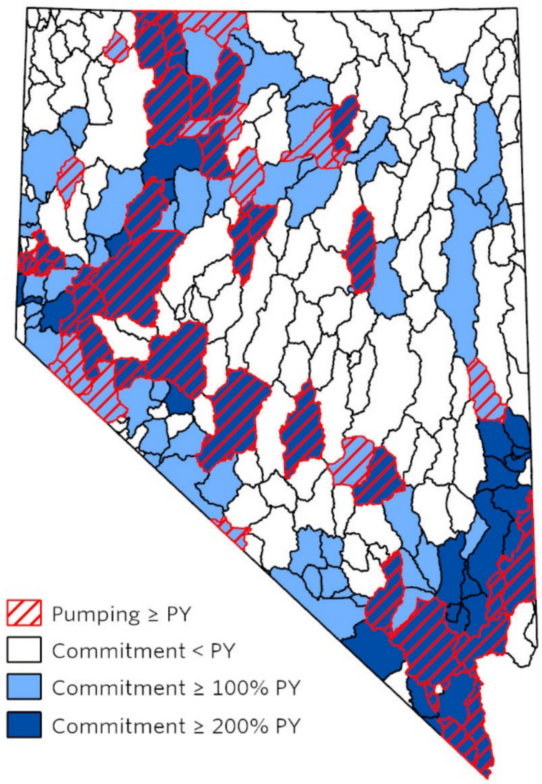


Figure 3. Actual pumping and water right commitments for hydrographic areas in Nevada. PY = perennial yield. See Table 1 for risk factor designations for GDEs in these hydrographic areas. Source: Wilson (2020).

from wells), an aquifer is in a state of dynamic equilibrium, where natural recharge is balanced by natural discharge so that overall, the water stored in the aquifer does not change. When new water use by wells is imposed upon this stable system, the water will come from a combination of stream or surface water capture, evapotranspiration capture, a reduction of aquifer storage, or a combination of these (see Box 2). The concept of perennial yield or safe yield applies the idea that pumping must not exceed recharge for groundwater development to not deplete the groundwater aquifer in the long term (Bredehoeft 2002). However, Bredehoeft (2002) demonstrates how capture is dynamic and depends on how close pumping is to areas of natural discharge, as well as aquifer characteristics like transmissivity, so that even if the pumping rate equals the discharge rate, water can still be withdrawn from storage until the system eventually reaches a new equilibrium amount of water stored in the aquifer that can take hundreds or even thousands of years to achieve.

Bredehoeft (2002) notes that the total groundwater discharge in Nevada is mostly evaporation from playas and evapotranspiration of phreatophytic plants, and this discharge is what was used to estimate perennial yield in many of Nevada's hydrographic basins. Thus, the premise of perennial yield in Nevada is that withdrawals can be allowed to the rate of natural discharge, which is the water used by GDEs. In other words, if groundwater use was exactly the perennial yield, GDEs would be progressively diminished as water stored in the aquifer reaches a new equilibrium.

A second consideration is that although groundwater pumping will likely not capture all discharge immediately, recovery of GDEs and the water table if detrimental effects are seen is also not immediate and could take longer than the time over which withdrawals occurred (Barlow and Leake 2012; Bredehoeft and Durbin 2009). Thus, there is a long-term threat to GDEs if pumping captures their discharge. Bredehoeft and Durbin (2009) showed that if a hydrographic area is primarily underlain by a basin-fill aquifer, groundwater withdrawals will eventually capture GDE discharge if pumping continues long enough. Because springs and streamflows are considered surface water and are regulated by surface water law, but groundwater is the source of spring discharges, and often contributes to streamflows and lake waters, capture of surface waters can be problematic for administration of water law. In 2017, the Nevada Legislature declared that it is the policy of the state to manage and administer groundwater and surface water together (§NRS 533.024). Since Nevada is a prior appropriation state and most surface waters were appropriated before groundwater (King 2019), there have been conflicts when junior groundwater right holders (i.e., those with more recent priority dates for their water rights) are pumping water that diminishes surface water flows from springs or GDE rivers that affect senior surface water right holders (Nevada State Engineer Order 1329; Taylor et al. 2021).

Another consideration is that the calculation of the perennial yield was done for most of the hydrographic areas in the 1950s to 1970s using approaches that used the best available data and science at the time, but which often were estimations based on approximate mapping of discharge areas, and generalizations about evapotranspiration and other components of the water balance. These calculations also often assumed that water used by vegetation was “wasted water” (Robinson 1958), that discharge by evapotranspiration is a good estimate of recharge, and that the “safe yield” was therefore equal to the discharge, which in Nevada was called the perennial yield. Better methods for estimating evapotranspiration and other components of the water budget are now available, and appreciation of the benefits of GDEs may be something that could be factored into updated calculations of water available for appropriation. The uncertainty associated with the outdated estimates of perennial yield could mean that it was overestimated and even hydrographic areas that are not fully appropriated could be experiencing continued declines in aquifer storage already. The Nevada Division of Water Resources is planning to implement the Nevada State Water Initiative to update estimates of water availability in Nevada (Allander et al. 2021).

A fourth consideration is that states administer groundwater, but groundwater does not adhere to state boundaries. Thus, hydrographic areas that may appear to have uncommitted water in Nevada may still be experiencing impacts to GDEs because of water use in neighboring states that have different rules about administering groundwater. Although Nevada administrators consider what is happening in neighboring states, those neighboring states may not regulate water development that could affect Nevada hydrographic areas.

We based our quantification of the risk factors for hydrographic areas solely on Nevada’s accounting of whether a hydrographic area is fully or over-appropriated or if pumping in the hydrographic area is at or above its perennial yield as of 2017 according to Wilson (2019). This approach does not address the third and fourth considerations about uncertainty associated with the perennial yield estimate or impacts from water use in neighboring states. Risk factors were assigned to hydrographic areas as summarized in Table 2, and GDEs in each hydrographic area were given the associated risk factors.

We considered groundwater pumping as a stressor risk factor and assigned all GDEs in hydrographic areas where pumping equals or exceeds perennial yield according to Wilson (2019) a stressor risk factor value of 1.0. All GDEs in hydrographic areas that had pumping less than the perennial yield were assigned a stressor risk factor value of 0.1 because even though the pumping in the hydrographic area may not exceed the perennial yield, there could still be groundwater withdrawals near GDEs that could be problematic since the stressor risk factor rating was basin-wide.

Hydrographic areas that were over-appropriated were considered to have higher threat risk than basins that were not fully appropriated because if all water rights are fully used on those basins, water use at or beyond the perennial yield could affect GDEs. Therefore, we assigned a threat risk factor value of 1.0 for GDEs in hydrographic areas that are over-appropriated by 200% or more and a threat risk factor value of 0.5 for GDEs in hydrographic areas that were fully or over-appropriated by less than 200% (Table 2; Figure 3). Basins that were not yet fully appropriated were assigned a threat risk factor value of 0.0 because although there still could be withdrawals near GDEs, that should be accounted for by the stressor risk factor for proximity of withdrawals to GDEs discussed later in this report.

Table 2. Risk factors assigned for stressors and threats to GDEs by hydrographic area appropriation and pumping status.

Hydrographic area appropriation and pumping status	Stressor	Threat
Pumping ≥ perennial yield	1.0	
Pumping < perennial yield	0.1	
Over-appropriated by ≥200 %		1.0
Fully or over-appropriated by <200%		0.5
Not fully appropriated		0.0

According to Wilson (2019), pumping in 19% of the hydrographic areas exceeded the perennial yield in 2017, and the percentages of the five types of GDEs in the NV iGDE database (i.e., springs, wetlands, phreatophyte communities, lakes and playas, and rivers and streams) that were stressed due to pumping exceeding the perennial yield were between 18.8% and 28.6% (Table 3). Over-appropriation status applied to 50% of the 256 hydrographic areas in Nevada, and at least 40% of all GDE types were at high or moderate risk for the appropriation status threat risk factor (Table 4). Notably, almost 40% of lakes and playas were in hydrographic areas that were over-appropriated by more than 200% (Table 4). GDE rivers and streams generally had the lowest percentage of risk for pumping status stressor risk factor (Table 3) and appropriation threat risk factor (Table 4). Still, thousands of springs and thousands of kilometers of rivers and streams were at high or moderate risk for these groundwater withdrawal risk factors.

Table 3. Percentage and quantity of GDE types at high risk for hydrographic area pumping status stressor risk factor. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. PY = perennial yield. ENU = English units.

GDE type	2017 pumping ≥ PY stressor	
	%	Amount (metric / ENU)
Springs	20.1	5,116 / 5,116
Wetlands	28.6	340,051 ha / 840,283 ac
Phreatophyte communities	25.1	545,116 ha / 1,347,011 ac
Lakes and playas	19.1	114,452 ha / 282,817 ac
Rivers and streams	18.8	3,525 km / 2,191 mi

Table 4. Percentage and quantity of GDE types at high or moderate risk for hydrographic area appropriation status threat risk factor. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. PY = perennial yield. ENU = English units.

GDE type	Over-appropriated by ≥200 % threat (high risk)		Fully or over-appropriated by <200% threat (moderate risk)	
	%	Amount (metric / ENU)	%	Amount (metric / ENU)
Springs	17.9	4,501 / 4,501	27.0	6,789 / 6,789
Wetlands	25.7	305,395 ha / 756,646 ac	25.4	302,324 ha / 747,058 ac
Phreatophyte communities	23.6	513,248 ha / 1,268,262 ac	24.5	532,481 ha / 1,315,789 ac
Lakes and playas	38.8	233,339 ha / 576,592 ac	16.1	96,608 ha / 238,725 ac
Rivers and streams	15.2	2,858 km / 1,776 mi	25.2	4,730 km / 2,939 mi

<ins>Threat risk factor due to proximity of water withdrawals to GDEs</ins>

There is always a decline in water levels at and near a well that is withdrawing groundwater (Alley et al. 1999), so GDEs that exist where the water table is fairly shallow are likely to be affected if water withdrawals are nearby (Patten et al. 2008). However, due to local and regional conditions and geology, the relationship of threat risk to GDEs to groundwater withdrawal proximity does not decay or decline uniformly with distance from the GDE (Alley et al. 1999). We therefore assigned a threat risk factor value of 1.0 to areas within 0.8 km (0.5 mile) of GDEs where water tables are 15 m (50 ft) or less according to Lopes et al. (2006; Figure 4) because it was presumed that when a water withdrawal occurs close to a GDE that is accessing the same shallow groundwater, the threat risk is high for impact to the GDE. All other areas were given threat risk factor values of 0.0 for proximity to water withdrawal (Table 5), although we stress that it is important to do site-specific regional and localized studies of potential impacts of groundwater withdrawals to GDEs, which may also require development, calibration, and use of numerical groundwater models. In cases with deeper water tables (i.e., >15 m), assessment of the specific situation is necessary to understand impacts and potential threats because of local and regional complexities of groundwater dynamics as explained in Appendix B.

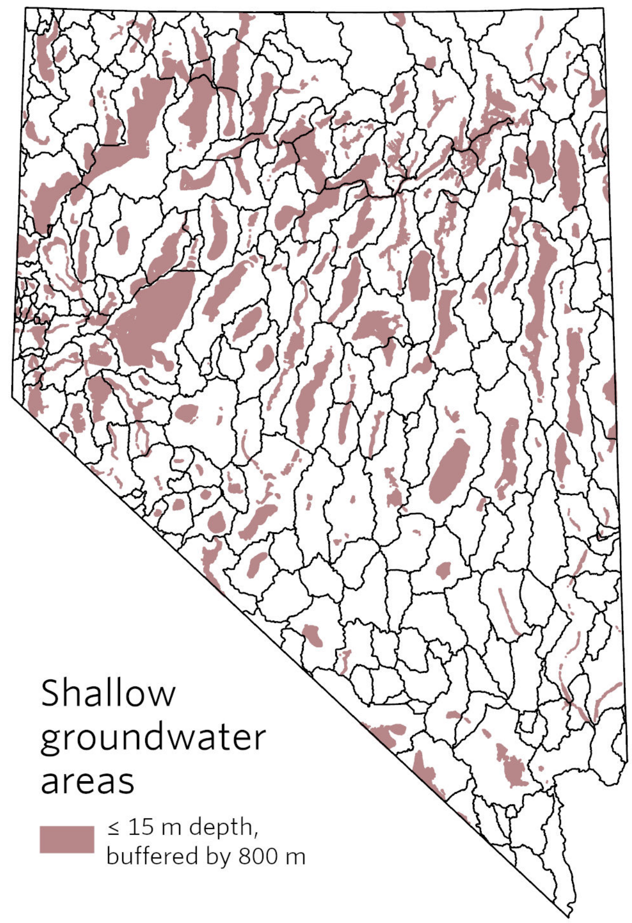


Figure 4. Shallow groundwater areas that have depth to groundwater of 15 m (50 ft) or less according to Lopes et al. (2006) which defines where GDEs are more threatened by groundwater withdrawals.

Table 5. Threat risk factor values for proximity of potential groundwater withdrawals to GDEs in Nevada when shallow groundwater is present. DTW = depth to water.

Proximity of potential groundwater withdrawals to GDE	DTW	Threat
≤ 800 m	≤ 15 m	1.0
> 800 m	≤ 15 m	0.0
≤ 800 m	> 15 m	0.0
> 800 m	> 15 m	0.0

High percentages of phreatophyte communities, wetlands, and lakes and playas were affected by this threat risk factor (Table 6), which was not surprising since the presence of these types of GDEs often signal that shallow groundwater is present (Chambers et al. 2021; Naumberg et al. 2005; Provencher et al. 2020). Only 13% of springs were in areas with shallow depth to groundwater, as many springs are not sourced from shallow groundwater (Springer and Stevens 2009).

Table 6. Percentage and quantity of GDE types affected by proximity of potential groundwater withdrawals to GDEs threat risk factor when shallow groundwater is present. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Proximity of potential groundwater withdrawals to GDEs threat	
	%	Amount (metric / ENU)
Springs	13.3	3,359 / 3,359
Wetlands	72.1	858,568 ha / 2,121,567 ac
Phreatophyte communities	80.0	1,736,921 ha / 4,292,022 ac
Lakes and playas	84.7	508,612 ha / 1,256,808 ac
Rivers and streams	30.3	5,685 km / 3,533 mi

Stressor risk factor due to declining groundwater level trends

Declining trends in groundwater levels can lead to reduced flows to springs, rivers, and lakes, and detach groundwater from vegetation (Figures 1 and 2), which can result in extirpation of native plants and animals (Fleishman et al. 2006). For example, excessive groundwater pumping led to extinction of the Pahrump Ranch poolfish (*Empetrichthys latos pahrump*) and Raycraft Ranch poolfish (*E. l. concavus*) (Williams and Sada 2020). We applied a simplified approach to locate GDEs near areas with declining groundwater levels using best-available data.

Well data from the US Geological Survey (USGS) were obtained using the 'dataRetrieval' package in R (De Cicco et al. 2021) to access water level data from the National Water Information System (NWIS) online database. Water level data from the Nevada Division of Water Resources (NDWR) was obtained from the WellNet database (http://water.nv.gov/WaterLevelData.aspx). Water level data collected by the Central Nevada Regional Water Authority in 2021 (https://cnrwa.com/resources-documents/groundwater-monitoring/) were used to update the trends of some USGS and NDWR wells because that data had not yet been incorporated into the NWIS or WellNet databases.

Both USGS and NDWR data were queried for data recorded between 1984 and 2021 so that we could use an approach similar to that used by Albano et al. (2021) and Rohde et al. (2021a) to analyze trends from wells with at least 5 years of data. Such data were not available in 23 of the 256 hydrographic areas (Figure 5). If a well had multiple readings in a single calendar year, levels were averaged to create an annual groundwater level (see Figure 6 for an example). The Modified Mann-Kendall approach was used to test whether the ordinary least squares slopes were significantly different than zero with the 'modifiedmk' package in R (Patakamuri and O'Brien 2021) at $p \leq 0.05$. A positive trend indicated the groundwater level was getting closer to the ground surface, whereas a negative trend indicated the groundwater was getting further from the ground surface over time.

Some well sites existed in both NWIS and WellNet databases, so the trend was calculated with the dataset with the most recent groundwater level measurements. For example, well 064 N34 E45 04ABDD in the WellNet database had data for 1991 to 2005. This well was the same as site number 40512116542801 in NWIS, which only had data for 1991 to 1996. Thus, the NWIS record for this site was not used, and the trend was calculated using the WellNet data. For sites that had the same data in both databases, the USGS data were used.

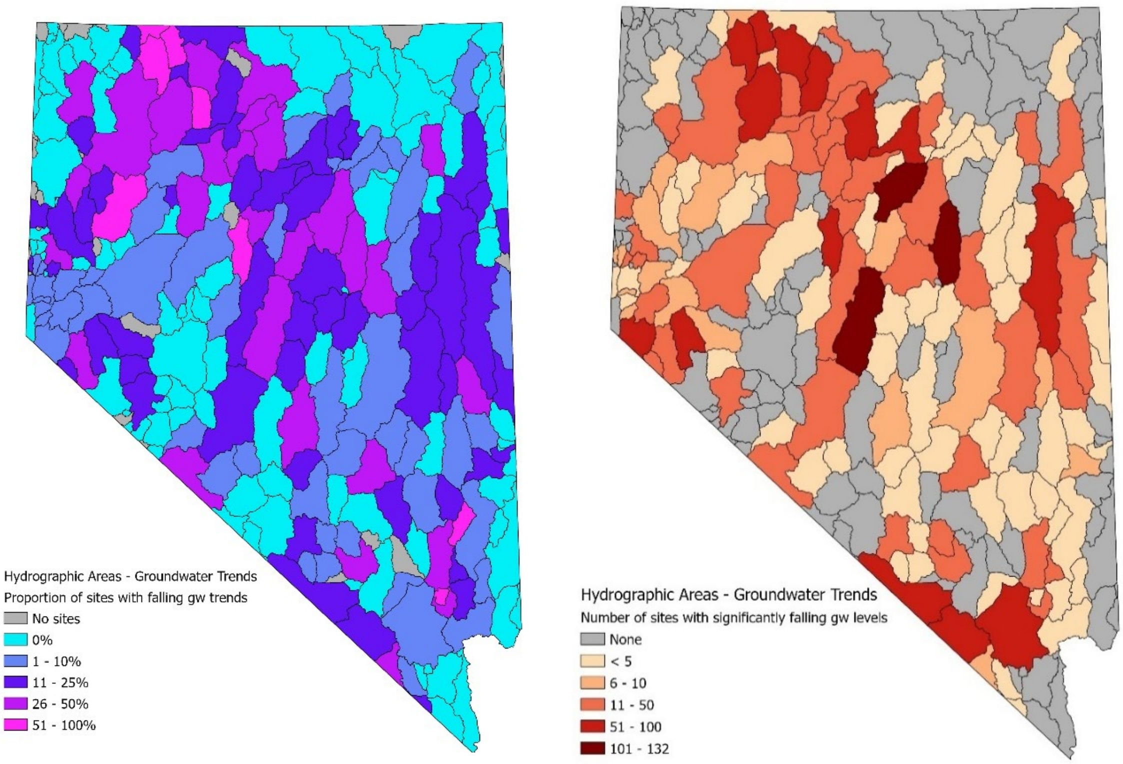


Figure 5. Left: Proportion of well sites with significantly declining groundwater trends in each hydrographic area. Right: Number of wells with significantly declining groundwater trends in each hydrographic area.

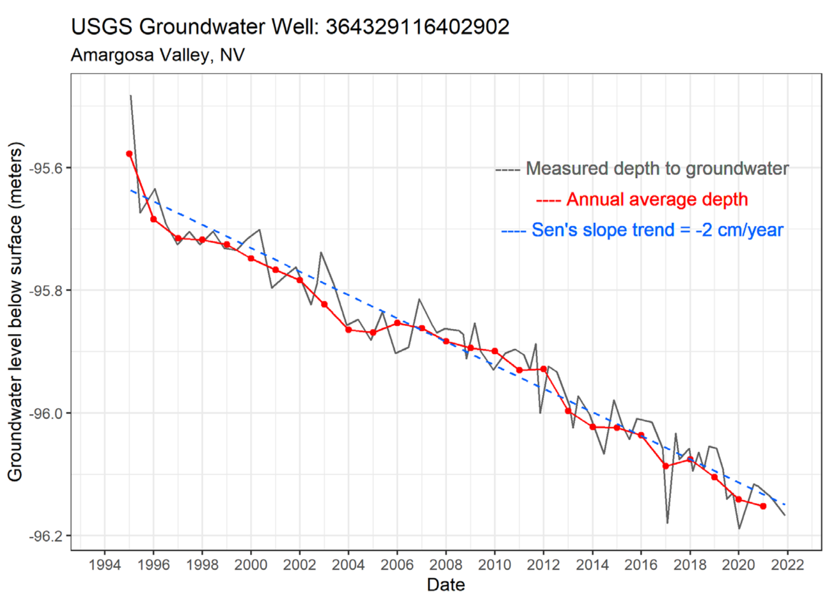


Figure 6. Example of analysis of groundwater trends. Annual average values were calculated where multiple measurements were made in a calendar year. The trend is significantly decreasing at p < 0.001, indicating that the groundwater level is falling.

GDEs within 800 m (0.5 miles) of wells with significantly declining trends ($p \leq 0.05$) were given a stressor risk factor value of 1.0 as it was assumed that the close proximity of the wells was highly probable for impacting the GDEs (Bredehoeft and Durbin 2009; Noordujin et al. 2019). GDEs in hydrographic areas that were within 800 m (0.5 miles) of wells that did not have significant declining trends were given stressor risk factor values of 0.1 to account for uncertainty associated with data availability. GDEs that were more than 800 m from wells regardless of the trend were given stressor risk factor values of 0.1 because distance may delay the impact of groundwater pumping on GDEs, but not the magnitude of the impact (Bredehoeft and Durbin 2009). GDEs in hydrographic areas that did not have any wells with sufficient data for a trend analysis were assigned stressor risk factor values of 0.5 because there could be more risk if data are unavailable (Table 7). The final product from the groundwater level analysis was a point shapefile of well sites. The well sites have attributes describing whether the groundwater levels are significantly falling, rising, or if there is no significant trend. The sites with significantly falling groundwater levels were buffered by 800 m (0.5 mile) and all GDEs that intersected with these areas were given a stress risk factor value of 1.0 (see Figure C-1 in Appendix C for an example). Although statistically some trends were stronger than others, because not all wells had the same number of data points for this analysis, we did not consider the magnitude of the trend, only whether the trend was significantly declining.

Table 7. Stressor and threat risk factor values for declining water level trend impacts for GDEs in Nevada.

Water level trend significance	Stressor
GDE within 800 m of well with significant ($p \leq 0.05$) declining trend	1.0
GDE within 800 m of well with no significant declining trend	0.1
GDE > 800 m from well regardless of trend	0.1
GDE in hydrograph area with no well data	0.5

Figures showing the direction of well trends in each hydrographic basin are in Appendix D. An online tool to see wells colored by whether the calculated groundwater levels are rising/falling/no significant trend is at https://arcg.is/1eCXL0 and includes well IDs that correspond with USGS or NDWR databases.

Over half (54%) of the hydrographic areas had at least one well site with significantly falling water levels, but only 8 hydrographic areas had most (>50%) of the wells in their basins with significant falling trends (Figure 5). We considered data from 17,121 wells in assessing water level trends, but only 6,536 satisfied our data criteria and 2,542 (39%) had significantly falling trends and 999 (15%) had significantly rising water level trends. The remainder did not have significant trends.

Over 40% of phreatophyte communities (over 900,000 hectares [~2.3 million acres]) were within 800 m (0.5 mile) of a well with a significantly falling trend and had a stressor risk factor value of 1.0 (Table 8). Phreatophytes can be obligate groundwater users (i.e., they must have access to groundwater to be sustained) or facultative (i.e., they grow more vigorously when groundwater is available; Naumberg et al. 2005). The loss of access to groundwater can affect the sustainability of either type of phreatophyte and can lead to transitions of these communities to ones with less ecological value (Provencher et al. 2020). Very small percentages of springs and GDE rivers and streams were near wells with significantly falling trends (Table 8), which could reflect past decisions by the State Engineer in evaluating applications for water rights for groundwater that may impact surface water rights. This result for springs and GDE rivers and streams could also reflect that groundwater development has been more prevalent where surface water resources are unavailable or that capture of surface water from springs and rivers could be occurring.

With the exception of GDE phreatophyte communities, the percentages of GDEs affected by the falling trend stressor risk factor were much less than the 43.7% of California GDEs affected by decreasing groundwater level trends over a similar time period to our assessment in Rohde et al. (2021a). That assessment used a random forest model to estimate groundwater levels wherever GDEs were located, whereas the assessment presented here relied on points where adequate well data were available, which could explain the lower estimate. Future work could consider applying the approach of Rohde et al. (2021a) to estimate groundwater levels wherever GDEs are located in Nevada.

Table 8. Percentage and quantity of GDE types at high risk of falling water level trend stressor risk factor. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Declining groundwater level trend stressor (high risk)	
	%	Amount (metric / ENU)
Springs	1.0	251 / 251
Wetlands	7.6	90,869 ha / 225,542 ac
Phreatophyte communities	42.9	932,346 ha / 2,303,874 ac
Lakes and playas	8.4	50,224 ha / 124,106 ac
Rivers and streams	2.6	480 km / 298 mi

<u>Combined groundwater withdrawal stressor and threat risk factor values</u>
Since we had more than one risk factor that we rated for stressors and threats from groundwater withdrawals, we combined the risk factors by adding the values for each risk factor and normalizing the values to get combined groundwater withdrawal stressor risk factor values between 0.0 and 1.0, and groundwater withdrawal threat risk factor values between 0.0 and 1.0 (Table 9). In other words, we added the hydrographic area pumping status stressor risk factor value and the groundwater level declining trends stressor risk factor value and then divided the result by 2 (sum of the maximum possible value for each stressor risk factor) to get a stressor risk factor value between 0 and 1 for each iGDE element in the Nevada iGDE database. Similarly, we summed the hydrographic area appropriation status threat risk factor value and the proximity of groundwater withdrawals to GDEs risk factor value and divided the result by 2 to get a threat risk factor value between 0 and 1 for each iGDE element.

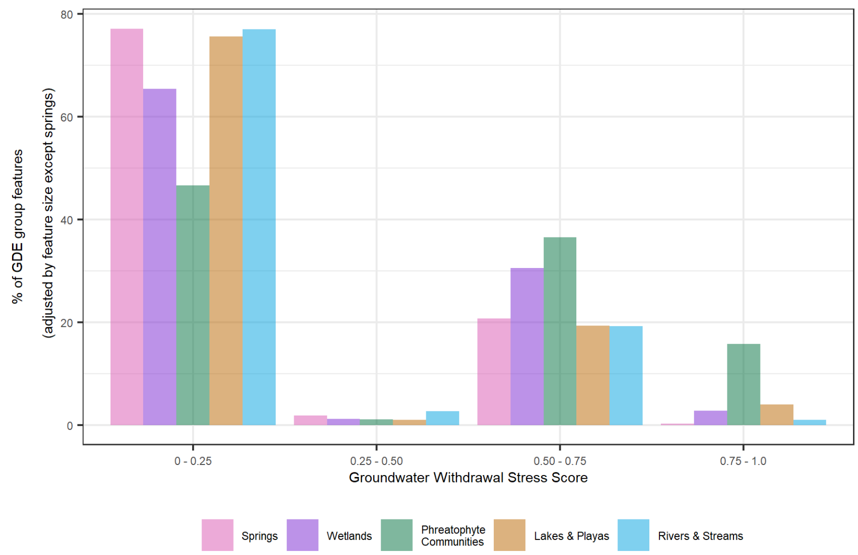
Table 9. Range of groundwater withdrawal risk factor values for GDEs in Nevada. Normalizing factor is the value that summed stressor or threat risk factors were divided by to get the final risk factor for groundwater withdrawal stressor and threat risk factors.

Groundwater withdrawal risk	Risk factor type	Values	Normalizing factor	Final range
Hydrographic area pumping status	Stressor	0.1 or 1	2.0	0.0 – 1.0
Groundwater level declining trends	Stressor	0.0 – 1.0		
Hydrographic area appropriation status	Threat	0, 0.5 or 1	2.0	0.0 – 1.0
Proximity of groundwater withdrawals to GDEs	Threat	0 or 1		

Overall, the largest percentage of phreatophyte communities (more than 50%) were at moderate to high risk for groundwater withdrawal stressor risk factors (Table 10; Figure 7) because of high risk for the falling groundwater level trend threat risk factor. Over 50% of lakes and playas were at moderate to high risk for groundwater threat risk factors because of large percentages being in over-appropriated hydrographic areas and also because they were in shallow groundwater areas. Lakes and playas are important locations in Nevada for endemic fish, migratory bird species and aquatic invertebrates (WAPT 2012). Maps showing overall stressor and threat risk factor values for GDEs due to groundwater withdrawals are included in Appendices E and F, respectively.

Table 10. Percentage and quantity of GDE types at moderate to high risk (0.5 or greater value) for overall groundwater withdrawal stressor and threat risk factors. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Combined groundwater withdrawal stressor		Combined groundwater withdrawal threat	
	%	Amount (metric/ENU)	%	Amount (metric/ENU)
Springs	21.0	5,299 / 5,299	6.4	1,621 / 1,621
Wetlands	33.4	397,454 ha / 982,155 ac	42.7	507,914 ha / 1,255,081 ac
Phreatophyte communities	52.3	1,135,113 ha / 2,804,922 ac	42.4	921,375 ha / 2,276,765 ac
Lakes and playas	23.4	140,523 ha/ 347,241 ac	50.3	302,348 ha / 747,118 ac
Rivers and streams	20.3	3,806 km / 2,365 mi	16.2	3,036 km / 1,886 mi



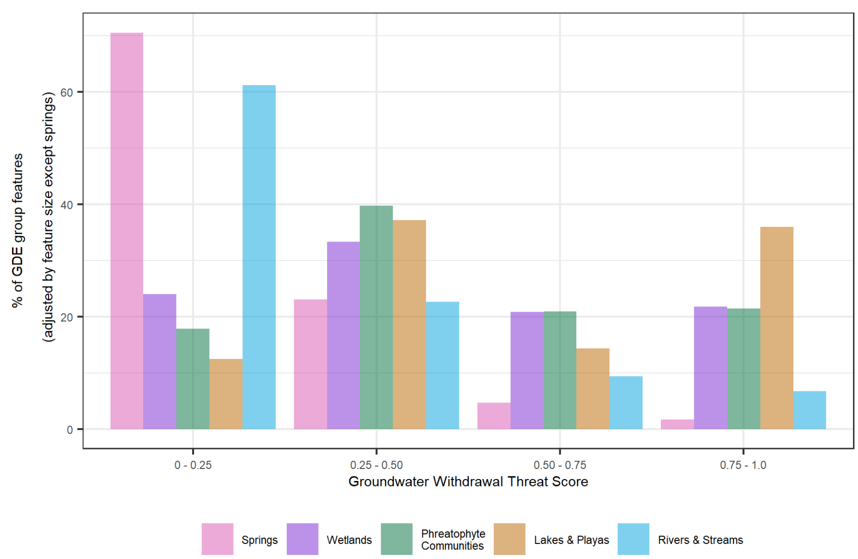


Figure 7. Percentage distribution of GDE types for overall groundwater withdrawal stressor (top) and threat (bottom) risk factor values. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types.

CLIMATE

Climate impacts GDEs primarily through precipitation and air temperature which affect evapotranspiration, snow accumulation and snowmelt (Kløve et al. 2014), soil moisture, runoff, and infiltration. In particular, these factors can affect groundwater availability by changing recharge rates and groundwater levels accessible to GDEs. At the same time, GDEs can provide ecological stability if they are resilient to climate, which can contribute to the evolution of assemblages of endemic taxa in environments that, while harsh, are relatively constant due to long flow paths or connections to deep aquifers such as springs at Ash Meadows, Nevada (Cantonati et al. 2020). We looked at two ways in which climate may stress or threaten GDEs: current climate interactions, and future climate interactions with projected climate change.

<u>Current climate stressor risk factor</u>

Ecosystems fed by local groundwater flow paths are more likely to respond quickly to variations in temperature and recharge than larger systems with longer groundwater flow paths (Toth 1963; Kløve et al. 2014; Figure 8). Thus, GDEs recharged by local groundwater flow paths are naturally less resilient to drought and more sensitive to changes in hydrology (Miller et al. 2011). As Toth (1963) showed analytically, areas with more topographic relief (i.e., mountainous areas) will tend to have more local flow paths. Similarly, Aldous and Gannett (2021) noted that systems with local flow paths tend to be at higher elevations with smaller contributing areas, resulting in small springs and wetlands with large seasonal variability. Discharge from these locally-sourced systems is closely coupled with meteorology and tends to be seasonal from precipitation and snowmelt. On the other hand, systems with longer regional flow paths have larger contributing areas and may span climatic and landscape gradients with a larger variety of potential recharge mechanisms (e.g., melting of seasonal snowpack, occasional melting of incidental snow, or infiltration of rainfall). These recharge sources can also be quite distant from the GDE (Aldous and Gannett (2021).

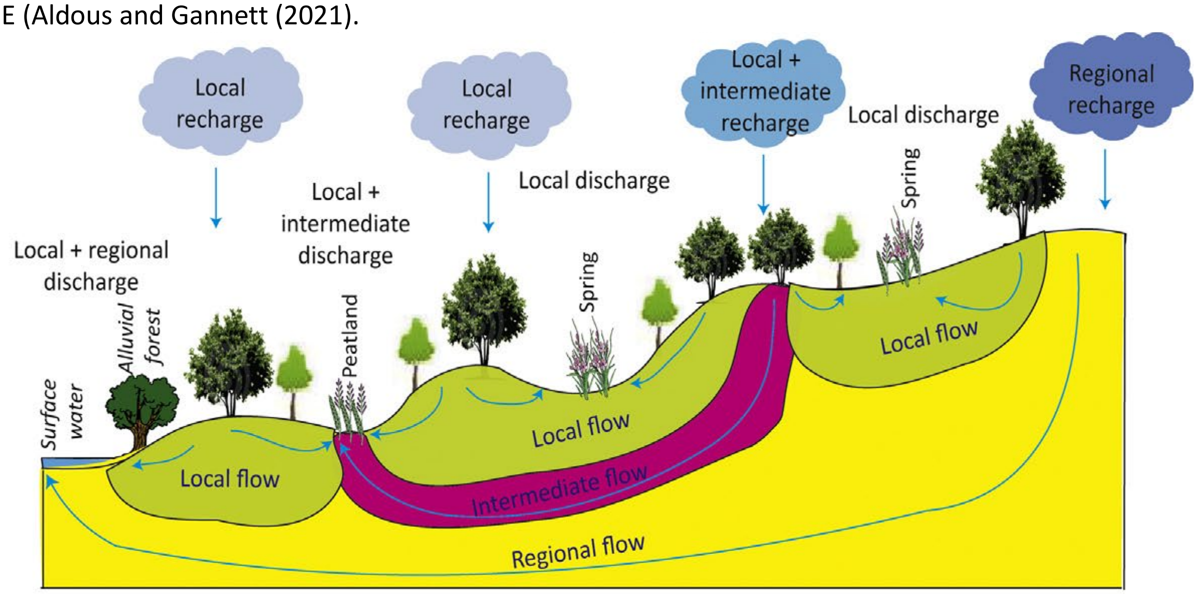


Figure 8. Illustration of local versus regional flow paths (from Kløve et al. (2014) and adapted from Toth (1963)).

For the current climate stressor risk factor, we assessed the vulnerability of GDEs to drought and drying conditions by focusing on areas of local groundwater flow paths. In his description of the hydrogeology of the Great Basin, Mifflin (1988) mapped recharge areas of the Great Basin which we have used to indicate where local groundwater flow paths are likely to interact with GDEs (Figure 9). The following portions of Nevada were not included in the map by Mifflin (1988): 1) a small area of the Columbia River Basin in the northern part of Nevada; 2) a small portion of southern Nevada in the Colorado River Basin; and 3) a portion of the Mojave Desert in southern Nevada. We assumed that none of these were areas of significant recharge and hence, not areas of local flow paths. GDEs in regions with local groundwater flow paths were considered to have a stressor risk factor value of 1.0 for current climate, and other GDEs were assigned a stressor risk factor value of 0.0 for current climate (Table 11).

Table 11. Stressor risk factor values for current climate on GDEs in Nevada.

Groundwater flow paths	Stressor
Local	1.0
Regional	0.0

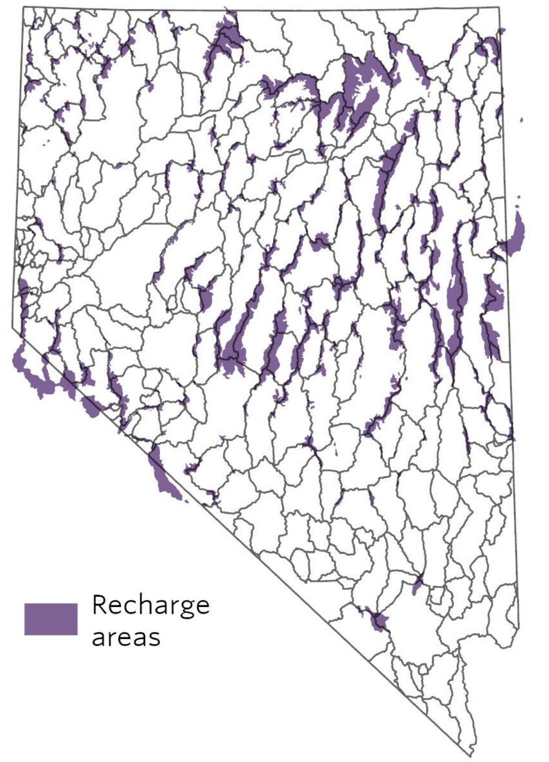


Figure 9. Recharge areas mapped in Mifflin (1988). The recharge areas were used to indicate locations of higher risk for current climate stressors for GDEs in Nevada.

The GDE types with the greatest percentage affected by the current climate stressor risk factor were springs and rivers and streams, indicating that a lot of them are located in recharge areas with local flow paths (Table 12). Much lower percentages of phreatophyte communities, wetlands, and lakes and playas were vulnerable to current climate because they are often located at lower elevations with longer flow paths (Aldous and Gannett 2021).

Table 12. Percentage and quantity of GDE types affected by the current climate stressor risk factor. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Current climate stressor	
	%	Amount (metric / ENU)
Springs	40.2	10,119 / 10,119
Wetlands	6.4	75,691 ha / 187,036 ac
Phreatophyte communities	9.8	212,697 ha / 525,584 ac
Lakes and playas	8.1	48,357 ha / 119,492 ac
Rivers and streams	32.0	6,011 km / 3,735 mi

<u>Future climate threat risk factor</u>
Future climate for Nevada is likely to be warmer which could increase evapotranspiration and reduce recharge (Somers and McKenzie 2020), thereby affecting the availability of groundwater to GDEs. Furthermore, much of Nevada's current hydrology is driven by snowmelt (Stonestrom and Harrill 2007), but as the climate warms, a greater proportion of precipitation will occur as rain instead of snow (Meixner et al. 2016; Mote et al. 2005). Siirila-Woodburn et al. (2021) describe how less snowpack could lead to less mountain recharge of groundwater because snowmelt infiltrates better than rainfall. This is

especially true in the southwestern US where mountain-block groundwater recharge is prevalent (Earman et al. 2006; Earman and Dettinger 2011), as in Nevada. On the other hand, focused recharge from surface water bodies like lakes, rivers and streams may increase if precipitation intensity increases due to a greater water vapor holding capacity in the atmosphere (Meixner et al. 2016). Another impact of future climate could be reduced baseflows if groundwater contributions to streams are decreased, which Miller et al. (2021) project could occur in the Upper Colorado River basin with possible basin-wide impacts to human and ecological water use. However, reduced mountain recharge if higher elevation areas transition to more rain than snow could lead to increased streamflows that allow more recharge through streambeds (Earman and Dettinger 2011). Changes in the water cycle and air temperatures can also increase the possibility of wildfires and insect outbreaks in GDEs in riparian areas (Dwire et al. 2018).

For lower elevation systems in the Great Basin, Grayson (1993) considered the past Holocene Thermal Maximum that was hotter and drier and suggested in a hotter future where water tables could fall. The lower water tables could transition groundwater-dependent vegetation to precipitation-based vegetation. If the transition period is long (i.e., hundreds of years), soils for phreatophyte communities like greasewood could become less sodic, allowing vegetation like mixed salt desert scrub and sagebrush to establish. However, if the transition period is short (as projected by climate change models), soils are unlikely to change and greasewood would likely be replaced by cheatgrass or, with more time, saltbush (Provencher et al. 2020).

Aside from the effects of a warming climate on the water balance that can affect GDEs, changes in the magnitude of air temperatures as well as the timing of seasonal temperatures and precipitation may affect species viability (Keller and Shea 2020). McInerny et al. (2021) noted that riverine ectotherms have only two options to survive if they reach their thermal maximum: 1) adapt to the warmer conditions, which can be difficult if the habitat warms faster than the species can adapt or 2) migrate to cooler water. Several studies have noted the importance of climate refugia for species adaptations to warming climates (Dobrowski 2011; Lawler et al. 2015). “Convergent environments” that are decoupled from regional climatic patterns such as valley bottoms, local depressions and sinks often also retain and accumulate water in arid regions (Dobrowski 2011), and the cooler air can benefit the local water balance and water temperatures.

We chose to focus the assessment of future climate threat to GDEs on ecological drought conditions. To estimate the threat that future climate poses, we prepared future temperature, precipitation, evaporative demand, and Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al. 2010) time series for the 256 hydrographic areas in Nevada. In semi-arid and arid landscapes, SPEI has been shown to more accurately describe hydrologic drought conditions over indices that only use precipitation (McEvoy et al. 2012) and to be a good indicator of ecological drought (Albano et al. 2020). Additionally, SPEI is calculated at user defined lag periods, unlike the Palmer Drought Severity Index which represents approximately a 12-month lag (Guttman 1998). The ability to estimate the drought conditions based on different lags allows the user to match the time period with ecologically relevant processes.

Global climate model (GCM) output from the Localized Constructed Analogs (LOCA; Pierce et al. 2014; 2015) database were summarized based on Nevada hydrographic area polygons. The following variables were obtained from the Scripps Institute of Oceanography LOCA database (http://loca.ucsd.edu/): maximum air temperature, minimum air temperature, precipitation, wind speed, specific humidity, and incoming shortwave radiation. All data are daily temporal resolution and 6 km spatial resolution. The

LOCA historical period covers 1950-2005 and the future period covers 2006-2100. Model output using representative concentration pathway (RCP) 4.5 and 8.5 were available, but only the RCP 8.5 ("business as usual") scenario was used for the GDE threat assessment. Seven of the 10 LOCA GCMs (ACCESS1-0, CanESM2, CNRM-CM5, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, and MIROC5) were used because they have archived all the necessary variables needed to compute evaporative demand.

Evaporative demand computed from the 7-model LOCA ensemble output and based on the ASCE Standardized Reference Evapotranspiration approach (Allen et al. 2005) was obtained from an archive developed by McEvoy et al. (2020). This approach required maximum and minimum air temperature, wind speed, specific humidity, and incoming shortwave radiation from LOCA.

Because of the 6 km spatial resolution, we performed the analysis of threats to GDEs from future climate at the level of hydrographic area. Daily LOCA data were averaged over each hydrographic area using all grid cells that lie within the basin polygon to form hydrographic area timeseries for each variable. Daily data were converted to monthly timeseries by computing monthly means for temperature, wind speed, specific humidity, and incoming shortwave radiation, and monthly sums for precipitation and evaporative demand. The SPEI was then computed using the monthly precipitation and evaporative demand timeseries.

A nonparametric method developed by Farahmand and AghaKouchak (2015) and adopted by Hobbins et al. (2016) for the Evaporative Demand Drought Index was used to estimate the probability distributions for SPEI. Three SPEI timescales were used: 8-month, 48-month, and 72-month. The 8-month lag tends to correlate with annual fluctuations in soil moisture and the ability for plants to respond to those changes (Albano et al. 2020), whereas the 48-month and 72-month lags indicate longer and more ecologically consequential (i.e., causing greater mortality of plant species) drought conditions. For this analysis we chose the September 8-month SPEI as this period aligns with when the majority of moisture is received and generally spans the active growing season for semi-arid and arid plants. SPEI converts accumulated [precipitation – evaporative demand] into a standard normal index in standard deviations from a specified mean (i.e., a value of 0 indicates the SPEI is at the specified mean), where negative values indicate drier conditions and positive values indicate wetter conditions than the mean. The mean can be calculated across the entire dataset or for a reference time period. Since we were interested in the change in future climate compared to historic conditions, a reference period of 1950 to 2019 was specified (note that this period does include recent trends in temperature and precipitation due to human induced climate change). SPEI values for 2020-2099 were estimated relative to the reference period following the approach of McEvoy et al. (2020), but we focused our analysis of future conditions between 2022 and 2060 because of higher uncertainty in LOCA estimates in the more distant future.

Additionally, we were interested in understanding not only the predicted changes in the moisture conditions by each LOCA model, but also if the models had similar results. While increased moisture would likely have impacts on vegetation structure and composition, we decided to focus on instances of increased drought conditions where the SPEI was less than -1 standard deviation from the mean (i.e., more negative SPEI). For each hydrographic area, we determined the future climate threat (see Appendix G for equations). Hydrographic areas with a high number of droughty months consistent across all LOCA models were given higher threat risk factor values. Consistency was measured by the variance among LOCA models. In other words, greater variance indicated less consistency of prediction (Appendix G), so more variable projections carried less weight in determining future threat risk factor values.

Figure 10 shows the resulting future climate threat risk factor value for each hydrographic area in Nevada. Between 2022 and 2060 and across all LOCA models, all hydrographic areas had mean SPEI values less than -0.40 (data not shown), indicating droughty conditions are projected throughout the state. As noted by McEvoy et al. (2020), although there are projected increases in precipitation in winter in Nevada, the very large projected temperature increases far outweigh the increases in precipitation and drive the SPEI values to more droughty values. As evaporative demand is projected to be higher due to increased air temperature in all assessed LOCA models, GDEs are expected to experience change in available soil moisture. Areas of highest climate threat risk were in southern Nevada and along the western boundary of the state. These hydrographic areas had high threat risk factors because of having high numbers of droughty months and high consistency among LOCA models. Lowest threat risk factor values were found in eastern Elko County, where the models projected consistently less drought conditions as compared to the historic data.

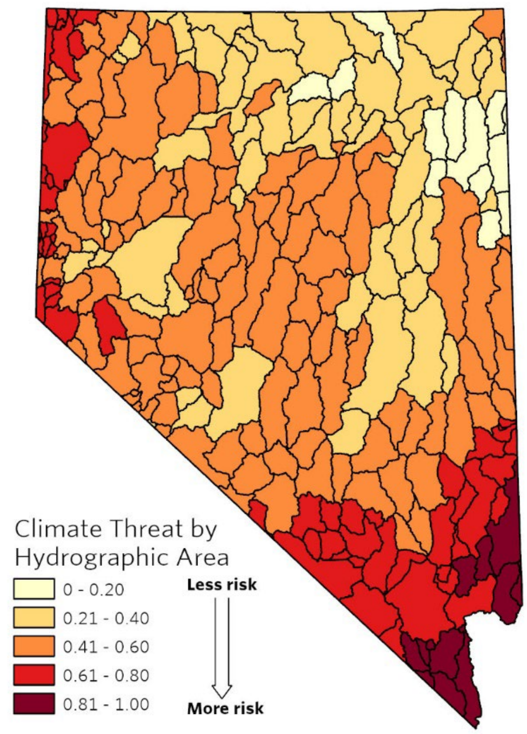


Figure 10. Climate threat risk factor values for each hydrographic area. Range is from 0.00 (lowest risk) to 1.00 (high risk). GDEs were assigned the threat risk factor value in the respective hydrographic areas in which they were located.

iGDEs were assigned the threat risk factor value associated with the respective hydrographic areas they were in. Over 20% of all GDE types were at moderate to high risk for the climate threat risk factor, with the highest percentage for lakes and playas (Table 13; Figure 11). Lakes harbor endemic fish species, and both lakes and playas are important locations for migratory birds and aquatic invertebrates, some of which are adapted to the temporary water presence in playa lakes (WAPT 2012).

We note that the future climate threat risk factor only addresses projections of climate variables, although areas of local groundwater flow paths are likely to experience the impacts of a changing climate more quickly than those with regional flow paths, as addressed by the current climate stressor risk factor. Maps showing climate stressor and threat risk factor values for GDEs are included in Appendices H and I, respectively.

Table 13. Percentage and quantity of GDE types at moderate to high risk (greater than 0.5) for the future climate threat risk factor. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Future climate threat	
	%	Amount (metric / ENU)
Springs	28.3	7,127 /7,127
Wetlands	25.9	308,032 ha / 761,163 ac
Phreatophyte communities	21.9	476,661 ha / 1,177,854 ac
Lakes and playas	48.8	293,433 ha / 725,088 ac
Rivers and streams	23.8	4,470 km / 2,777 mi

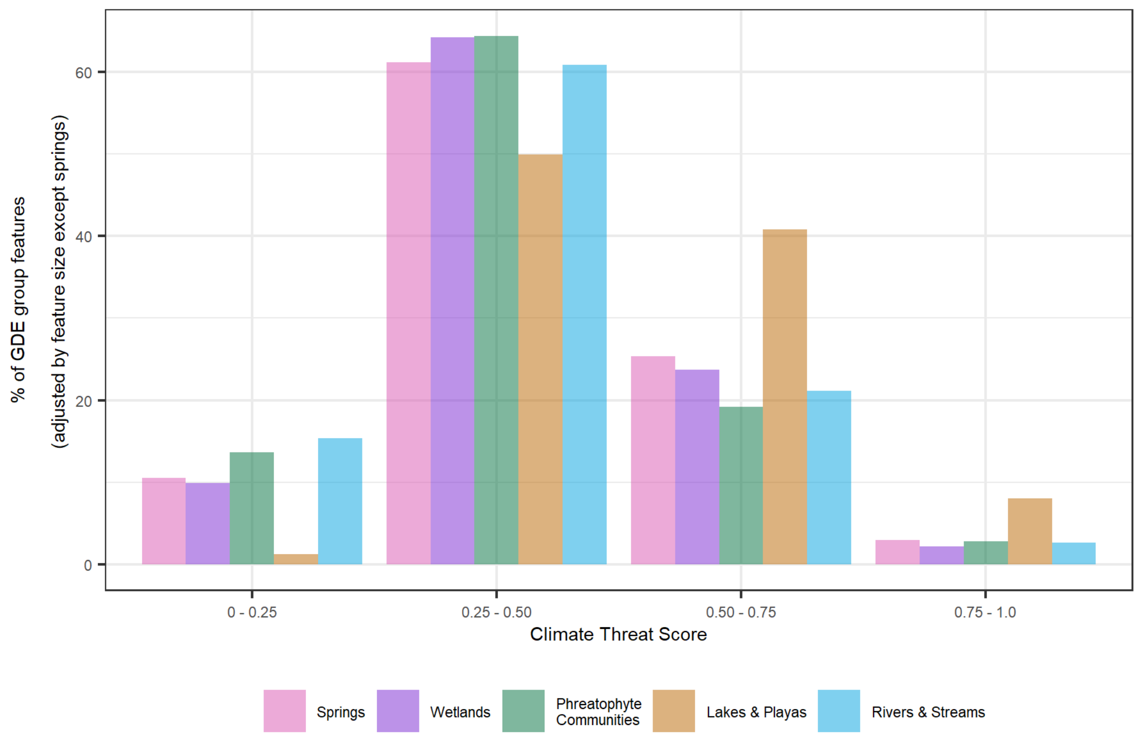


Figure 11. Percentage distribution of GDE types for climate threat risk factor values. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types.

UNGULATES

Ungulates such as cattle, domestic sheep, horse, burro and elk outside native range can affect GDEs through trampling and unsustainable grazing. Trampling can eliminate riparian vegetation and modify aquatic conditions by raising water temperatures, changing the amount of fine substrates, dispersing non-native plants and pathogens, and increasing nutrient loading (Armour et al. 1991; NRC 2002; Sada and Nachlinger 1998; Sada and Pohlmann 2006). Foraging impacts can vary depending on species characteristics, season, intensity, and water availability (Naumburg et al. 2005). Longer-term impacts of grazing include changes in hydrology and fire patterns, as well as declines in biotic richness and diversity (NRC 2002).

In a study of plants and animals protected under the federal Endangered Species Act, livestock grazing harmed 22 percent of federally endangered, threatened or proposed species, subspecies, or populations, including 33 percent of listed plants, and 30 percent of listed crustaceans (Wilcove et al. 1998). In the Great Basin, livestock grazing has been a major land use for centuries (Chambers and Wisdom 2009; Sada and Vinyard 2002). Overgrazing by livestock can result in changes in the structure and composition of vegetation as well as changes in soil properties and water quality (Chambers et al. 2011; Chambers and Miller 2011). For example, overgrazing by livestock can lead to extensive arroyo cutting and filling in the southwestern United States (NRC 2002).

The overall impacts of livestock grazing vary by ecosystem, historical context, current condition, and management. For example, in northern Great Basin sagebrush, strategic grazing has been shown to reduce exotic species (Davies et al. 2021). Studies that have looked at the effects of excluding or managing livestock grazing have observed improvements in range conditions and native plant and animal communities in Nevada (Pendleton et al. 2013), although Courtois et al. (2004) did not find significant changes in species composition, cover, density, and production within and outside of exclosures in other parts of Nevada after 65 years. Albano et al. (2020) observed NDVI trends indicating improved riparian vegetation vigor along the Upper Humboldt River after shifts from year-round grazing to rest-rotation management.

Surveys by Sada and Nachlinger (1998) in the Spring Mountains in southern Nevada documented impacts by ungulates at springs, including grazing and trampling by cattle, horse, burro and elk outside their native range. Sada and Lutz (2016) compiled data from 2,213 springs sampled from the late 1980s to 2013 and found that cattle use affected over 50% of the springs. Assessment of disturbance at springs in the Spring Mountains by Fleishman et al. (2006) found that native species richness declined as grazing intensity increased, but non-native species richness was greater at springs with moderate grazing intensity as compared to springs with no grazing.

Native ungulates can also impact riparian and wet areas by consuming plants, dispersing seeds, disturbing soil, affecting geomorphology (NRC 2002), and impacting rare species near springs and seeps (Pendleton et al. 2013). Some vegetation regenerate because of concentrated seasonal browsing, and impacts can vary depending on ungulate populations that are affected by predation, competition, climate, and other factors (NRC 2002). However, the impact of native ungulates is often less than that of livestock in areas that support both (NRC 2002).

Data on ungulate use of GDEs are very limited, so we made assumptions about how different ungulates might impact different types of GDEs (Table 14). We assumed that ungulates would not impact GDE lakes and playas. Playas do not have drinkable water for ungulates and have limited forage. Ungulates are not usually in lakes and many of Nevada's lakes are saline so they also do not offer drinkable water.

Table 14. GDEs assumed to be affected by different types of ungulates. The Lakes and Reservoirs layer is not included because it was assumed to not be affected by ungulates. See Saito et al. (2020) for more information on the Nevada iGDE layers.

Nevada iGDE layer	GDE community or system	Ungulates
Springs	Springs	Horse/burro, livestock
Wetlands	Palustrine	Horse/burro, livestock
	Riparian	Horse/burro, livestock
Phreatophyte Communities	Aspen woodland	Livestock, elk
	Aspen mixed-conifer	Livestock, elk
	Mesquite	Horse/burro, livestock
Rivers and Streams	Rivers, streams	Horse/burro, livestock

We relied on the spatial extents for which ungulates are expected to access, as follows (Figure 12):

- Elk: The Nevada Department of Wildlife has mapped occupied distribution of elk in Nevada)
- Livestock (cattle and sheep):
  - Grazing allotments are mapped by the BLM and includes polygon data and information about allotment seasonal use by animal type
  - Grazing allotments are a feature class in the Range Management Unit dataset for the U.S. Forest Service
- Wild horses and burros: Herd management areas (HMAs) are federally managed lands for wild horses and burros in Nevada

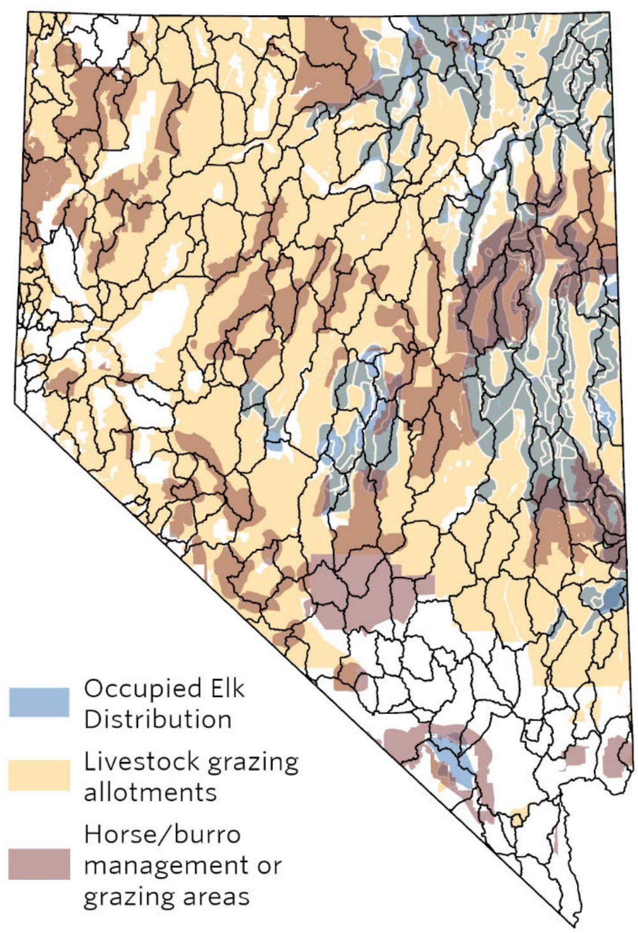


Figure 12. Areas where GDEs may be impacted by horses/burros (red), elk (blue), or livestock (yellow).

We assigned GDEs within ungulate management and distribution areas shown in Figure 12 stressor and threat values of 1.0. GDEs that were not in these areas received values of 0.1 because of the possibility that ungulates could still be present outside of the management or distribution areas (Table 15). We recognize that ungulates may not be present or affect all GDEs in these spatial extents, and they may also exist outside of these mapped areas. We considered ungulates to be both stressor and threat risk factors because we assumed they would continue to be a threat in the future and did not have data about how the threat would change in the future.

Table 15. Stressor and threat risk factor values for ungulate impacts to GDEs in Nevada

Ungulates	Stressor	Threat
Within an allotment or HMA or elk distribution area	1.0	1.0
Outside of an allotment or HMA or elk distribution area	0.1	0.1

For each Nevada GDE type in Table 14, the maximum number of ungulate types that could impact a GDE was 2. Thus, ungulate risk factor values for each iGDE in the Nevada iGDE database were normalized by dividing by 2. For example, an aspen woodland system might be affected by both cattle grazing and over-use by elk outside its historic range. This would result in a raw ungulate risk factor value of 2.0 for this system, but it was normalized to an ungulate risk factor value of 1.0. An aspen woodland system only impacted by elk would have a final ungulate risk factor value of 0.5. We used this approach to note that different ungulates have different impacts and having more than one type of ungulate affecting a GDE can have compounded impacts, so that type of situation was assigned a higher risk factor value than a GDE impacted by only one ungulate type.

Springs and GDE rivers and streams had the greatest percentage at high risk from the ungulate stressor and threat risk factors (Table 16), which agreed with observations of Sada and Lutz (2016) in their surveys of Great Basin and Mojave Desert springs. Lakes and playas were not affected by ungulates because of the assumption that ungulates were unlikely to have interactions with lakes and playas. Maps showing stressor and threat risk factor values for GDEs from ungulates are included in Appendices J and K.

Table 16. Percentage and quantity of GDE types with high risk for the ungulate stressor or threat risk factors. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Ungulate stressor or threat (high risk)	
	%	Amount (metric / ENU)
Springs	87.4	22,008 / 22,008
Wetlands	21.1	250, 567 ha / 619,165 ac
Phreatophyte communities	26.1	567,064 ha / 1,401,244 ac
Lakes and playas	0.0	0 ha / 0 ac
Rivers and streams	71.6	13,431 km / 8,346 mi

NON-NATIVE SPECIES

As with other ecosystems in Nevada, non-native species can be very problematic for GDEs. Invasive and non-native aquatic species can displace natural species and affect natural foodwebs (Kolosovich et al. 2012; Vitousek et al. 1996) by competing with natural species, altering habitat conditions and affecting ecosystem properties (Brooks et al. 2013). Miller et al. (1989) found that 68% of extinctions of fishes in North America were associated with detrimental effects of introduced species, with the Great Basin being a region that has lost a substantial proportion of native fish fauna. For example, the Pahranagat Spinedace (*Lepidomeda altivelis*) once occupied the outflow of Ash Springs and Upper Pahranagat Lake, but most likely became extinct due to competition or predation by non-native common carp, mosquitofish (*Gambusia affinis*) and bullfrogs (Miller et al. 1989). The disappearance of Pahrump Ranch poolfish (*Empetrichthys latos Pahrump*) and Raycraft Ranch poolfish (*E. latos concavus*) was partly due to introduction of common carp, goldfish (*Carassius auratus*), and bullfrogs (Williams and Sada 2020). Sada and Vinyard (2002) found that the abundance and distribution of over half of 135 distinctive endemic aquatic taxa in the Great Basin were affected by non-native species. Of 44 springs in Nevada with springs-dependent taxa in severe decline, extirpation or extinction in the Great Basin and Mojave Desert, one of the largest causes of the declines, extirpation or extinction was non-native species (37%; Sada and Lutz 2016). Comer et al. (2013) found invasive aquatic species in lakes, reservoirs, springs and seeps, and Great Basin foothill and lower montane riparian woodland and shrublands and streams in their ecological assessment of the Central Basin and Range in the western United States.

Non-native plants can affect the local water balance as well as soil, nutrient, and light dynamics (Stevens et al. 2020). They can even increase fire frequency; for example, black greasewood systems, the largest GDE type by area in Nevada (Saito et al. 2020), historically did not experience fires, but can transition to weedy, fire-prone systems dominated by non-native vegetation if access to groundwater is lost (Provencher et al. 2020). In an ecoregional assessment of the Central Basin and Range, Comer et al. (2013) found that invasive plant species were impacting springs, seeps, greasewood flats, rivers and streams. Several studies have found that non-native plant species richness and cover tend to increase at GDEs with higher disturbance, whereas native species richness decreases as intensity of disturbance increases (Bart et al. 2020; Fleishman et al. 2006; Nielson et al. 2019).

Climate change may also provide opportunities for non-native species to invade and change GDEs (Woodward et al. 2010). Changes in the timing and magnitude of air temperatures can favor species that have less phenological sensitivity (Keller and Shea 2020). For aquatic species, warmer water temperatures due to climate warming could increase predation by non-native fishes on native prey species or enable non-native parasites and pathogens to achieve higher population densities more rapidly (Rahel and Olden 2008).

To assess non-native species as stressors, non-native animal species in Deacon and Williams (1984) and non-native plant and animal species well-known to negatively affect GDEs in Nevada according to experts (Table L-1 in Appendix L). Although non-native equines and livestock can also impact GDEs they are included in the "ungulate" risk theme so they were not accounted for here. We aggregated available data on these species from the following data sources to map locations of where these species have been recorded:

- Non-Indigenous Aquatic Species (NAS) database: Managed by the USGS, this database is a resource for spatially referenced occurrence data of introduced aquatic species throughout the United States;

geographic data for all species in Table L-1 were downloaded from the NAS database and converted to a point feature class.

- Early Detection and Distribution Mapping System (EDDMapS): EDDMapS is a repository of geographic information on observations of invasive species or pests from agencies and individuals; point data for Nevada from EDDMapS and were merged to create a single point feature class for EDDMapS data.
- Springs Stewardship Institute (SSI) data: Data from springs surveys in Nevada were acquired for the GDE mapping project in 2019 (Byer et al. 2019); springs where non-native species in Table L-1 were found were saved as point data to represent non-native species occurrence.

Point data from NAS, EDDMapS, and SSI were aggregated to create a single point feature class of non-native species occurrence. iGDEs within 800 m (0.5 mile) of these locations were assigned a stressor risk factor value of 1.0. Because the lack of data on non-native species does not necessarily mean that they do not exist at a location (e.g., there may have been no surveys done, species may not have been present at time of survey, etc.), all other iGDEs were assigned a stressor risk factor value of 0.1 (Table 17).

Humans activities often increase populations of non-native species (Bart et al. 2020; Nielson et al. 2019; Sada and Pohlmann 2006; Stevens et al. 2020) in part because people may knowingly or unknowingly transport non-native species from one system to another as seeds, pollen, or individuals (e.g., stuck on surfaces like boots, shoes, boats, etc.; intentional release of unwanted fauna, etc.; Fleishman et al. 2006). To assess the threat of human introduction of non-native species to GDEs, we used current road density to estimate potential distribution and impacts. Roads also provide access to GDEs, which Sada and Nachlinger (1998) found to be an indicator of disturbance severity of springs in the Spring Mountains. The TIGER database from the U.S. Census Bureau (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html) contains a road density layer for the entire United States. We clipped this raster to the extent of Nevada and normalized the density values to be between 0 and 1. At each iGDE, we used the average road density value to represent the threat risk factor value from non-native species (Table 18). Figure C-2 in Appendix C illustrates the application of the non-native species stressor and threat risk factors to iGDEs in the Nevada iGDE database.

Table 17. Stressor and threat risk factor values due to non-native species on GDEs in Nevada.

Non-native species risk	Stressor	Threat
Current non-native species presence	1.0	--
Current non-native species absence	0.1	--
Road density normalized	--	0 to 1

Lakes and playas and phreatophyte communities had the highest percentages of area at high risk by current non-native species presence whereas springs had the lowest percentage at high risk (Table 18). This result contradicted Miller et al. (1989) and Sada and Lutz (2016) who found that non-native species were a strong factor in the decline of native species at springs in Nevada and the Great Basin. Since we used non-native species databases for this analysis, the discrepancy could be due to low levels of reporting of non-native species at springs in these databases. The larger footprint of phreatophyte community polygons (as compared to spring point data) could have also affected the determination of presence or absence in our analysis. On the other hand, Stevens et al. (2021) suggest that springs may be more protected from non-native species introductions because of their isolated nature.

All GDE types had very few, if any, iGDEs at moderate to high risk for the road density threat risk factor (Table 18). The normalized road density values for the threat risk factor were very low because many GDEs are in rural areas where road density is low. Maps showing stressor and threat risk factor values for GDEs from non-native species are included in Appendices M and N.

Table 18. Percentage and quantity of GDE types at high risk for non-native species stressor risk factor due to non-native species presence and at moderate to high risk (greater than 0.5) for non-native species threat risk factor due to road density. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Non-native species stressor		Non-native species threat	
	%	Amount (metric / ENU)	%	Amount (metric / ENU
Springs	6.8	1,713 / 1,713	0.0	1 / 1
Wetlands	18.4	220,057 ha / 543,773 ac	0.0	13 ha / 33 ac
Phreatophyte communities	45.7	991,967 ha / 2,451,202 ac	0.0	0 ha / 0 ac
Lakes and playas	62.4	375,109 ha / 926,914 ac	0.0	0 ha / 0 ac
Rivers and streams	14.5	2,716 km / 1,688 mi	0.0	4 km / 2 mi

ADDITIONAL IMPACTS DUE TO HUMAN DEVELOPMENT

Many of the stressors and threats we assessed in the other four themes are associated with human activities, so in this theme we focused on two additional areas of human activities that could impact GDEs: 1) urbanization and 2) surface water diversions. In addition to dewatering GDEs (covered in the water withdrawals section), urbanization can impact GDEs by disturbing them, fragmenting them, covering up areas that would naturally provide recharge for groundwater, and altering local air temperature patterns (Marchionni et al. 2020). Urban areas can also be sources of groundwater contamination that can negatively affect GDEs (Cantonati et al. 2020). The Great Basin has experienced high population growth and increasing urbanization in past decades (Chambers and Wisdom 2009), with Nevada having the highest growth rate in the nation between 1960 and 2010 (Pendleton et al. 2013). We used housing density estimates as a proxy for urbanization, with housing density estimates for 2010 from Comer et al. (2013)[4] as an indicator of stressor risk. We normalized the estimates with the maximum value to get a range of 0.0 (negligible risk) to 1.0 (high risk; Table 19). Future increased housing density was considered a threat risk factor, so we compared housing density maps from 2010 and projected maps of 2060 from Comer et al. (2013)[5] to identify locations where housing density increased. At each iGDE, the average increase in housing density was calculated, and the values were normalized across all iGDEs to range from 0.0 to 1.0 (Table 19).

Surface water diversions can impact GDEs such as riparian zones along rivers by altering interactions between surface water and groundwater (Rohde et al. 2021b). Diversions are also common at springs to enable use of water for irrigation, drinking water, or livestock watering (Sada and Nachlinger 1998).

In Nevada, spring discharges are administered as surface water, so such diversions are considered surface water diversions. Williams and Sada (2020) describe extinctions of species like the Tecopa pupfish (*Cyprinodon nevadensis calidae*) that were due in part to diversions. In a compilation of data for 2,213 springs surveyed from the late 1980s to 2013, 36% of the springs had been impacted by diversions, with 24% being highly disturbed (Sada and Lutz 2016). Sada and Lutz (2016) also found 44 springs in Nevada with springs-dependent taxa in severe decline, extirpation or extinction in the Great Basin and Mojave Desert, and the largest cause of the declines, extirpation or extinction was diversion. Fleishman et al. (2006) found that species richness of native plants was lower at springs in the Spring Mountains of southern Nevada with high levels of diversion as compared to springs with no diversion or moderate diversion, but species richness of non-native plants was higher at springs with slight diversion as compared to no diversion or high diversion.

To assess the stressor of surface water diversions on GDEs, we used Point of Diversion (POD) from the Nevada Division of Water Resources (NDWR). GDEs with PODs within 800 m (0.5 mile) were given a stressor risk factor value of 1.0. All other GDEs were given a stressor risk factor value of 0.1 due to uncertainty in where actual PODs are located because they are not always located where noted in the NDWR database (Table 19). Figures illustrating the approach for applying the stressor and risk factors for additional human development to iGDEs in the Nevada iGDE database are included in Appendix C.

---

[4] 2010 dataset in Comer et al. (2013) is available at https://landscape.blm.gov/geoportal/catalog/search/resource/details.page?uuid=%7BC4DFABE8-080C-441B-8E3D-6F0C54A22F5C%7D

[5] 2060 dataset in Comer et al. (2013) is available at https://landscape.blm.gov/geoportal/catalog/search/resource/details.page?uuid=%7B3B268D03-86D5-4D89-A105-AED557D2D89A%7D

Because we had two risk factors that we rated as stressor risk factors for additional impacts due to human development, we combined the risk factors by adding the values for each risk factor and dividing the result by a normalizing factor of 2.0 to get combined additional human development stressor risk factor values between 0.0 and 1.0 (Table 19).

Table 19. Summary of additional human development risk factor calculation approach for GDEs in Nevada.

Additional human development risk	Risk factor type	Values	Normalizing factor	Final range
Current housing density	Stressor	0.0 to 1.0	2	0.0 to 1.0
Surface water points of diversion	Stressor	0.1 or 1.0		
Increased housing density in 2060	Threat	0.0 to 1.0	NA	0.0 to 1.0

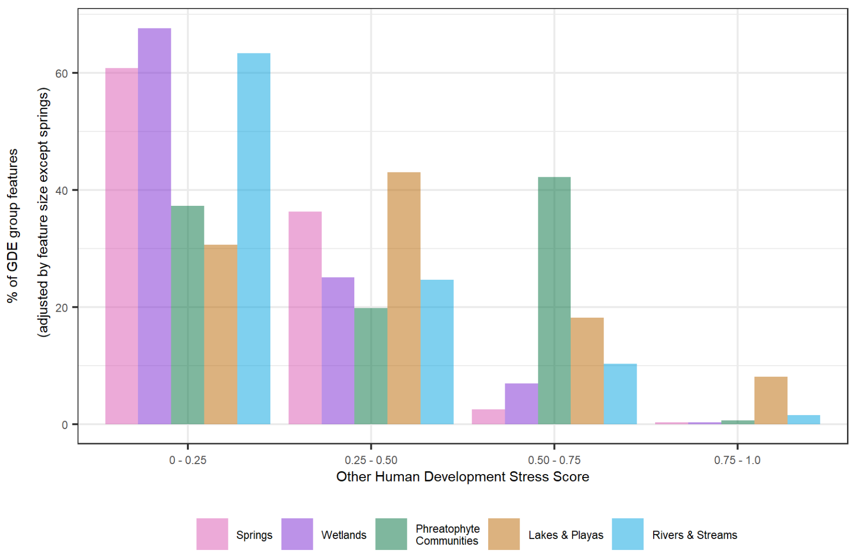
Large percentages of phreatophyte communities and lakes and playas were at high risk for the surface water POD stressor risk factor (Table 20). This resulted in phreatophyte communities having the largest percentage at moderate to high overall risk for the combined additional human development stressor risk factors (Table 21; Figure 13), in part because of the larger areas of the polygons (as opposed to points for springs, and lines for rivers and streams). Almost 10,000 springs and over 6,000 km (over 4,000 mi) of rivers and streams were at high risk for the surface water POD stressor risk factor, which seems reasonable considering where surface water diversions usually occur. All GDE types had fairly low percentages at moderate to high risk for the housing density stressor because many GDEs are located in rural areas that have very low housing density values relative to larger urban areas. This causes the normalized housing density risk factor values to be very small, which also affected the increased housing density threat (Table 21; Figure 13). Appendices O and P show overall stressor and threat risk factor values for GDEs from additional human development.

Table 20. Percentage and quantity of GDE types at high risk for surface water POD stressor risk factor and at moderate to high risk for housing density stressor risk factor. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Surface water POD stressor (high risk)		Housing density stressor (moderate to high risk)	
	%	Amount (metric / ENU)	%	Amount (metric / ENU)
Springs	38.7	9,756 / 9,756	1.0	191 / 191
Wetlands	31.7	377,200 ha / 932,080 ac	1.0	11,432 ha / 28,248 ac
Phreatophyte communities	61.7	1,340,868 ha / 3,313,355 ac	1.4	30,127 ha / 74,446 ac
Lakes and playas	66.5	399,304 ha / 986,701 ac	10.9	65,573 ha / 162,035 ac
Rivers and streams	34.9	6,442 km / 4,072 mi	3.1	580 km / 360 mi

Table 21. Percentage and quantity of GDE types at moderate to high risk for overall other human development stressor risk factors and other human development threat risk factor. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. ENU = English units.

GDE type	Other human development stressor (moderate to high risk)		Other human development threat (moderate to high risk)	
	%	Amount (metric / ENU)	%	Amount (metric / ENU)
Springs	2.9	735 / 735	0.1	22 / 22
Wetlands	7.3	86,828 ha / 214,557 ac	0.1	1,713 ha / 4,234 ac
Phreatophyte communities	42.9	931,567 ha / 2,301,951 ac	0.4	9,085 ha / 22,449 ac
Lakes and playas	26.3	157,794 ha / 389,916 ac	5.8	34,579 ha / 85,447 ac
Rivers and streams	11.9	2,241 km / 1,393 mi	0.3	56 km / 35 mi



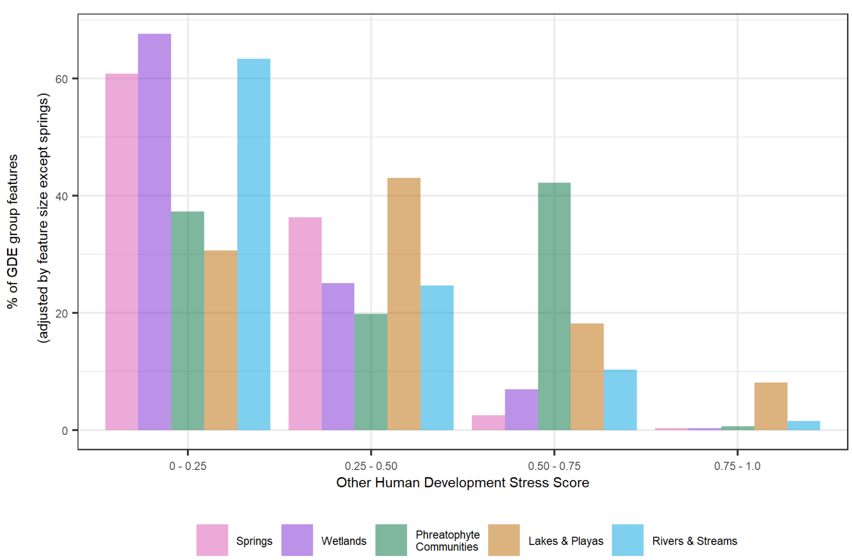


Figure 13. Percentage distribution of GDE types for other human development stressor (top) and threat (bottom) risk factor values. Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types.

COMBINED RISK FACTORS

Most, if not all, GDEs in Nevada are affected by multiple stressors and threats. The combined effects of multiple drivers can jeopardize species more than indicated in assessments of single causes (Hof et al. 2011). Sada and Lutz (2016) found that 42% of disturbed springs they visited were affected by more than one disturbance factor. In a literature review of threats to aquatic amphibians in the southwest, 28 of 34 species had identified species:threat relationships in combinations of climate, biological and land use categories (Mims et al. 2020). Thus, the risk factor values (each ranging from 0.0 to 1.0) from the five themes of stressors and threats were combined to create an overall risk factor value for each iGDE between 0.0 and 1.0. We applied weights to each of the themes to emphasize those that are riskier to GDEs (Table 22). Groundwater withdrawals were given the strongest weight because without water, GDEs do not function and the other themes will make no difference on the outcome. The next strongest weight was given to climate because it can create less water availability and it can also exacerbate other stressors or threats. Stressor and threat risk factor values due to ungulates, non-native species, and additional human development were given equal weights (Table 22). Applying these weights resulted in overall risk factor values for each iGDE in the Nevada iGDE database between 0.0 and 8.0.

Table 22. Weights applied to each theme to calculate overall risk factor values for GDEs in Nevada

Theme	Weight
Groundwater withdrawals	3.0
Climate	2.0
Ungulates	1.0
Non-native species	1.0
Additional human development	1.0

Figures 14 and 15 show the amount of iGDEs at high risk for each of the stressor and threat risk factors assessed, and Figures 16, 17 and 18 summarize stressor and threat risks in each risk factor theme by GDE type. The stressor risk factor that had the largest number of springs and rivers and streams at high risk was the ungulate stressor risk factor, whereas the surface water diversions stressor risk factor had the largest areas of wetlands, phreatophyte communities, and lakes and playas at high risk (Figure 14). Large areas of wetlands were also at high risk for the pumping status stressor risk factor. The ungulates threat risk factor also had the largest number of springs and rivers and streams at high risk (Figure 15), and the threat risk factor for proximity of GDEs to potential groundwater withdrawals had the largest areas of wetlands, phreatophyte communities and lakes and playas at high risk.

Among themes, ungulates were the largest stressor and threat risk factors for springs (Figures 16 and 17). More than 25,000 springs are in the Nevada iGDE database and they often are critical sources of water supply in large, remote areas for both people and wildlife (Williams and Sada 2020). Groundwater withdrawals had moderate to high stressor and threat risk for the largest areas of wetlands and phreatophyte communities (Figures 16 and 17), and all GDE types had substantial amounts at moderate to high risk for the future climate threat theme (Figure 17).

Among GDE types, lakes and playas were at highest risk for the non-native species stressor risk factor theme, with over 60% at moderate to high risk (Figure 18). Groundwater withdrawals and other human development stressor themes had moderate to high stressor risk for about 50% of phreatophyte communities. The latter was due mostly to the surface water points of diversions stressor risk factor (Figure 14). Among stressors overall, phreatophyte communities had the largest percentage at moderate to high risk, followed by springs and rivers and streams. For threats overall, lakes and playas had the highest percentage at moderate to high risk, mostly due to threats for the groundwater withdrawals and climate themes. Overall stressor and threat risk factors values could range from 0.0 to 8.0 after the weights in Table 22 were applied (Figures 19-21; larger figures are available in Appendix Q).

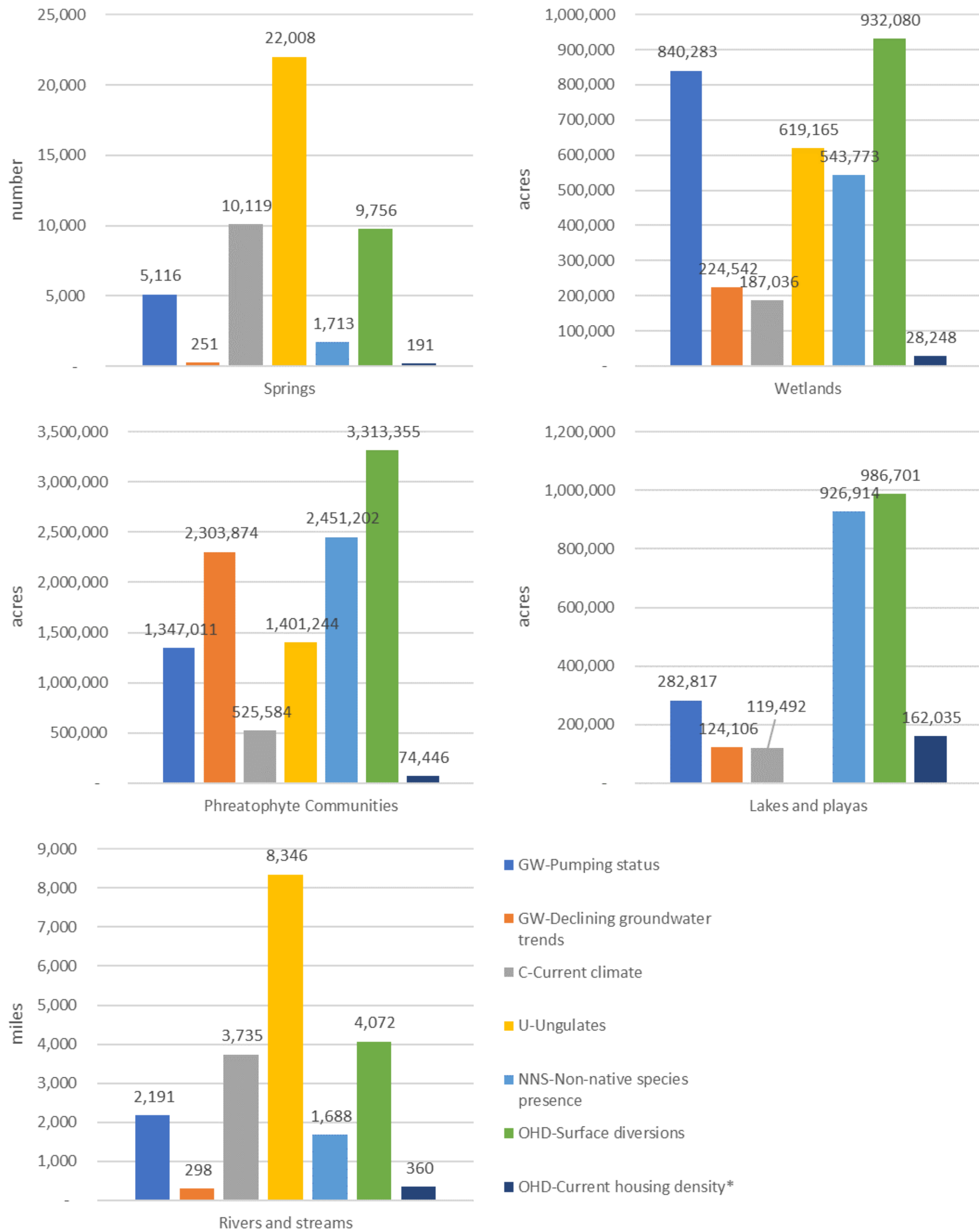


Figure 14. Amount of iGDEs in Nevada at high risk for stressor risk factors (asterisk [*] indicates amount of iGDEs at moderate to high risk for current housing density). Legend abbreviations for stressor risk factor themes: GW = groundwater withdrawal; C = climate; U = ungulates; NNS = non-native species; OHD = other human development.

Figure 15. Amount of iGDEs in Nevada at high risk for threat risk factors (asterisk [*] indicates amount of iGDEs at moderate to high risk for future climate, road density and housing density increase threat risk factors). Legend abbreviations for threat risk factor themes: GW = groundwater withdrawal; C = climate; U = ungulates; NNS = non-native species; OHD = other human development.

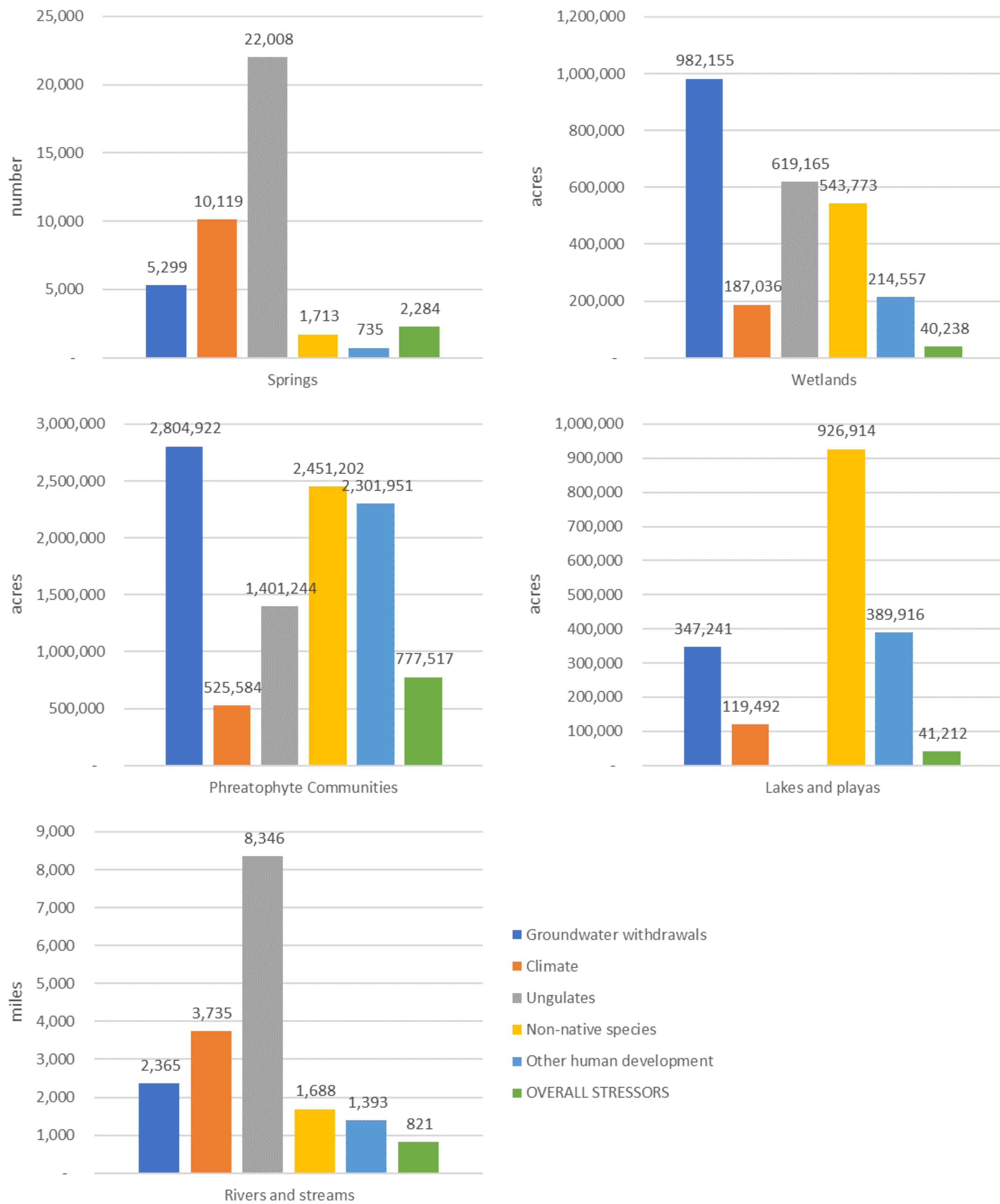


Figure 16. Amount of iGDEs in Nevada at moderate to high risk for stressor risk factors by theme.

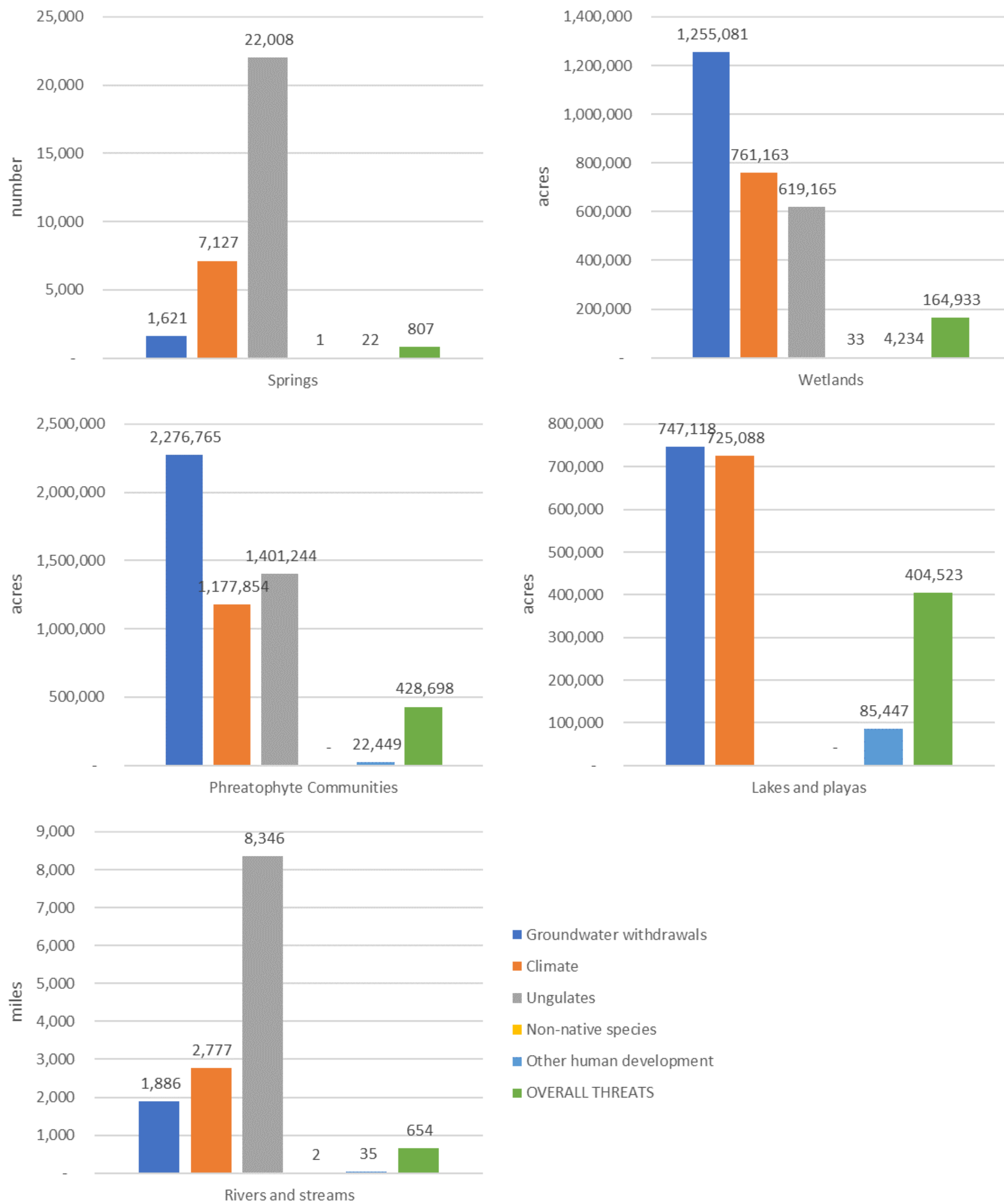


Figure 17. Amount of iGDEs in Nevada at moderate to high risk for threat risk factors by theme.

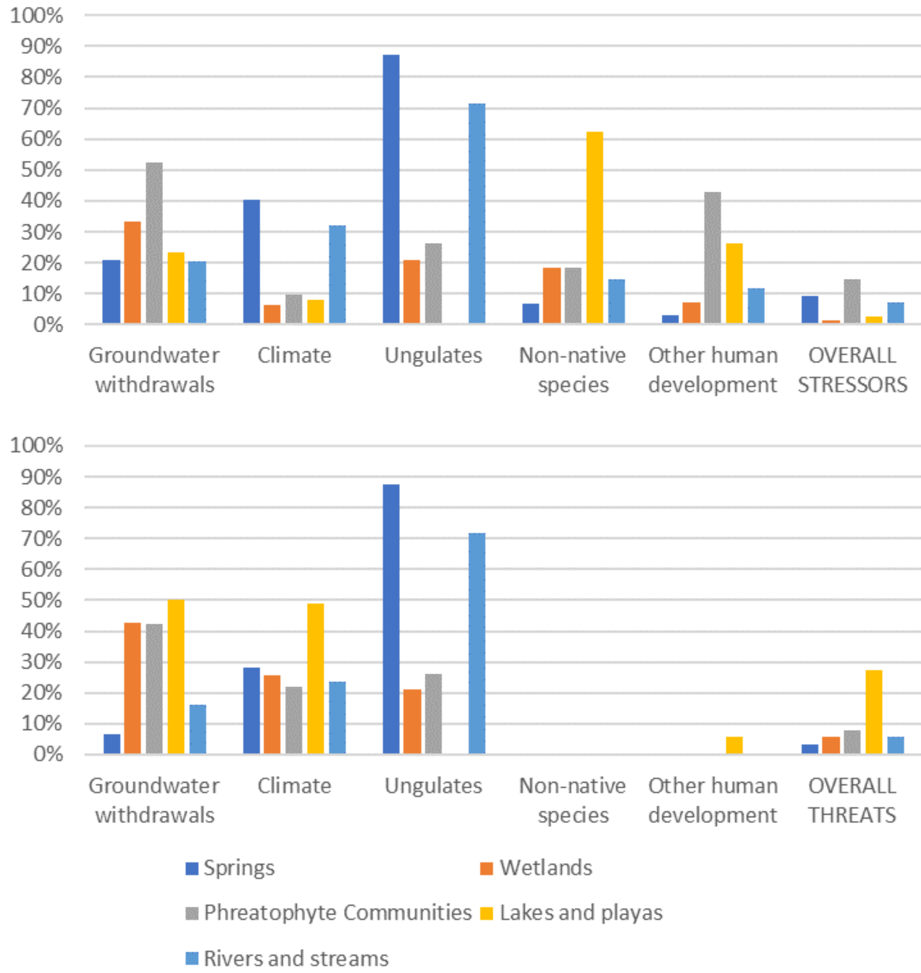


Figure 18. Percentages of GDE types at moderate to high risk by stressor theme (top) and threat theme (bottom). Percentages are percent of points for springs, percent of length for rivers and streams, and percent of area for other GDE types. PY = perennial yield.

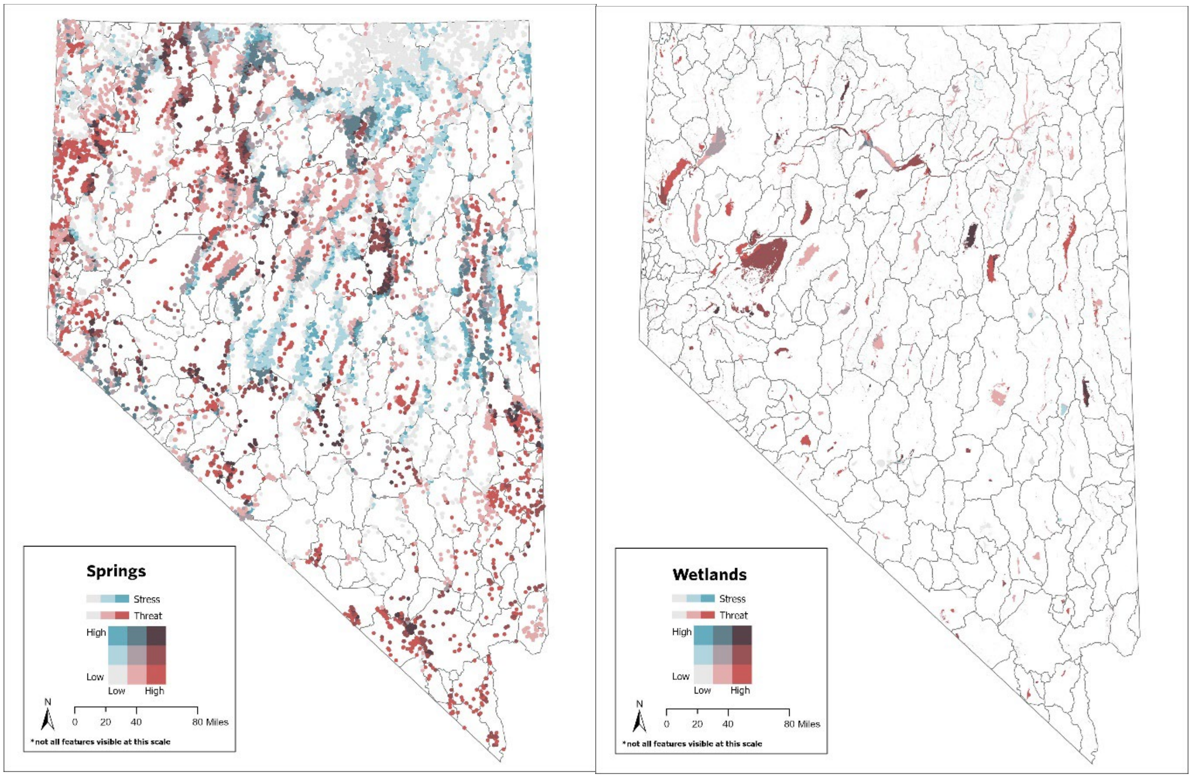


Figure 19. Overall stressor and threat risk factor values for GDE springs (left) and wetlands (right). Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

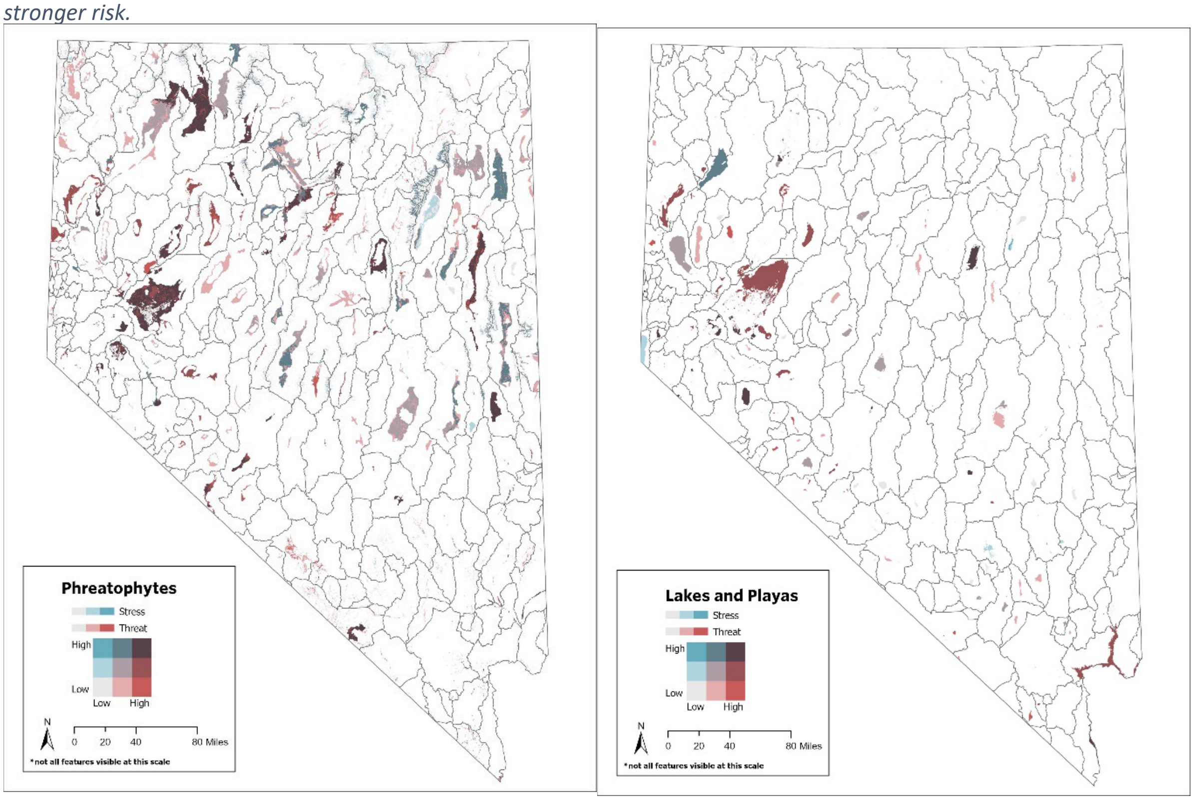


Figure 20. Overall stressor and threat risk factor values for GDE phreatophytes (left) and lakes and playas (right). Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

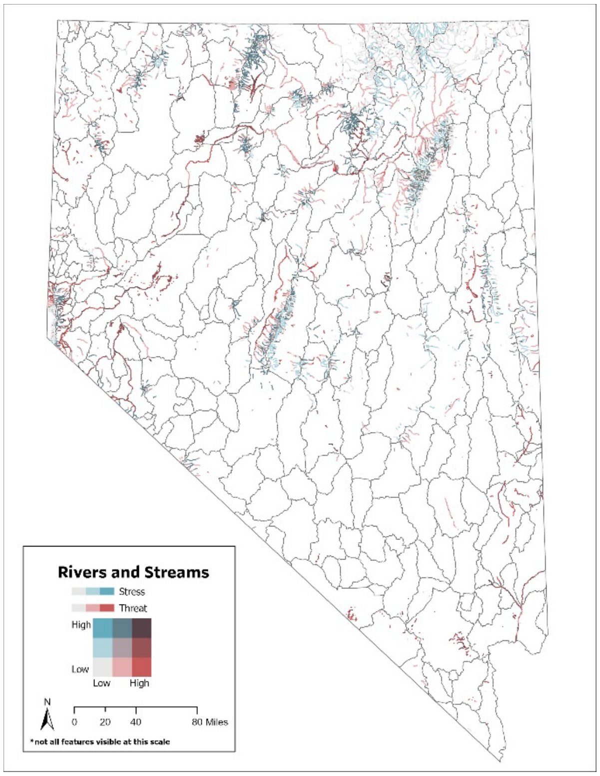


Figure 21. Overall stressor and threat risk factor values for GDE rivers and streams. Blue gradations indicate strength of stressor risk factors, and red gradations indicate strength of threat risk factors. Darker hues indicate stronger risk.

KEY TAKEAWAYS

- GDEs provide important services to people, plants and wildlife, so continued attention to managing stressors and threats to GDEs is important.

- Overall, more than 2,000 springs, over 16,000 hectares (>40,000 acres) of wetlands, over 300,000 hectares (>700,000 acres) of phreatophyte communities, over 16,000 hectares (>40,000 acres) of lakes and playas, and over 1,300 kilometers (>1,000 miles) of rivers and streams are at moderate to high risk for stressor risk factors.

- Over 800 springs, over 60,000 hectares (>160,000 acres) of wetlands, almost 175,000 hectares (>425,000 acres) of phreatophyte communities, over 160,000 hectares (>400,000 acres) of lakes and playas, and over 1,000 kilometers (>650 miles) of rivers and streams are at moderate to high risk for overall combined threat risk factors.

- Among stressors overall, phreatophyte communities had the largest percentage at moderate to high risk, followed by springs and GDE rivers and streams.

- For threats overall, lakes and playas had the highest percentage at moderate to high risk, mostly due to threats for the groundwater withdrawals and climate themes.

- The stressor and threat risk factors that pose the highest risk for springs and rivers and streams are the ungulate stressor and threat risk factors, with over 22,000 springs at high risk, and over 13,000 km (over 8,000 miles) at high risk.

- Over 370,000 hectares (> 900,000 acres) of wetlands, 1.3 million hectares (3.3 million acres) of phreatophyte communities, and over 320,000 hectares (>800,000 acres) of lakes and playas are at high risk for the surface water diversions stressor risk factor.

- The proximity of potential groundwater withdrawals in areas with shallow groundwater was the threat risk factor that had the largest areas at high risk for wetlands (>850,000 hectares [>2.1 million acres]), phreatophyte communities (>1.7 million hectares [almost 4.3 million acres]), and lakes and playas (>430,000 hectares [>1 million acres]).

- On average, about one-fifth of all GDEs, regardless of type, are in hydrographic areas that are over-pumped, which can put them at risk of having groundwater they use captured by excessive groundwater withdrawals.

- At least 40% of all GDE types are at high or moderate risk for the appropriation status threat risk factor.

- Over 70% of wetlands, phreatophyte communities, and lakes and playas are at high risk for the threat of potential groundwater withdrawals within 800 m (0.5 mile) when shallow groundwater is present.

- Out of 6,536 wells analyzed for groundwater level trends, 39% had significantly falling trends,15% had significantly rising trends, and the remainder did not have significant trends.

- Over half of the hydrographic areas in Nevada had at least one well site with significantly falling water level trends, but only 8 had most of the wells in their basins with significant falling trends.

- Over 40% of phreatophyte communities (over 800,000 hectares [~2 million acres]) are within 800 m (0.5 mile) of a well with a significant falling trend, which could affect their sustainability and lead them to transition to a community with less ecological value.

- The small percentage of springs and GDE rivers and streams that are within 800 m (0.5 mile) of a well with a significant falling trend could reflect decisions by the State Engineer in evaluating water right applications for groundwater use near surface waters, indicate that groundwater development has been more prevalent where surface water resources are unavailable or occur because of capture of surface water from springs, rivers or other water bodies.

- Because they are often located in recharge areas with local flow paths at higher elevations, more springs and GDE rivers and streams are at high risk for the current climate stressor risk factor than other GDE types, and this high risk will continue into the future.

- Between 2022 and 2060 and across all Localized Constructed Analogs (LOCA) models, all hydrographic areas in Nevada had mean Standardized Precipitation and Evapotranspiration Index (SPEI) values that indicated more droughty conditions than current conditions are expected throughout the state.

- Over 20% of all GDE types were at moderate to high risk for the climate threat risk factor, with almost 50% of lakes and playas at moderate to high risk, which are important locations for endemic fish, migratory bird species, and aquatic invertebrates.

- Almost 90% of springs and over 70% of GDE rivers and streams are at high risk for ungulate stressor and threat risk factors.

- Over 60% of lakes and playas are at high risk from the non-native species presence stressor risk factor, whereas springs had the lowest percentage at high risk, which may reflect a lower rate of reporting non-native species at springs in the databases used.

- Over 60% of phreatophyte communities and GDE lakes and playas are at high risk for the surface water points of diversion stressor risk factor.

ASSUMPTIONS

We made a number of assumptions in doing this analysis. The assessment presented here did not account for all possible stressors and threats to GDEs in Nevada. For example, we did not consider water quality and the threat of groundwater contamination. Brown et al. (2011) assessed the threat of groundwater contamination from agricultural practices by identifying areas where mobile pesticides were used on agricultural soils in Oregon. For urban areas, they used urban land use as a surrogate for urban chemical use (Brown et al. 2011). Levy et al. (2021) considered measurements of nitrate water quality in groundwater as an overall indicator of groundwater quality and found a correlation between increased nitrate levels and declining groundwater levels. We did not explicitly use water quality data for this analysis but did consider housing and road density which are both associated with human interactions that could be sources of water quality impairment.

We also did not consider development of mining or renewable energy sites and their impacts on GDEs. Comer et al. (2013) had projections of Solar Energy Programmatic Environmental Impacts Statement Zones (SEZs) in 2025, noting that some of them could counterintuitively overlap with HMAs in their rapid ecological assessment of the Central Basin and Range. Renewable energy sites could have cascading effects on GDEs that we didn't address.

In assessing the future climate threat risk factor, we relied on projections of climatic variables and not on associated processes other than evapotranspiration. Areas with local groundwater flow paths are likely to experience the impacts of a changing climate more quickly than those with regional flow paths, and this was addressed with the current climate stressor risk factor, but not in the future climate threat risk factor. Our analysis also did not explore the nuances of changing timing and mode of precipitation (i.e., snow versus rain) which may further impact GDEs.

We used the best available data, but data may have been incomplete or inaccurate. For example, the location of springs in the Nevada iGDE database are based on a snapshot of data from the Springs Stewardship Institute's SpringsOnline database in 2019 (Saito et al. 2020) but many springs are unmapped because of complex topography, scale issues with remotely sensed data, subaqueous settings (e.g., caves), and other factors that make them difficult to detect and locate (Stevens et al. 2021). We also used Lopes et al. (2006) maps of groundwater levels to determine where groundwater levels were 50 m or less from the ground surface, and those maps were based on data from 1947-2004. It is likely that current groundwater levels are different than those in Lopes et al. (2006) but we could not find more recent groundwater level maps for Nevada. Based on conversations with experts, we assumed that 800 m (0.5 miles) was a reasonable distance threshold for the impacts to GDEs from stressor and threat risk factors like proximity of GDEs to potential water withdrawals, invasive species, and declining groundwater level trends, but it is possible that GDEs can be impacted by stressor and threat risk factors located farther away.

The Nevada iGDE database relies on the National Hydrography Dataset (NHD) for the determination of perennial reaches of rivers and streams that are considered groundwater-dependent, but the NHD is not always accurate in where these reaches are located in Nevada. This could have affected estimates of the rivers and streams within 800 m of shallow groundwater (Table 6). In addition, our use of NHD data for the Nevada iGDE database may not reflect previously groundwater-dependent rivers and streams that have had discharge captured and become intermittent or ephemeral. Our analysis of well water levels was dependent on available data, and there were 23 hydrographic areas that did not have enough well data for our analysis. If multiple well readings were recorded in a year, those readings were averaged, which could incorporate measurements in pumping wells during irrigation season. A better approach may be to only use late winter/early spring water levels before annual pumping for irrigation begins if adequate data are available.

We did not incorporate explicit projections of future groundwater or surface water withdrawals in our estimate of future threats due to groundwater withdrawals or additional human development. Our use of appropriation status to indicate the threats due to groundwater withdrawals did consider those hydrographic areas that are already over-appropriated to have higher threats to GDEs than those that were not yet fully appropriated. The Nevada Legislature passed a bill to set aside 10% of available groundwater from ever being appropriated in hydrographic areas that were not fully appropriated as of June 5, 2019 (§ NRS 533.0241) to reduce the likelihood that those hydrographic areas would become fully appropriated. Thus, the risk factor values for the hydrographic areas are unlikely to change regardless of future groundwater or surface water withdrawals. However, the State is planning to re-examine estimates of perennial yield in all 256 hydrographic areas in the next ten years (Allander et al. 2021), which could change the status of some of the hydrographic areas and bring new science to understanding how perennial yield concepts could affect GDEs.

We also recognize that when surface water resources are scarce due to climate, groundwater withdrawals tend to increase (Aldous and Gannett 2021). Groundwater is easier to develop on an individual basis because surface water projects often require large amounts of capital and cooperation with neighbors to deliver and divide the water (Edwards and Smith 2018). We tried to account for the increased risk to GDEs of increased groundwater withdrawals by having a higher climate threat risk for hydrographic areas that were likely to experience more dry periods in the future (Aldous and Gannett 2021).

We assumed that HMAs, grazing allotments, and elk distribution areas would not change in the future so that areas associated with stressors and threats for ungulates remained the same. We also assumed that ungulates were unlikely to have an impact on lakes and playas. Comer et al. (2013) indicated that rural private roads were likely to increase in HMAs by 2025, but such increases were not accounted for in our analysis.

ACKNOWLEDGMENTS

We thank the following people especially for contributing time and effort to helping us prepare this assessment:

- Phil Gardner (USGS) and Dave Prudic (retired from USGS) for their generous help in thinking about stressors and threats to GDEs, especially in relation to climate and water withdrawals
- Blake Minor with Desert Research Institute for providing Python scripts for trend analysis and providing Lopes et al. (2006) depth to groundwater surface data
- Stephanie Snider with Nevada Division of Water Resources for providing water data throughout the state

We greatly appreciate the thorough and thoughtful reviews of an earlier version of this report by the following: Christine Albano, Mauricia Baca, Michael Clifford, Mike Dettinger, Zach Freed, Phil Gardner, Mickey Hazelwood, Jaina Moan, Sarah Peterson, Boris Poff, and Don Sada and conversations with Kip Allander, Jon Benedict, Bunny Bishop, Will Boyer, Nicole Goehring, and Levi Kryder at the Nevada Division of Water Resources about the draft report.

Funding for this work was provided by the Bureau of Land Management. The California-Nevada Climate Applications Program (CNAP) provided funding for Dr. McEvoy's work to produce the future climate data.

REFERENCES

Albano CM, McGwire KC, Hausner MB, McEvoy DJ, Morton CG, Huntington JL. 2020. Drought sensitivity and trends of riparian vegetation vigor in Nevada, USA (1985-2018). Remote Sensing 12(9):1362. Doi: 10.3390/rs12091362.

Albano CM, Minor BA, Morton CG, Huntington JL. 2021. Baseline assessment of groundwater dependent vegetation in relation to climate and groundwater levels in select hydrographic basins of Nevada: Pueblo, Continental Lake, Mud Meadow, Dixie, Railroad-North, Steptoe, Goshute, and Independence Valleys. Reno: Desert Research Institute. 198 p. Available at https://www.dri.edu/project/groundwater-dependent-ecosystem-assessments/ (accessed 5/11/21).

Aldous AR, Gannett MW. 2021. Groundwater, biodiversity, and the role of flow system scale. Ecohydrology e2342. https://doi.org/10.1002/eco.2342.

Allander K, Benedict J, Gardner P, Huntington J, Kryder L, Sullivan A. 2021. The Nevada State Water Initiative (NV SWI) proposal. Presentation at Nevada Water Resources Association 2021 Annual Conference. Available at https://onedrive.live.com/?authkey=%21ADgNnNLBKZs84TE&cid=16BA3DB0E0CE6624&id=16BA3DB0E0CE6624%219907&parId=16BA3DB0E0CE6624%219650&o=OneUp (accessed 2/19/22).

Allen RG, Walter IA, Elliott R, Howell T, Itenfisu D, Jensen M. 2005. The ASCE standardized reference evapotranspiration equation. ISBN 0-7844-0805-X. Reston: American Society of Civil Engineers, 59 pp.

Alley WM, Reilly TE, Franke OL. 1999. Sustainability of ground-water resources. US Geological Survey Circular 1186. Denver: US Geological Survey. 79 pp. Available at https://pubs.usgs.gov/circ/1999/circ1186/pdf/circ1186.pdf (accessed 1/19/22)

Armour CL, Duff DA, Elmore W. 1991. The effects of livestock grazing on riparian and stream ecosystems. Fisheries 16(1):7-11.

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, VA: US Geological Survey. 84 p. Available at http://pubs.usgs.gov/circ/1376.

Bart D, Booth E, Loheide II SP, Bernthal T. 2020. Impacts of groundwater extraction on calcareous fen floristic quality. Journal of Environmental Quality 49:723-734. DOI: 10.1002/jeq2.20059

Bredehoeft JD. 2002. The water budget myth revisited: Why hydrogeologists model. Groundwater 49(4):340-345.

Bredehoeft J, Durbin T. 2009. Ground water development – the time to full capture problem. Groundwater 47(4): 506-514. Doi: 10.1111/j.1745-6584.2008.005138x.

Bredehoeft JD, Papdopulos SS, Cooper HH. 1982. Groundwater: The water-budget myth. In National Research Council. Scientific Basis of Water-Resource Management. Washington, D.C.: The National Academies Press, P. 51-57.

Brooks M, Ostoja S, Chambers J. 2013. Invasive species in Southern Nevada. Chapter 4 (pp. 59-73) in Chambers JC, Brooks ML, Pendleton BK, Raish CB, eds. The Southern Nevada Agency Partnership Science and Research Synthesis: Science to support land management in Southern Nevada. General Technical Report RMRS-GTR-303. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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

Byer S, Saito L, Larkin J, Badik K, Provencher L, McGwire K, Anderson T. 2019. Indicators of Groundwater Dependent Ecosystems in Nevada: Methods Report. Reno, Nevada. Available at https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/nevada/water/Pages/database-collaboration.aspx (accessed 12/10/20)

Cantonati M, Poikane S, Pringle CM, Stevens LE, Turak E, Heino J, Richardson JS, Bolpagni R, Borrini A, Cid N, Ctvrtlikova M, Galassi DM, Hajek M, Hawes I, Levkov Z, Naselli-Flores L, Saber AA, Di Cicco M, Fiasca B, Hamilton PB, Kubecka J, Segadelli S, Znachor P. 2020. Characteristics, main impacts, and stewardship of natural and artificial freshwater environments: Consequences for biodiversity conservation. Water 12:260. Doi: 10.3390/w12010260.

Chambers JC, Miller JR, Germanoski D. 2011. Chapter 1: Introduction and overview. Pp. 1-10 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: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 125 p.

Chambers JC, Miller JR. 2011. Chapter 8: Meadow management and treatment options. Pp. 113-125 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: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 125 p.

Chambers JC, Miller JR, Lord ML, Board DI, Knight AC. 2021. Geomorphic sensitivity and ecological resilience of Great Basin streams and riparian ecosystems. General Technical Report RMRS-GTR-426. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 159 p. https://doi.org/10.2737/RMRS-GTR-426.

Chambers JC, Wisdom MJ. 2009. Priority research and management issues for the imperiled Great Basin of the Western United States. Restoration Ecology 17(5): 707-714. doi: 10.1111/j.1526-100X.2009.00588.x.

Comer P, Crist P, Reid M, Hak J, Hamilton H, Braun D, Kittle G, Varley I, Unnasch B, Auer S, Creutzburg M, Theobald D, Kutner L. 2013. Central Basin and Range Rapid Ecoregional Assessment Report. Prepared for the US Department of the Interior, Bureau of Land Management. 168 pp + Appendices. Available at https://landscape.blm.gov/REA_General_Docs/CBR_1_ReportBody.pdf (accessed 11/2/2021)

Courtois DR, Perryman BL, Hussein HS. 2004. Vegetation change after 65 years of grazing and grazing exclusion. Journal of Range Management. 57:574-582.

Davies KW, Bates JD, Boyd CS, O'Connor R, Copeland S. 2021. Dormant-season moderate grazing prefire maintains diversity and reduces exotic annual grass response postfire in imperiled Artemisia steppe. Rangeland Ecology and Management 79(1):91–99. Doi:10.1016/j.rama.2021.08.002.

Deacon JE, Williams JE. 1984. Annotated list of the fishes of Nevada. Proceedings of the Biological Society of Washington 97(1): 103-118.

De Cicco LA, Lorenz D, Hirsch RM, Watkins W, Johnson M. 2021. dataRetrieval: R packages for discovering and retrieving water data available from U.S. federal hydrologic web services. doi: 10.5066/P9X4L3GE, https://code.usgs.gov/water/dataretrieval.

de Graaf IEM, Gleeson T, van Beek LPH, Sutanudjaja EH, Bierkens MF. 2019. Environmental flow limits to global groundwater pumping. Nature 574:90-94. https://doi.org/10.1038/s41586-019-1574-4.

Dieter CA, Maupin MA, Caldwell RR, Harris MA, Ivahnenko TI, Lovelace JK, Barber NL, Linsey KS. 2018. Estimated use of water in the United States in 2015. US Geological Survey Circular 1441. https://doi.org/10.3133/cir1441.

Dobrowski SZ. 2011. A climatic basis for microrefugia: the influence of terrain on climate. Global Change Biology 17:1022-1035. Doi: 10.1111/j.1365-2486.2010.02263.x.

Dudley WW, Larson JD. 1976. Effect of irrigation pumping on desert pupfish habitats in Ash Meadows, Nye County, Nevada. Geological Survey Professional Paper 927. Washington, DC: US Government Printing Office.

Dwire KA, Mellmann-Brown S, Gurrieri JT. 2018. Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. Climate Services 10: 44-52. https://doi.org/10.1016/j.cliser.2017.10.002

Earman S, Campbell AR, Phillips FM, Newman BD. 2006. Isotopic exchange between snow and atmospheric water vapor: Estimation of the snowmelt component of groundwater recharge in the southwestern United States. Journal of Geophysical Research 111:D09302. doi: 10.1029/2005JD006470.

Earman S, Dettinger M. 2011. Potential impacts of climate change on groundwater resources – a global review. Journal of Water and Climate Change 2(4):213-229. doi:10.2166/wcc.2011.034.

Edwards EC, Smith SM. 2018. The role of irrigation in the development of agriculture in the United States. Journal of Economic History 78(4): 1103-1141. Doi: 10.1017/S0022050718000608

Farahmand A, AghaKouchak A. 2015. A generalized framework for deriving nonparameteric standardized drought indicators. Advances in Water Resources 76:140-145.

Fleishman E, Murphy DD, Sada DW. 2006. Effects of environmental heterogeneity and disturbance on the native and non-native flora of desert springs. Biological Invasions 8(5): 1091-1101. DOI 10.1007/s10630-005-7564-9.

Glazer AN, Likens GE. 2012. The water table: The shifting foundation of live on land. Ambio 41:657-669. https://doi.org/10.1007/s13280-012-0328-8.

Grayson DK. 1993. The Desert's Past: A Natural Prehistory of the Great Basin. Washington, D.C.: The Smithsonian Institution.

Guttman NB. 1998. Comparing the Palmer Drought Index and the Standardized Precipitation Index. Journal of the American Water Resources Association, 34, 113–121.

Halford KJ, Jackson TR. 2020. Groundwater characterization and effects of pumping in the Death Valley regional groundwater flow system, Nevada and California, with special reference to Devils Hole. U.S. Geological Survey Professional Paper 1863. Reston: U.S. Geological Survey. 178 p. Available at https://pubs.er.usgs.gov/publication/pp1863 (accessed 11/29/21)

Hobbins MT. 2016. The variability of ASCE standardized reference evapotranspiration: A rigorous, CONUS-wide decomposition and attribution. Transactions of the ASABE 59(2):561-576. https://doi.org/10.13031/trans.59.10975

Hof C, Araújo MB, Jetz W, Rahbek C. 2011. Additive threats from pathogens, climate and land-use change for global amphibian diversity. Nature 480(7378):516-519. https://doi.org/10.1038/nature10650.

Keller JA, Shea K. 2020. Warming and shifting phenology accelerate an invasive plant life cycle. Ecology 102(1):e03219. Doi: 10.1002/ecy.3219.

King J. 2019. Groundwater Management in Nevada. Presentation to American Water Resources Association Specialty Conference on June 19, 2019 in Reno, NV. Available at https://aquadoc.typepad.com/files/awra_gw_management_nevada.pdf (accessed 1/27/22).

Kløve B, Pertti A-A, Bertrand G, Gurdak JJ, Kupfersberger H, Kvaerner J, Muotka T, Mykrä, Preda E, Rossi P, Uvo CB, Velasco E, Pulido-Velazquez M. 2014. Climate change impacts on groundwater and dependent ecosystems. Journal of Hydrology 518:20-266. http://dx.doi.org/10.1016/j.hydrol.2013.06.037

Kolosovich AS, Chandra S, Saito L, Davis CJ, Atwell L. 2012. Short-term survival and potential grazing effects of the New Zealand mudsnail in an uninvaded Western Great Basin watershed. Aquatic Invasions 7(2): 203-209. http://dx.doi.org/10.3391/ai.2012.7.2.006.

Konikow LF, Leake SA. 2014. Depletion and capture: Revising "The source of water derived from wells." Groundwater 52:100-111. Doi: 10.1111/gwat.12204.

Lawler JJ, Ackerly DD, Albano CM, Anderson MG, Dobrowski SZ, Gill JL, Heller NE, Pressey RL, Sanderson EW, Weiss SB. 2015. The theory behind, and the challenges of, conserving nature's stage in a time of rapid change. Conservation Biology 29(3):618-629. Doi: 10.111/cobil.12505.

Leake SA. 2007. Use of models to map potential capture of surface water by ground-water withdrawals. USGS Water Research Lecture. Powerpoint presentation.

Leake SA. 2011. Capture – Rates and directions of groundwater flow don't matter! Groundwater 49(4):456-458. Doi: 10.1111/j.1745-6584.2010.00797x.

Leake SA, Pool DR, Leenhouts JM. 2008. Simulated effects of ground-water withdrawals and artificial recharge on discharge to streams, springs, and riparian vegetation in the Sierra Vista Subwatershed of the Upper San Pedro Basin, southeastern Arizona (ver. 1.1, April 2014). US Geological Survey Scientific Investigations Report 2008-5207. Menlo Park: US Geological Survey. 14 p. Available at http://pubs.usgs.gov/sir/2008/5207/ (accessed 11/28/21).

Levy ZF, Jurgens BC, Burow KR, Voss SA, Faulkner KE, Arroyo-Lopez JA, Fram MS. 2021. Critical aquifer overdraft accelerates degradation of groundwater quality in California's Central Valley during drought. Geophysical Research Letters 48:e2021GL094398. https://doi.org/10.1029/2021GL094398

Lohman SW. 1972. Definitions of selected ground-water terms – Revisions and conceptual refinements. Geological Survey Water-Supply Paper 1988. Washington: United States Government Printing Office. Available at https://pubs.er.usgs.gov/publication/wsp1988 (accessed 2/16/22).

Lopes TJ, Buto SG, Smith JL, Wellborn TL. 2006. Water-Table Levels and Gradients, Nevada, 1947-2004. Scientific Investigations Report 2006-5100. Carson City: US Geological Survey. 35 p. Available at https://pubs.usgs.gov/sir/2006/5100/ (Accessed 8/24/20).

Marchionni V, Daly E, Manoli G, Tapper NJ, Walker JP, Fatichi S. 2020. Groundwater buffers drought effects and climate variability in urban reserves. Water Resources Research 56:e2019WR026192. https://doi.org/10.1029/2019WR026192.

McEvoy DJ, Huntington JL, Abatzoglou JT, Edwards LM. 2012. An evaluation of multiscalar drought indices in Nevada and Eastern California, Earth Interact., 16, 1–18. doi:10.1175/2012EI000447.1.

McEvoy DJ, Pierce DW, Kalansky JF, Cayan DR, Abatzoglou JT. 2020. Projected changes in reference evapotranspiration in California and Nevada: Implications for drought and wildland fire danger. Earth's Future 8(11):e2020EF001736.

McInerney PJ, Doody TM, Davey CD. 2021. Invasive species in the Anthropocene: Help or hindrance? Journal of Environmental Management 293:112871. https://doi.org/10.1016/jenvman.2021.112871.

Meixner T, Manning AH, Stonestrom DA, Allen DM, Ajami H, Blasch KW, Brookfield AE, Castro CL, Clark JF, Gochis DJ, Flint AL, Neff KL, Niraula R, Rodell M, Scanlon BR, Singha K, Walvoord MA. 2016. Implications of projected climate change for groundwater recharge in the western United States. Journal of Hydrology 534: 124-138. https://dx.doi.org/10.1016/j.hydrol.2015.12.027

Mifflin MD. 1988. Chapter 8: Region 5, Great Basin. Pp. 69-78 and Plate 3 in Back W, Rosenshin JS, Seaber PR. The Geology of North America, Volume O-2: Hydrogeology.

Miller JR, Lord ML, Germanoski D. 2011. Chapter 5: Meadow sensitivity to natural and anthropogenic disturbance. Pp. 68-84 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: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 125 p.

Miller OL, Miller MP, Longley PC, Alder JR, Bearup LA, Pruitt T, Jones DK, Putman AL, Rumsey CA, McKinney T. 2021. How will baseflow respond to climate change in the Upper Colorado River Basin? Geophysical Research Letters (in press) – https://doi.org/10.1029/2021GL095085.

Miller RR, Williams JD, Williams JE. 1989. Extinctions of North American fishes during the past century. Fisheries 14(6): 22-38.

Mims MC, Moore CE, Shadle EJ. 2020. Threats to aquatic taxa in an arid landscape: Knowledge gaps and areas of understanding for amphibians of the American Southwest. Wiley Interdisciplinary Reviews – Water 7(4): e1449. Doi: 10.1002/wat2.1449.

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86:39.49. DOI: 10.1175/BAMS-86-1-39.

Naumburg E, Mata-Gonzalez R, Hunter RG, McLendon T, Martin DW. 2005. Phreatophytic vegetation and groundwater fluctuations: A review of current research and application of ecosystem response modeling with an emphasis on Great Basin vegetation. Environmental Management 35(6): 726-740.

[NDWR] Nevada Division of Water Resources. 2018. Preliminary draft regulations for the mitigation of surface water conflicts in the Humboldt River Basin. Legislative Council Bureau File No. R027-18I. Available at https://www.leg.state.nv.us/Register/2018Register/R027-18I.pdf (accessed 11/28/21).

Nielson KG, Gill KKM, Springer AE, Ledbetter JD, Stevens LE, Rood SB. 2019. Springs ecosystem: vulnerable ecological islands where environmental conditions, life history traits, and human disturbance facilitate non-native plant invasions. Biological Invasions 21:2963-2981. https://doi.org/10.1007/s10530-019-02025-6.

Noordujin SL, Cook PG, Simmons CT, Richardson SB. 2019. Protecting groundwater levels and ecosystems with simple management approaches. Hydrogeology Journal 27:225-237. https://doi.org/10.1007/s10040-018-1849-4.

[NRC] National Research Council. 2002. Riparian Areas: Functions and Strategies for Management. Washington DC: The National Academies Press. https://doi.org/10.17226/10327.

Ostoja SM, Brooks ML, Chambers JC, Pendleton BK. 2013. Species of conservation concern and environmental stressors: Local, regional and global effects. Chapter 6 (pp. 35- 39) in Chambers JC, Brooks ML, Pendleton BK, Raish CB, eds. The Southern Nevada Agency Partnership Science and Research Synthesis: Science to support land management in Southern Nevada Executive Summary. General Technical Report RMRS-GTR-304. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 79 p. Available at https://www.fs.fed.us/rm/pubs/rmrs_gtr304.pdf (accessed 3/4/22).

Patakamuri SK, O'Brien N. 2021. modifiedmk: Modified Versions of Mann Kendall and Spearman's Rho Trend Tests. R package version 1.6.0. https://CRAN.R-project.org/package=modifiedmk

Patten DT, Rouse L, Stromberg JC. 2008. Isolated spring wetlands in the Great Basin and Mojave Deserts, USA: Potential response of vegetation to groundwater withdrawal. Environmental Management 41: 398–413. https://doi.org/10.1007/s00267-007-9035-9.

Pendleton BK, Chambers JC, Brooks ML, Ostoja SM. 2013. Ecosystem stressors in southern Nevada. Chapter 2 (pp. 17- 36) in Chambers JC, Brooks ML, Pendleton BK, Raish CB, eds. The Southern Nevada Agency Partnership Science and Research Synthesis: Science to support land management in Southern Nevada. General Technical Report RMRS-GTR-303. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Pierce DW, Cayan DR, Maurer EP, Abatzoglou JT, Hegewisch KC. 2015. Improved bias correction techniques for hydrological simulations of climate change. Journal of Hydrometeorology 16(6):2421– 2442. https://doi.org/10.1175/JHM-D-14-0236.1

Pierce DW, Cayan DR, Thrasher BL. 2014. Statistical downscaling using localized constructed analogs (LOCA). Journal of Hydrometeorology 15(6):2558– 2585. https://doi.org/10.1175/JHM-D-14-0082.1

Provencher L, Saito L, Badik K, Byer S. 2020. All systems are equal: In defense of undervalued ecosystems. Rangelands 42(5): 159-167.

Rahel FJ, Olden JD. 2008. Assessing the effects of climate change on aquatic invasive species. Conserv. Biol. 22:521–533. https://doi.org/10.1111/j.1523-1739.2008.00950.x

Robinson TW. 1958. Phreatophytes. Geological Survey Water-Supply Paper 1423. Washington, DC: US Government Printing Office. 84 p.

Rohde MM, Biswas T, Housman IW, Campbell LS, Klausmeyer KR, Howard JK. 2021a. A machine learning approach to predict groundwater levels in California reveals ecosystems at risk. Frontiers in Earth Science 9: 784499. doi: 10.3389/feart.2021.784499.

Rohde MM, Stella JC, Roberts DA, Singer MB. 2021b. Groundwater dependence of riparian woodlands and the disrupting effect of anthropogenically altered streamflow. Proceedings of the National Academy of Sciences 118(25):e2026453118. https://doi.org/10.1073/pnas.2026453118.

Sada DW, Lutz AD. 2016. Environmental characteristics of Great Basin and Mojave Desert Spring Systems. Report. Reno: Desert Research Institute. 51 p.

Sada DW, Nachlinger JL. 1998. Spring Mountains ecosystem: Vulnerability of spring-fed aquatic and riparian systems to biodiversity loss: Part II, springs surveyed in 1997. Report. Reno: Desert Research Institute. 46 p.

Sada DW, Pohlmann KF. 2006. Spring Inventory and Monitoring Protocols: U.S. National Park Service Mojave Inventory and Monitoring Network. Reno: Desert Research Institute. 98 p.

Sada DW, Vinyard GL. 2002. Anthropogenic changes in biogeography of Great Basin aquatic biota. Pp. 277-292 in Hershler R, Madsen DB, Currey DR, eds. Great Basin Aquatic Systems History. Washington, DC: Smithsonian Institution Press.

Saito L, Byer S, Badik K, McGwire K, Provencher L, Minor B. 2020. Mapping indicators of groundwater dependent ecosystems in Nevada: Important resources for a water-limited state. Journal of Nevada Water Resources Association, Winter 2020: 48-72. Available at http://www.nvwra.org/journal (accessed 12/10/20). DOI: 10.22542/jnwra/2020/1/3

Siirila-Woodburn ER, Rhoades AM, Hatchett BJ, Huning LS, Szinai J, Tague C, Nico PS, Feldman DR, Jones AD, Collins WD, Kaatz L. 2021. A low-to-no snow future and its impacts on water resources in the western United States. Nature Reviews Earth & Environment 2: 800-819. https://doi.org/10.1038/s43017-021-00219-y.

Somers LD, McKenzie JM. 2020. A review of groundwater in high mountain environments. WIREs Water 7:e1475. https://doi.org/10.1002/wat2.1475.

Springer AE, Stevens LE. 2009. Spheres of discharge of springs. Hydrogeology Journal 17:83-93. DOI 10.1007/s10040-008-0341-y.

Springsnail Conservation Team. 2020. Conservation Strategy for Springsnails in Nevada and Utah, Version 1.0. Reno: Nevada Department of Wildlife and Salt Lake City: Utah Division of Wildlife Resources. Available at https://springstewardshipinstitute.org/springsnail-conservation-strategy (accessed 11/14/2021)

Stevens LE, Aly AA, Arpin SM, Apostolova I, Ashley GM, Barba PQ, Barquin J, Beauger A, Benaabidate L, Bhat SU, Bouchaou L, Cantonati M, Carroll TM, Death R, Dwire KA, Felippe MF, Fensham RJ, Fryar AE, Garsaball RP, Gjoni V, Glazier DS, Goldscheider N, Guerrieri JT, Gudmundsdottir R, Guzman AR, Hajek M, Hassel K, Heartsill-Scalley T, Herce JSI, Hinterlang D, Holway JH, Imonen JI, Jenness J, Kapfer J, Karaouzas I, Knight RL, Kreiling A-K, Lameli CH, Ledbetter JD, Levine N, Lyons MD, Mace RE, Mentzafou A, Marle P, Moosdorf N, Norton MK, Pentecost A, Perez GG, Perla B, Saber AA, Sada D, Segadelli S, Skaalsveen K, Springer AE, Swanson SK, Schwartz BF, Sprouse P, Tekere M, Tobin BW, Tshibalo EA, Voldoire O. 2021. The ecological integrity of spring ecosystems: A global review. Imperiled: The Ecosystem of Conservation. https://doi.org/10.1016/B978-0-12-821138-7.00111-2

Stevens LE, Jenness J, Ledbetter JD. 2020. Springs and springs-dependent taxa of the Colorado River Basin, Southwestern North America: Geography, ecology and human impacts. Water 12:1501. Doi: 10.3390/w12051501.

Stonestrom DA, Harrill JR. 2007. Ground-water recharge in the arid and semiarid Southwestern United States – climatic and geologic framework. Pp. 1-27 in Stonestrom DA, Constantz J, Ferre TPA, Leake SA, eds. Groundwater Recharge in the arid and semiarid southwestern United States. USGS Professional Paper 1703-A. Available at https://pubs.usgs.gov/pp/pp1703/a/ (accessed 11/22/21).

Sullivan A. 2021. Water Resource Management Challenges. Presentation to Nevada Assembly Committee on Natural Resources on March 1, 2021. Available at https://www.leg.state.nv.us/App/NELIS/REL/81st2021/Meeting/8862?p=3000000&p=6047783 (accessed 1/17/2022)

Taylor MH, Kingsley J, Rollins K, Bowman A. 2021. The economic cost of unanticipated water supply reductions for agricultural producers in the Humboldt River region. Journal of the Nevada Water Resources Association, Winter 2021: 5-41. Available at http://www.nvwra.org/journal (accessed 1/28/22). DOI: 10.22542/jnrwa/2021/1/1.

Theis CV. 1940. The source of water derived from wells: Essential factors controlling the response of an aquifer to development. Civil Engineer 10(5):277-280.

Toth J. 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research 68(16): 4795-4812.

Vicente-Serrano SM, Beguería S, López-Moreno JI. 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate 23(7):1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Vitousek PM, D'Antonio CM, Loope LL, Westbrooks R. 1996. Biological invasions as global environmental change. American Scientist 84:468-478.

[WAPT] Wildlife Action Plan Team. 2012. Nevada Wildlife Action Plan. Reno: Nevada Department of Wildlife. Available at https://www.ndow.org/wp-content/uploads/2022/01/2013-NV-WAP-Complete-NOT-ADA.pdf (accessed 2/21/22).

Wilcove DS, Rothstein D, Dubow J, Phillips A, Losos E. 1998. Quantifying threats to imperiled species in the United States. BioScience 48(8): 607-615.

Williams JE, Sada DW. 2021. Ghost of our making: Extinct aquatic species of the North American desert region. Chapter 6 (pp. 89-105) in Probst D, William JE, Bestgen K, Hoagstrom C (eds). Standing Between Life and Extinction: Ethics and Ecology of Conserving Aquatic Species in North American Deserts. University of Chicago Press.

Wilson T. 2019. Division of Water Resources Overview. Presentation to Nevada Assembly Committee on Natural Resources, Agriculture and Mining on February 27, 2019. Available at https://www.leg.state.nv.us/App/NELIS/REL/80th2019/Meeting/7331?p=3000000&p=6036745 (accessed 2/22/22).

Wilson T. 2020. Division of Water Resources. Presentation to Nevada Interim Legislative Committee on Public Lands on May 29, 2020. Available at https://www.leg.state.nv.us/App/InterimCommittee/REL/Document/15480 (accessed 11/20/21)

Winograd IJ, Pearson FJ. 1976. Major carbon 14 anomaly in a regional carbonate aquifer: Possible evidence for megascale channeling, south central Great Basin. Water Resources Research 12(6):1125-1141.

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. 79 p. Available at https://pubs.er.usgs.gov/publication/cir1139 (Accessed 8/24/20).

Woodward G, Perkins DM, Brown LE. 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philosophical transaction: Biological Sciences 365(1549):2093-2106.