SNAKE VALLEY HYDROLOGIC MONITORING: TEN-YEAR REPORT

by Peter Goodwin, Paul Inkenbrandt, Diane Menuz, Hugh Hurlow, and Drew Dittmer




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Cover photo: *(clockwise from upper left) Juvenile Columbia Spotted Frog, emergent wetland north of Miller Spring, Darkthroat shootingstar in the Gandy Salt Marsh, and Central Spring in the Bishop Springs complex.*

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EXECUTIVE SUMMARY

Spring and wetland complexes in Snake Valley are critical habitats for many wildlife species, seven of which are State of Utah species of greatest conservation need, including Least Chub (*Iotichthys phlegethontis*), Columbia Spotted Frog (*Rana luteiventris*), and five mollusk species, referred to collectively as "sensitive species." A proposal by the Southern Nevada Water Authority (SNWA) to withdraw 50,000 acre-feet per year of groundwater from the area raised concerns about potential habitat impacts from potential changes in water availability. Although SNWA's groundwater development plan appears indefinitely delayed, local applications for increased groundwater pumping continue, and water levels in monitoring wells near the main areas of pumping have declined by 0.2 to 0.6 feet per year since the mid-1990s.

In 2009, the Utah Geological Survey (UGS) installed a network of shallow wells, referred to herein as "piezometers" in Snake Valley to collect hydrologic data. The primary goal of this network is to provide baseline data on the magnitude and timing of surface water and groundwater fluctuations in wetlands crucial to sensitive species, and this report aims to provide recommendations for the future of this network. Initially conceived as a ten-year project, stakeholders have identified a clear need for continued data collection. The ten-year anniversary of this project is a good juncture to 1) summarize data collected to date and 2) determine how to apply those data in future studies to better understand how changing water levels affect sensitive species.

Considerable hydrologic, climatic, and species data have been collected in Snake Valley over the past ten years. Eighty-nine piezometers have been installed during that time, 50 of which are currently active with a transducer recording hourly water level measurements. The UGS maintains a network of 70 monitoring wells and 5 spring gauges in the region, and there are 4 climate stations and 2 SNOTEL stations nearby as well. Columbia Spotted Frog egg mass count data are available going back to the late 1990s, though with some data gaps in recent years. Least Chub data include catch per unit effort (CPUE) values for most years dating back to about 2007. Mollusk data are less available; the most records exist for Longitudinal Gland Pyrg (*Pyrgulopsis anguina*), which was surveyed for five times between 2005 and 2019; four of those surveys included density estimates.

We used Mann-Kendall analysis to evaluate long-term trends in hydrologic, climate, and sensitive species data. For the hydrologic data, we evaluated both individual piezometers, wells, and gauges, and wetland complexes as a whole. The largest declining trends in both individual features and complexes were seen in southern Snake Valley near areas having the highest density of irrigated agriculture, at Big Springs and Burbank Meadows. These complexes had overall declining trends of -0.082 and -0.096 feet per year, respectively, as well as declining trends in most individual piezometers, wells, and spring gauges. Clay Spring, also in southern Snake Valley, has a decline in spring flow of 0.01 cubic feet per second per year (cfs/yr), but nearby piezometers showed a mix of increasing and decreasing trends and may be more closely related to the Pruess Lake system. The Leland Harris wetland complex had a slight overall declining trend and most monitoring stations also had decreasing trends. Central, Twin, and Foote Springs wetland complexes, sometimes collectively referred to as Bishop Spring, all had overall increasing trends in water levels, though some individual wells and piezometers at both Twin and Foote were decreasing. Other wetland complexes either had no overall trend or a limited number of years of data to evaluate.

No climate stations showed significant long-term trends in climate variables when data were aggregated by water year from 2000 to 2019. Daily data from Eskdale and Partoun climate stations showed significant warming and drying trends over the same period, with both Eskdale and Partoun having significant increases in maximum and minimum temperature and Partoun having a decrease in precipitation and increase in reference evapotranspiration.

Bishop Springs had an increasing trend in Columbia Spotted Frog egg mass numbers from 1998 to 2019 and Gandy and Bishop had decreasing trends in Least Chub CPUE from 2007 to 2019; other sites had no significant trends during the years in which they had continuous records. When we categorized years between 2005 and 2019 based on climate and species parameters, we found the period from 2005 to 2009 had low Columbia Spotted Frog egg mass numbers, high Least Chub CPUE values, and the two driest years on record. The years 2011 through 2016 generally had high Columbia Spotted Frog egg mass numbers, low Least Chub CPUE values, and several of the wettest years in the record. There appears to be a positive association between wet years and egg mass counts for Columbia Spotted Frog and the reverse for Least Chub CPUE values, though the pattern in Least Chub was fairly weak. Least Chub may become more concentrated in a few pools when water levels are low, leading to a higher trapping rate in those years.

We conducted a literature review to identify key habitat parameters for Columbia Spotted Frog, Least Chub, and sensitive mollusk species. We also identified sensitive life stages for both Columbia Spotted Frog and Least Chub. Least Chub and Columbia Spotted Frog utilize similar habitats: shallow, seasonally flooded areas during spring breeding and deeper, more permanent waters throughout the summer and winter. Surface water connectivity between these two habitats is crucial for these species and both the extent and depth of surface water throughout the year and connectivity between these habitats have been identified as key habitat parameters. Other important habitat parameters for both Least Chub and Columbia Spotted Frog include water temperature and vegetation encroachment into open water. While existing survey data can evaluate basic relationships between habitat parameters and population metrics, more detailed mark-recapture data would be invaluable for understanding population demographics and dynamics in relation to wetland hydrology.

Metrics including spring discharge, groundwater levels, and water depth are likely important for sensitive mollusk species. However, research examining how decreased discharge and water levels impact mollusk density, abundance, and distribution is limited. A few studies have linked decreased spring discharge to altered water temperature and water chemistry, changes in microbial community distribution and abundance (food resources for some springsnails), and reductions in available habitat. Further research into the relationship between water availability and mollusk species is important for understanding potential impacts of declining water levels.

Based on the results of our literature review and analysis of our hydrologic data, we propose a series of studies that could fill knowledge gaps or improve our understanding of the relationship between groundwater levels, surface water conditions, and sensitive species parameters. UGS staff could complete much of the work, but detailed studies on sensitive species should be conducted by aquatic biologists. We recommend first conducting a remote-sensing and aerial imagery analysis to estimate the extent of permanent and seasonal open water in each wetland complex. Next, we recommend developing species regression models to identify basic relationships between habitat parameters and species success using readily available hydrologic and climate variables (e.g., egg mass number versus mean springtime water elevation and air temperature). This initial modeling effort would be improved in future iterations with improved surface water estimates from hydrologic analysis, water temperature data, and additional years of species data, but would be a useful first exploration to look for initial relationships between variables. Next, we suggest focusing on hydrologic studies, first developing hypsometric curves to predict surface water extent based on groundwater elevation data collected at UGS groundwater monitoring wells and piezometers. We could then conduct studies of the vertical hydraulic gradients that feed spring discharge over time and quantify whether and how they change over time. Regression and step-change analyses will provide insight into how wetland hydrology responds to changing precipitation, temperature, and reference evapotranspiration. Existing groundwater modeling predictions from the USGS MODFLOW software are our best approach to understand how pumping does and will influence wetland hydrology. A better understanding of Snake Valley wetland hydrology is crucial for the development of models that will aid evaluation of a species response to hydrologic metrics. Most detailed data collection for sensitive species could occur concurrently with the studies above to help refine our understanding of habitat needs. There is a particularly strong need for more mollusk data, as several consecutive years of density data and habitat parameters (e.g., water depth, flow, vegetation cover) are very helpful for modeling efforts. The proposed work will allow us to determine the relationships between hydrology, habitat coverage, inundation area, and species counts, and to predict habitat availability and population level changes under different climate and pumping scenarios.

Piezometer data are crucial to our understanding of Snake Valley wetland hydrology. Direct water level measurements over time are the best way to establish baseline information on hydrologic conditions under different climate scenarios. Baseline data are crucial for determining whether changes in water levels are due to climate change, drought, groundwater extraction, or a combination of factors. Hourly piezometer data can also serve as a proxy for key habitat metrics for sensitive species, such as March 1 to April 15 groundwater levels representing the extent of Columbia Spotted Frog breeding habitat. Piezometer data are also crucial inputs for developing hypsometric functions and modelling the relationship between climate and inundation using past data or forward modelling habitat changes that may occur from changing climate or groundwater pumping conditions. Inkenbrandt (2020) also demonstrated that piezometer data can be used to examine variations in wetland inundation, understand wetland trends, determine wetland hydroperiods, and estimate evapotranspiration and groundwater recharge rates. We also anticipate that data from the piezometer network may be used for future water rights application protests and to help with water rights administration.

Based on the importance of Snake Valley wetland habitat to sensitive species and data needs outlined in this report we offer the following recommendations:

1. We recommend continuing to record data in the Snake Valley piezometer network for at least another ten years.
2. We recommend maintaining the current distribution of active piezometers.
3. We recommend Least Chub and Columbia Spotted Frog basic monitoring data be collected on an annual basis and to start developing more frequent monitoring strategies for the five sensitive mollusk species.

4. We recommend undertaking the analyses outlined above to better understand relationships between hydrology, habitat, and sensitive species.
5. We recommend evaluating all data and reevaluating the project as a whole again in another five to ten years.

INTRODUCTION

In 2009, the Utah Geological Survey (UGS) began a ten-year project to collect hydrologic data in Snake Valley wetlands using a network of shallow (~6 ft deep) wells, referred to herein as "piezometers." The primary goal of this network is to provide baseline data on the magnitude and timing of surface water and groundwater fluctuations in wetlands crucial to state-sensitive species. These data are important for documenting baseline conditions and aiding with early detection of water level declines. The data could be used to help prove habitat impairment to the Utah Division of Water Rights in the event that future groundwater withdrawals in the region cause water level declines that impact sensitive species.

Part of the impetus for the Snake Valley wetland hydrologic study was the Southern Nevada Water Authority's (SNWA) application for 50,000 acre-feet per year of groundwater withdrawals from Snake Valley near the Nevada-Utah border and for 96,000 acre-feet per year from Spring Valley, the next valley west, which is hydraulically connected to southern Snake Valley by deep groundwater flow (Welch and others, 2007). Although SNWA's groundwater development plan appears to be indefinitely delayed (Wilson, 2020), local applications for increased groundwater pumping continue. These local applications are of concern to the Bureau of Land Management (BLM) and to Utah wildlife and water managers.

The UGS convened a meeting of stakeholders in December 2018 to discuss the future of the Snake Valley wetland piezometer network. Stakeholders were interested in using the data to produce predictive models to assess how changes in water levels would affect sensitive species. Current groundwater models for the region focus on the effect of withdrawals on groundwater levels and spring flow rather than surface-water levels and area of inundation, which are more representative of sensitive species habitat. More sensitive predictive models could be used to support a groundwater management plan that may be developed for Snake Valley or to protest individual water rights applications that threaten sensitive species.

We reached out to Roy Smith, a BLM water rights specialist, to better understand the value of the piezometer network for administering water rights and protesting new water rights applications. He has not yet cited the wetland piezometer data in Snake Valley water rights hearings because other wells have longer records and are closer to areas impacted by current water use in the valley, but foresees the data being useful if impacts spread (R. Smith, January 2020, written communication). Shallow piezometers could become important for water rights administration purposes if the State Engineer starts to award water rights with terms and conditions specifying that pumping will be reduced or ceased if critical springs show negative effects (R. Smith, January 2020, written communication). Smith also stated that the network provides important baseline data that will make it easier to attribute future changes to climate change, drought, pumping, or some combination of factors.

Based on the importance of the network as identified in the stakeholder meeting and verified by Roy Smith, the UGS decided to maintain transducers at higher priority locations while reducing the overall number of piezometers to reduce costs. A number of factors were used to prioritize the piezometers. First, we prioritized piezometers located in wetland complexes occupied by sensitive species and asked native aquatic ecologists about important locations within each complex. Next, we prioritized piezometers near UGS spring gradient wells. These are two to three adjacent wells that are open to the aquifer at different discrete depth ranges, allowing for measurement of the vertical hydraulic gradient adjacent to the springs that serves as a proxy for spring discharge. We prioritized piezometers near these wells so we could easily relate proxy flow measurements with piezometer water levels. We also prioritized maintaining one piezometer triad at each wetland complex. Piezometer triads are three piezometers installed near one another along a gradient from fairly dry to saturated to standing water. Last, we assigned low priority to piezometers that had a very similar water regime to nearby piezometers and that had issues with data quality or major data gaps. The initial network consisted of 60 wetland piezometers; 29 additional wetland piezometers were added between 2012 and 2014, and 12 were retired (piezometer removed) or inactivated (transducer removed) in 2014. Wetland piezometers were equipped with non-vented pressure transducers set to record hourly water pressure. We ended up with 43 high priority, 12 moderate priority, and 34 low priority piezometers, though subsequently one moderate and four priority piezometers had to be removed due to new issues that arose. Transducers in the wetland piezometers started failing in spring of 2018; there are currently transducers in only 50 of the 89 wetland piezometers. There are currently transducers in 39 high priority and 11 moderate priority piezometers and in none of the low priority ones. Maintaining the network at this current level is estimated to cost $17,000 per year, including personnel time, travel expenses, and transducer repair or replacement costs.

The goal of this report is to provide recommendations for the future of this network. The initial project was conceived as a ten-year study, but stakeholders have identified a clear need for continued data collection. The ten-year anniversary of this project is a good juncture to evaluate the data collected to date and determine how we can use that data in future studies to ultimately better understand how changes in surface water levels affect sensitive species. In the first section of this report, we provide background on the hydrogeologic setting of Snake Valley and sensitive species that are known from the area. In the second section, we summarize existing hydrologic, climate, and species data to illustrate what data are available and identify notable patterns or trends. In the third section, we describe potential future studies that could be conducted with existing, and in some cases, new data. The future studies section includes a literature review summarizing habitat needs for sensitive species that occur in Snake Valley and identifying potential studies that could be used to better understand sensitive life stages and response to hydrologic changes. We then discuss aerial imagery analysis and hydrologic studies that could be conducted to better estimate habitat conditions and predict conditions under different climate and pumping scenarios, before tying all the future study recommendations together into a recommended approach. After a brief discussion of project costs and current funding sources, we conclude with recommendations for the next stage of this project.

STUDY AREA BACKGROUND

Hydrogeologic Setting

Geography and Climate

Snake Valley is in the Great Basin hydrologic region of the Basin and Range Physiographic Province (figure 1). The Basin and Range Province is characterized by predominantly north-south-trending mountain ranges separated from adjacent valleys along sharply defined mountain fronts. The Great Basin is defined hydrologically by the limit of surface-drainage basins having internal drainage, where streams do not exit the regional topographic basin. Most streams in the Great Basin terminate on the valley floor within the surface-drainage basin in which they originate. The Snake Valley valley-floor elevation is about 4300 feet in the north and about 5900 feet in the south. Peak elevations in adjacent ranges are between 7000 and 13,000 feet. Thirty-year mean annual precipitation ranges from more than 33 inches per year in the Snake Range high country to 7 inches or less on the valley floor (based on data from PRISM Climate Group, 2016). Overall climate ranges from semiarid to arid on the valley floors to humid continental in the mountains (Prudic and others, 2015, p. 20–21) and precipitation falls predominantly as winter snowfall in the mountains and, to a lesser extent, summer monsoon thunderstorms (Prudic and others, 2015, p. 21). Evapotranspiration and precipitation vary significantly from year to year (figure 2). Vegetation is mixed conifer-aspen forest in the higher mountain elevations, pinyon-juniper and scrub-shrub in the lower mountain elevations and mountain fronts, and scrub shrub and playa on the valley floors. Wetlands occur adjacent to spring heads, along spring outflow streams, and along perennial streams. Perennial stream flow is rare below the mountains; most streams are absorbed into the sediments or captured for irrigation along the mountain fronts. Notable exceptions include (1) Lake Creek in southern Snake Valley, which is fed by Big Springs in Nevada, and Dearden (aka Stateline) Springs in Utah, both of which support Burbank Meadows; (2) Snake Creek and Baker Creek, which originate in the southern Snake Range; and (3) Warm Creek, which is fed by Warm Springs (see figure 1 for locations).

Hydrogeology

This section describes aspects of Snake Valley hydrogeology that explain the sources of discharge from the springs of interest in this study. The hydrogeologic setting is described in greater detail by Plume (1996), Harrill and Prudic (1998), Dixon and others (2007), Welch and others (2007), and Hurlow (2014). These reports form the basis for the following summary.

Aquifers in the Snake Valley drainage basin include unconsolidated Quaternary-Tertiary sedimentary deposits, semiconsolidated to consolidated Tertiary sedimentary deposits, Quaternary and Tertiary volcanic rocks, and Paleozoic carbonate rocks (Welch and others, 2007). Unconsolidated Quaternary-Tertiary deposits make up the valley floor and mountain fronts, and mantle bedrock in the mountains. Tertiary sedimentary and volcanic rocks crop out along the mountain fronts and underlie Quaternary-Tertiary aquifers below the valley floor. Carbonate-rock units crop out in the mountains and along the mountain fronts and underlie the unconsolidated Quaternary-Tertiary aquifers in much of the region. Aquitards include Proterozoic-Paleozoic quartzite, schist, and metamorphic and igneous rocks that crop out in the northern part of the southern Snake Range and in the southern part of the northern Snake Range. The mountain fronts are defined by steeply dipping, valley-side-down normal faults that created the Basin-Range topography and accommodated deposition of thick (>5000 feet in places) deposits of Quaternary-Tertiary basin fill below the valley floor.

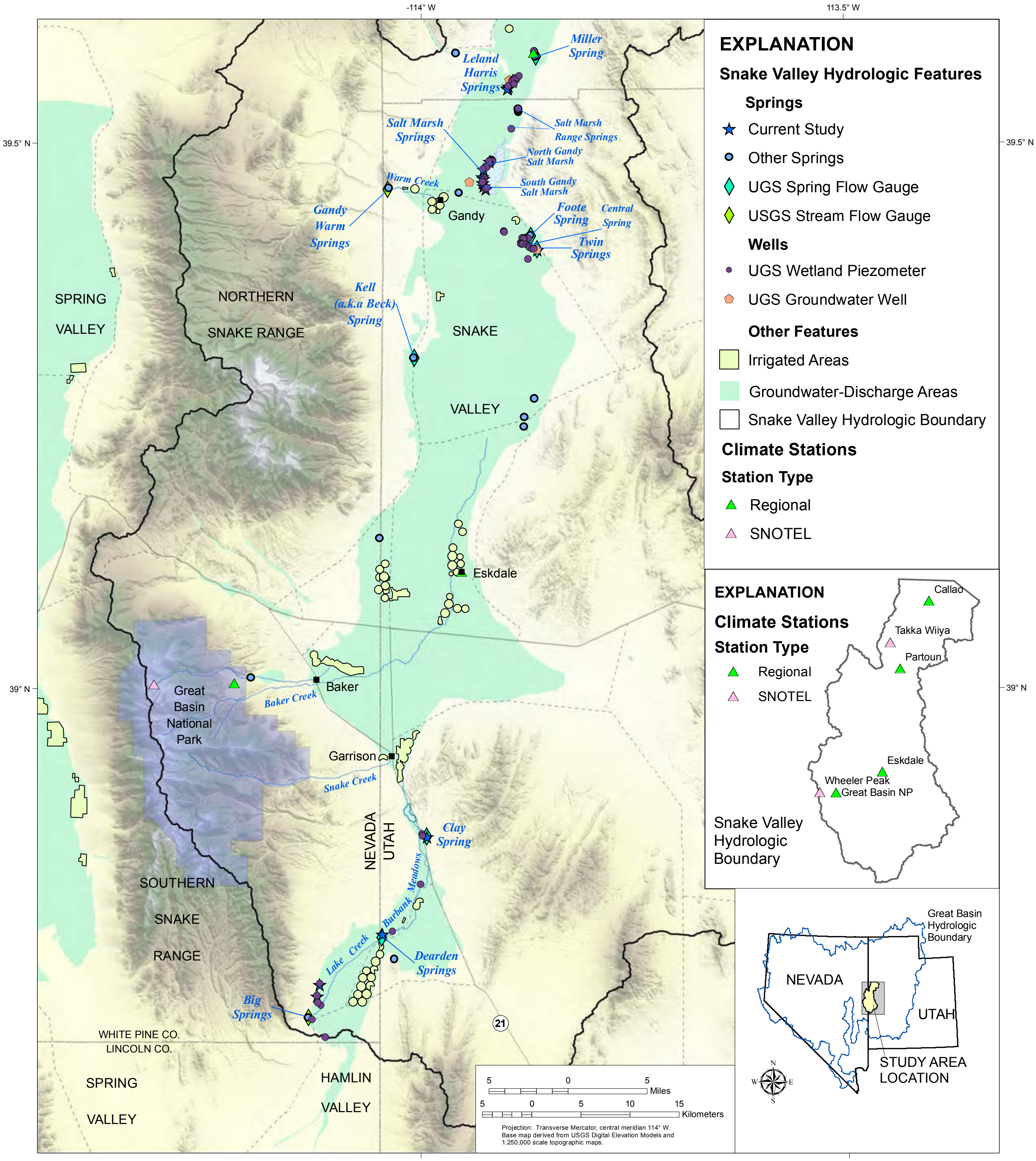

Figure 1. *Study area location map.*

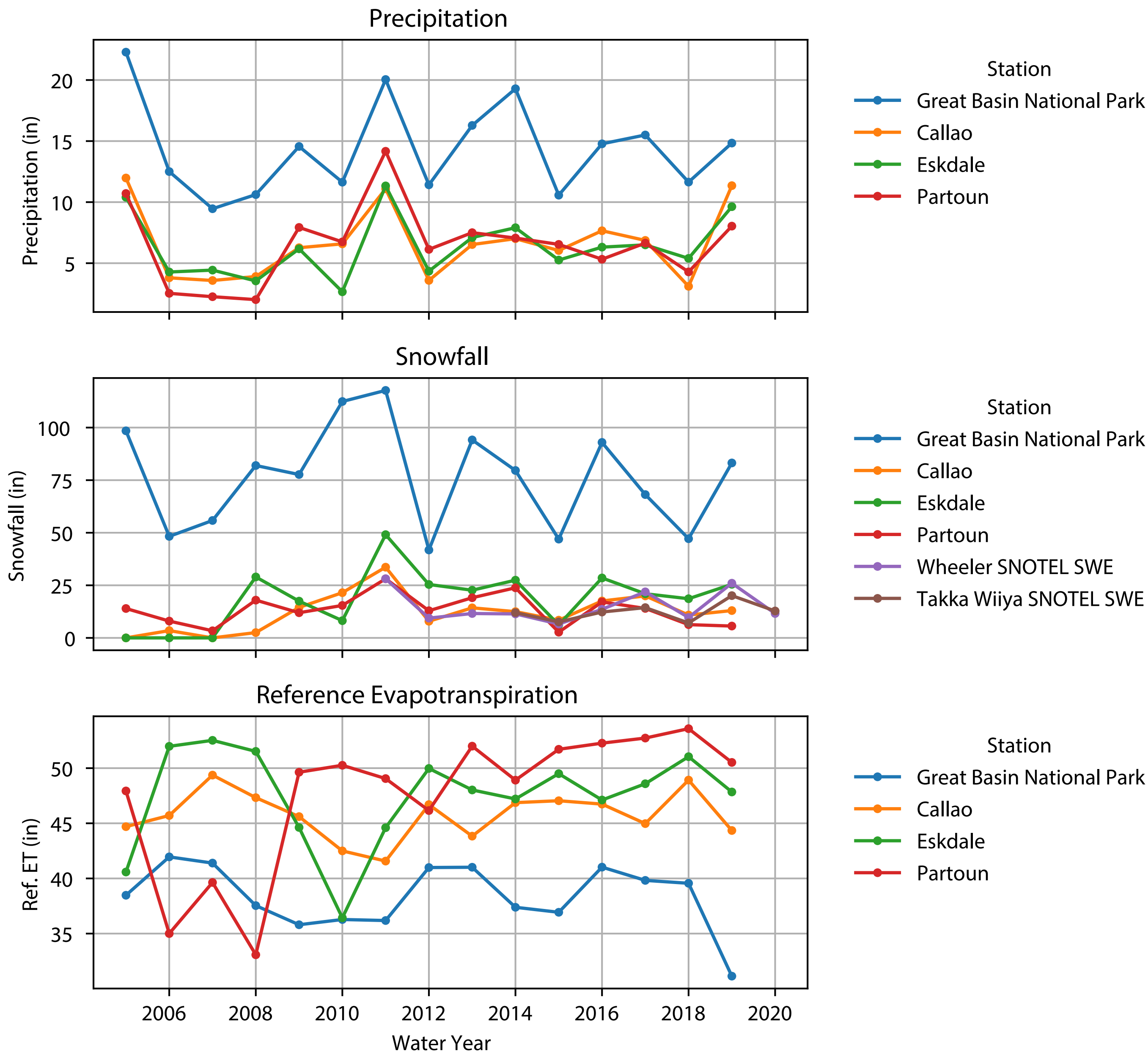

Figure 2. *Annual water year precipitation, snowfall, and reference evapotranspiration at climate stations near Snake Valley.*

In situ groundwater recharge to the Snake Valley aquifers occurs where mean annual precipitation is greater than 12 inches per year (Prudic and others, 2015), i.e., along the upper mountain fronts and in the mountain ranges (figure 1). In the mountains, recharge of snowmelt occurs into the Paleozoic carbonate-rock aquifers (Heilweil and Brooks, 2011); this groundwater moves through solution-widened fractures in the carbonate-rock aquifer into the basin-fill aquifer, or continues in the carbonate-rock aquifer below the basin fill. Groundwater recharged in the mountain block must cross the range-bounding normal faults, which localize springs along the mountain front and likely slow or divert cross-fault subsurface flow (e.g., Wilson and Guan, 2004). Surface runoff is more prevalent in mountain areas underlain by Proterozoic-Paleozoic aquitards (Heilweil and Brooks, 2011). In those areas, streams are more likely to run onto the mountain fronts and valley floors, where they provide direct recharge to the basin-fill aquifer, bypassing the range-bounding normal faults.

Potentiometric-surface contours indicate groundwater flow in the basin-fill aquifer from the mountain fronts toward the valley floor, and generally from south to north below the valley floor (Gardner and others, 2011; Heilweil and Brooks, 2011). Potentiometric-surface contours, groundwater chemistry and age, and hydrogeology define local (mountain and mountain front) and intermediate (from mountain recharge to valley-floor discharge) scale flow paths in Snake Valley (Harrill and others, 1988; Hurlow, 2014, p. 251). Analysis of regional patterns of potentiometric-surface contours, water budgets, groundwater chemistry and age, and hydrogeology indicate that groundwater flows from Snake Valley to Tule Valley, either entirely within the carbonate-rock aquifer or from the Snake Valley basin-fill aquifer to the bedrock aquifers in the Confusion Range, and into the basin-fill and bedrock aquifers below Tule Valley (Harrill and others, 1988; Heilweil and Brooks, 2011; Hurlow, 2014).

Groundwater pumping for irrigation ranged from about 4000 to 7500 acre-feet per year between 1974 and 2005, then increased significantly during the following decade, averaging about 22,000 acre-feet per year from 2010 through 2014 (Masbruch and others, 2014; Hurlow and Inkenbrandt, 2016, figure 3). Groundwater levels in monitoring wells within 5 miles of the main areas of agricultural pumping have been declining by 0.2 to 0.6 feet per year since the mid-1990s (Hurlow, 2014; Hurlow and Inkenbrandt, 2016). Rates of decline in some of these monitoring wells increased markedly during the time of increasing pumping. Long-term water level records show declines since the late 1980s (Hurlow, 2014; Hurlow and Inkenbrandt, 2016).

Springs

Springs of interest in this study occur along the mountain fronts and on the lower valley floors (figure 1; table 1) (Kistinger and others, 2009; Rowley and others, 2009; Hurlow, 2014, p. 117–122). The mountain-front springs are fault-controlled whereas those on the valley floors are contact springs, with the exception of Miller Spring in Snake Valley which is interpreted as fault-controlled (Hurlow, 2014, p. 117).

Discharge from the springs of interest varies from about 0.3 cubic feet per second (cfs) from Clay and Miller Springs to 6 cfs from Dearden Springs (table 1). Flow rates at most springs were at their lowest values around 2012 through 2014 and increased to higher values by 2018 to 2020. Exceptions are Clay and Foote Springs, where flow has been steadily declining since 2012.

Spring and groundwater chemistry evolves systematically from mountain front to valley floor (Hurlow, 2014). Water type along the mountain fronts is Ca-HCO_3 having low total dissolved solids (TDS) concentrations. Major-solute chemistry acquires greater Na, Cl, and TDS toward the valley floors due to ion exchange with the basin-fill aquifer, and groundwater age also increases from mountain front to valley floor (Hurlow, 2014).

Table 1. *Summary of springs that support wetlands of interest in this study.*

Spring	Wetland System(s) (Table 3)	Type[1]	Aquifer(s)[2]	Flow (cfs)[3]	Groundwater Water Type[4]	Qualitative Age[4]	Flow System Scale[4]
Big Springs	Big Springs	Fault	Basin Fill & Carbonate Rock	~3.5	Ca-HCO_3	Mixed	Regional & Local
Dearden aka Stateline	Burbank Meadows	Fault	Carbonate Rock	~6	Ca-HCO_3	Old	Intermediate & Regional
Clay Spring	Clay Spring	Contact (?)	Basin Fill	~0.3	Ca-HCO_3	Old	Local
Twin Springs	Twin Springs, Central Springs	Fault	Basin Fill & Carbonate Rock	~2.7	Ca-HCO_3	Old	Intermediate
Foote Reservoir Spring	Foote, Foote Rd. North, Foote Rd. South	Fault	Basin Fill & Carbonate Rock	~3.5	--	--	Intermediate
North Gandy Salt Marsh[5]	North Gandy Salt Marsh	Contact (?)	Basin Fill	--	Ca-HCO_3, Mg-HCO_3	Old	Intermediate
Leland Harris[6]	Leland Harris	Contact (?)	Basin Fill	--	Ca-HCO_3, Na-HCO_3	Old	Intermediate
Miller Spring	Miller Spring	Fault	Basin Fill & Carbonate Rock	~0.3	Na-HCO_3	Old	Intermediate

-- No Data
[1] Based on Kistinger and others (2009) and Hurlow (2014).
[2] Dearden Springs discharge directly from bedrock. Big, Twin, Foote, and Miller Springs discharge from basin fill but are interpreted to be sourced primarily from the Paleozoic carbonate-rock aquifer.
[3] From UGS data (https://apps.geology.utah.gov/gwdp/), and U.S. Geological Survey (https://maps.waterdata.usgs.gov/mapper/) for Big Springs.
[4] From Hurlow (2014).
[5] Data from wells SG26B and SG26C.
[6] Data from wells SG25B and SG25C.

Hydrogeology, groundwater chemistry and age, and discharge records collectively indicate that the springs that are the sources of water for the wetlands of interest in this study are fed by intermediate to regional-scale groundwater flow systems, as opposed to more local and ephemeral sources such as spring snowmelt and runoff. "Local flow systems include relatively young (predominantly modern to premodern qualitative ages) groundwater directly down gradient from the areas of highest average annual precipitation and recharge in the Snake Range and Deep Creek Mountains, and intermediate flow systems represent longer, and likely deeper, flow paths from the mountains and mountain fronts to springs and evapotranspiration (ET) areas in the valley centers" (Hurlow, 2014, p. 249).

Snake Valley spring flows are susceptible to decline via capture of groundwater discharge by large-scale pumping for irrigation (Halford and Plume, 2011; Masbruch and others, 2014; Masbruch and Brooks, 2017; Masbruch, 2019). Declining groundwater levels in Snake Valley indicate that either groundwater mining is occurring or capture of discharge has not yet reached equilibrium with pumping rates.

If the current rate of groundwater pumping continues, spring flow and groundwater levels will decrease. Of the total groundwater that flows to pumping wells, the relative proportion of captured discharge (i.e., declining spring flow) to removal from storage (i.e., declining groundwater levels) increases over time (Barlow and Leake, 2012), and a time lag between pumping and spring-flow reduction is inversely proportional to the hydraulic diffusivity of the aquifer system (Bredehoeft and Durbin, 2009). Capture of Snake Valley groundwater discharge, including spring flow, therefore, will continue to increase for the foreseeable future at present groundwater pumping rates (Halford and Plume, 2011; Masbruch and Gardner, 2014; Masbruch and Brooks, 2017; Masbruch, 2019), and will increase if future pumping increases. The rate of recovery of groundwater levels and spring flow can be as much as ten times slower than the rate of drawdown (Bredehoeft and Durbin, 2009). Superposition of climate and pumping effects occurs in the observed spring flow and groundwater level records, so that declines caused by pumping may be difficult to separate from fluctuations related to drought at current pumping levels (Hurlow and Inkenbrandt, 2016).

Sensitive Species

Springs and wetland complexes in Snake Valley are critical habitats for many wildlife species, seven of which are State of Utah species of greatest conservation need, including Least Chub, Columbia Spotted Frog, and five mollusk species, referred to collectively as sensitive species. Least Chub and Columbia Spotted Frog are both Conservation Agreement species with multi-agency plans developed to implement conservation measures in Utah (Utah Division of Wildlife Resources [UDWR], 2006; Least Chub Conservation Team, 2014). Three of the mollusk species—Hamlin Valley Pyrg (*Pyrgulopsis hamlinensis*), Longitudinal Gland Pyrg (*Pyrgulopsis anguina*), and Sub-globose Snake Pyrg (*Pyrgulopsis saxatilis*)—are springsnails currently on the U.S. Fish and Wildlife Service National Listing Workplan. A fourth mollusk species, Winged Floater (*Anodonta nuttalliana*), is a species of freshwater mussel found in shallow lakes like Pruess Lake; recent surveys there have found more dead individuals than live (K. Holcomb, Utah Division of Wildlife Resources, written communication, July 2020). The last sensitive mollusk species, Cloaked Physa (*Physa megalochlamys*), was documented in Snake Valley historically but has not been documented in more recent surveys. Except for Columbia Spotted Frog and Winged Floater, these sensitive species have limited distributions and are either Utah-endemic or known from a handful of occurrences in western Utah and eastern Nevada. In addition to the intrinsic threats faced by small, isolated populations, these species face a threat common to spring-fed wetlands in general—the loss or degradation of habitat through dewatering resulting from groundwater withdrawal and inter-basin water transfers. The SNWA proposal to develop water supplies in far western Snake Valley focused attention on this particular threat to these species, but ongoing water withdrawal within local basins continues to threaten these species.

Least Chub

Least Chub is a small minnow endemic to the Bonneville basin of Utah that was historically distributed throughout the Bonneville basin with numerous known occurrences along the Wasatch Front, Beaver River, Sevier River, and in spring-fed pools of Utah and Snake Valleys (UDWR, 2005). Habitat loss as well as competition with and predation by non-native species have caused population declines and a severe range contraction with current distribution limited to six wild populations (UDWR, 2005) and numerous refuge populations across the state (Least Chub Conservation Team, 2014). Of the six wild populations, three are in Snake Valley: Gandy Salt Marsh, Leland Harris Springs, and the Bishop Springs complex which includes the Foote Reservoir, Twin Springs, and Central Spring (UDWR, 2005). Within these three wetland complexes, Least Chub utilizes two distinct habitats: (1) deep, groundwater-fed pools or springheads as overwintering or low-water refuges and (2) shallow, seasonally flooded areas for spring spawning. A more detailed species description including habitat requirements and key life history traits, and current, best available literature is included in appendix A.

Columbia Spotted Frog

Columbia Spotted Frogs are a highly aquatic frogs that are broadly distributed across western North America, but known in Utah from a few occurrences along the Wasatch Front, Sevier River, and isolated springs and wetland complexes in the west desert, including Snake Valley (UDWR, 2006). The species is known to occur at five locations within the Utah part of Snake Valley—Kell (a.k.a. Beck) Spring, Miller Spring, Leland Harris Springs, Gandy Marsh, and the Bishop Springs complex (UDWR, 2006). Columbia Spotted Frogs use several distinct habitats within these wetlands: (1) shallow, seasonally flooded areas for breeding and larval development, (2) permanent areas of relatively open water for foraging and persisting through hot, dry summers, and (3) saturated areas connecting foraging and breeding habitats that function as dispersal corridors for breeding adults and juveniles. A more detailed species description including habitat requirements, key life history traits, and current, best available literature is included in appendix A.

Mollusks

All five mollusk species known from Snake Valley are aquatic species that require perennial water. Winged Floater, a freshwater mussel, typically occupies lakes or slow-moving rivers and occurs throughout Utah. Within Snake Valley, it is known from Pruess Lake south of Garrison, where it was last documented in 2018. Longitudinal Gland Pyrg is known from Clay Spring and Stateline Spring and Sub-globose Snake Pyrg is known solely from Gandy Warm Springs. The Hamlin Valley Pyrg is known from White Rock Cabin Spring, located about 40 miles south of the southern end of Snake Valley in Hamlin Valley on the Nevada-Utah border. Though not technically found in Snake Valley, the Hamlin Valley Pyrg is included in this report due to its regional relevance and impending review by the U.S. Fish and Wildlife Service. Cloaked Physa was documented at the Bishop Springs Complex in 1988 but has not been found in more recent surveys. A more detailed species description including habitat requirements, key life history traits, and current, best available literature is included in appendix A.

SUMMARY OF EXISTING DATA

Hydrologic Data

Of the 89 wetland piezometers that have been installed in Snake Valley, we have measured water levels in 31 wetland piezometers for more than 10 years, which is equivalent to about 87,000 records per transducer assuming no gaps in data (table 2). Eight piezometers have less than 5 years of data and the remaining piezometers have between 8 and 10 years of data, disregarding data gaps. The UGS groundwater level database (available here: https://apps.geology.utah.gov/gwdp/) currently contains almost six million records of water level from wetland piezometers alone. Site 1002 at Miller Spring currently has the most water level measurements. South Gandy Salt Marsh has the shortest period of observation in Snake Valley, with records starting in October of 2014. Leland Harris has 19 wetland piezometers, 10 of which are considered active, the most for any site. The site also includes a weather station, a telemetered spring-gradient well (ID 64) and three other spring-gradient wells (61, 62, and 63). With over a million measurements, Leland Harris also has the most wetland transducer water level records.

Wetland piezometer transducer data are downloaded by UGS field staff twice per year. During data collection, field staff also manually measure depth to water to calibrate pressure readings. Because they are not vented, the transducers record absolute pressure, which is the atmospheric pressure plus the pressure of water above the transducer. Scripts process the transducer data to remove atmospheric pressure and linear deviation from manual measurements. Linear deviation exceeding 0.3 feet triggers a reevaluation of the manual data. If the manual data are determined to be correct, then the data are assessed for other issues and either discarded or corrected.

For the past 12 years, the UGS has maintained a network of more than 70 monitoring wells and 5 spring gauging stations in Snake Valley and adjacent basins in addition to the wetland piezometers. Pressure transducers in most of the wells record hourly water level and temperature. Spring gauges are installed at Dearden Springs, Clay Spring, Kell (a.k.a. Beck) Spring, Twin Springs, Foote Reservoir, and Miller Spring. The spring gauges have measurements at 10- to 30-minute intervals. Due to multiple points of discharge, other surface water flows, and anthropogenic diversions, Dearden Springs and Foote Reservoir have multiple points of measurement used to calculate the spring flow. For these sites, we examined the calculated discharge. Twin Springs, Gandy Salt Marsh, and Leland Harris all have nested sets of spring gradient wells screened at different depths to measure changes in hydraulic gradient at the spring systems over time.

Table 2. *Hydrologic monitoring stations discussed in the report and organized by wetland system.*

Wetland System	Location ID	Feature Type[1]	Location Status[2]	X Coord (Long)	Y Coord (Lat)	Measure Begin Date	Most Recent Measure in DB	Years of Record	Data Gaps (days)	Mann-Kendall Water Level Trend[3]	Piezometer Priority[4]	2020 Vegetation Community[5]	Vegetation Trend	Hydro-period[6]
Big Springs	39	W	active	-114.04902	38.72977	12/2/2009	3/3/2020	10.25	0	-0.113				
Big Springs	1050	P	retired	-114.11686	38.71044	11/10/2009	10/30/2014	4.97	0		low			6
Big Springs	1051	P	active	-114.12056	38.71250	11/10/2009	4/28/2020	10.46	63		moderate	JUNC	Stable	6
Big Springs	1075	P	active	-114.11176	38.68114	5/28/2013	4/28/2020	6.92	0	-0.20	high	CARX	Stable	6
Big Springs	1076	P	inactive	-114.12765	38.69709	5/28/2013	4/13/2016	2.88	0	-1.36	low			9
Big Springs	1077	P	active	-114.12158	38.71925	5/30/2013	4/28/2020	6.91	329	-0.35	high	JUNC	Stable	6
Big Springs	1078	P	active	-114.11836	38.73016	5/30/2013	4/28/2020	6.91	0	-0.28	high	JUNC	Stable	6
Burbank Meadows	4	W	active	-114.04747	38.78089	2/11/2009	8/14/2017	8.50	103	-0.03				
Burbank Meadows	5	W	active	-114.04747	38.78089	2/11/2009	3/2/2020	11.05	174	-0.06				
Burbank Meadows	40	W	active	-114.00929	38.79862	2/11/2009	3/2/2020	11.05	0	-0.19				
Burbank Meadows	41	W	active	-114.00935	38.79874	2/11/2009	3/2/2020	11.05	490	-0.22				
Burbank Meadows	42	W	active	-114.00935	38.79874	2/11/2009	3/2/2020	11.05	0	-0.24				
Burbank Meadows	71	W	active	-114.07200	38.78400	8/17/2006	3/2/2020	13.54	0	-0.01				
Burbank Meadows	1072	P	inactive	-114.03292	38.77786	5/27/2013	11/6/2018	5.45	0		low		Drying	8
Burbank Meadows	1073	P	inactive	-114.00038	38.82108	5/27/2013	4/16/2018	4.89	0	-1.11	low		Drying	6
Central Spring	1039	P	inactive	-113.88066	39.40785	3/29/2010	6/26/2018	8.24	0		low		Stable	8
Central Spring	1042	P	active	-113.88182	39.40926	3/30/2010	11/22/2019	9.65	0	0.15	high	OPEN	Flooding	2
Central Spring	1043	P	active	-113.88183	39.40859	3/29/2010	4/29/2020	10.09	0	0.02	high	SCAM	Stable	4
Central Spring	1044	P	active	-113.88179	39.40803	3/29/2010	4/29/2020	10.09	294	0.01	moderate	JUNC	Stable	5
Central Spring	1045	P	inactive	-113.88088	39.40776	3/30/2010	11/6/2018	8.61	0	0.0	low		Stable	3
Central Spring	1046	P	active	-113.87940	39.40789	3/29/2010	4/29/2020	10.09	0	0.01	high	SCAM	Stable	3
Clay Spring	10006	S	active	-113.99360	38.86551	9/21/2009	11/14/2019	10.15	0	-0.01				
Clay Spring	1048	P	retired	-113.99818	38.86703	11/9/2009	10/30/2014	4.97	0	0.10	low			5
Clay Spring	1049	P	inactive	-113.99833	38.86704	11/9/2009	11/6/2018	8.99	0	0.05	low		Stable	3
Clay Spring	1070	P	inactive	-113.99757	38.86524	9/11/2012	11/6/2018	6.15	251	-0.10	low		Stable	5
Clay Spring	1071	P	inactive	-113.99804	38.86530	5/27/2013	12/17/2014	1.56	0		low			2
Foote	1021	P	inactive	-113.87553	39.41420	3/29/2010	12/18/2018	8.72	0	0.02	low		Stable	8
Foote	1022	P	active	-113.87564	39.41384	3/29/2010	4/29/2020	10.09	118	0.01	high	JUNC	Stable	6
Foote	1023	P	active	-113.87617	39.41339	3/29/2010	4/29/2020	10.09	0	-0.01	high	SCAM	Stable	5
Foote	1024	P	active	-113.87951	39.41359	3/29/2010	4/29/2020	10.09	134	0.01	high	JUNC	Stable	7
Foote	1025	P	active	-113.87997	39.41368	3/29/2010	4/29/2020	10.09	134	0.01	high	DISP	Stable	8
Foote	1026	P	active	-113.88042	39.41354	3/29/2010	4/29/2020	10.09	83	0.03	high	SCAM	Stable	2
Foote	1037	P	active	-113.87320	39.41302	3/29/2010	4/29/2020	10.09	134	-0.01	high	SCAM	Stable	2
Foote	1038	P	active	-113.87306	39.41299	3/29/2010	4/29/2020	10.09	160	-0.05	moderate	JUNC	Stable	4
Foote	1040	P	inactive	-113.87811	39.41253	3/29/2010	12/18/2018	8.72	0	-0.02	low		Stable	8
Foote	1041	P	inactive	-113.87897	39.41269	3/29/2010	11/7/2018	8.61	0	-0.01	low		Stable	7
Foote	10013	S	active	-113.87041	39.41626	6/7/2005	11/30/2019	14.48	0	-0.03				
Foote Road	1058	P	retired	-113.90209	39.42002	3/30/2010	12/30/2014	4.75	0	0.05	low			3
Foote Road	1059	P	retired	-113.90197	39.41970	3/30/2010	10/30/2014	4.59	0	-0.02	low			6
Foote Road	1060	P	active	-113.90163	39.41931	3/30/2010	4/29/2020	10.08	0	-0.02	high	SCAC	Stable	5
Foote Road	1081	P	inactive	-113.87362	39.39433	5/29/2013	11/6/2018	5.44	350		low			5
Leland Harris	61	W	active	-113.89177	39.55861	2/11/2009	3/4/2020	11.06	150	-0.01				
Leland Harris	62	W	active	-113.89167	39.55871	2/10/2009	3/4/2020	11.06	59	-0.08				
Leland Harris	63	W	active	-113.89172	39.55867	2/10/2009	3/4/2020	11.06	59	-0.02				
Leland Harris	64	W	active	-113.89567	39.55860	2/10/2009	3/4/2020	11.06	378	-0.02				
Leland Harris	1011	P	active	-113.89131	39.55810	3/29/2010	5/1/2020	10.09	0	-0.03	high	ELEO	Stable	5
Leland Harris	1012	P	active	-113.89132	39.55838	3/29/2010	5/1/2020	10.09	354	0.01	high	SCAM	Flooding	2

Table 2. *Continued.*

Wetland System	Location ID	Feature Type[1]	Location Status[2]	X Coord (Long)	Y Coord (Lat)	Measure Begin Date	Most Recent Measure in DB	Years of Record	Data Gaps (days)	Mann-Kendall Water Level Trend[3]	Piezometer Priority[4]	2020 Vegetation Community[5]	Vegetation Trend	Hydro-period[6]
Leland Harris	1013	P	active	-113.89180	39.55721	3/29/2010	4/30/2020	10.09	184		high	DISP	Stable	8
Leland Harris	1014	P	inactive	-113.89185	39.55774	3/29/2010	12/18/2018	8.72	0		low		Stable	6
Leland Harris	1015	P	inactive	-113.88796	39.55782	3/29/2010	12/18/2018	8.72	0	-0.04	low		Stable	8
Leland Harris	1016	P	active	-113.88790	39.55792	3/29/2010	4/30/2020	10.09	0	-0.02	high	SCAC	Stable	3
Leland Harris	1017	P	inactive	-113.88845	39.55858	11/12/2009	10/31/2014	4.97	0		low			3
Leland Harris	1018	P	active	-113.88821	39.55928	3/29/2010	4/30/2020	10.09	183	0.00	high	JUNC	Stable	5
Leland Harris	1019	P	active	-113.88853	39.56007	3/29/2010	4/30/2020	10.09	0		high	SCAC	Stable	3
Leland Harris	1020	P	inactive	-113.88859	39.56021	3/29/2010	4/17/2018	8.05	70		low		Stable	8
Leland Harris	1061	P	retired	-113.88764	39.55817	8/10/2013	2/13/2016	2.51	0	0.17	low			4
Leland Harris	1062	P	retired	-113.88601	39.56027	8/10/2013	2/13/2016	2.51	0	0.45	high			4
Leland Harris	1063	P	inactive	-113.88370	39.56190	9/11/2012	9/26/2017	5.04	0	-0.170	low		Drying	0
Leland Harris	1064	P	retired	-113.88901	39.55876	9/11/2012	10/30/2014	2.13	0	-0.08	low			1
Leland Harris	1065	P	active	-113.89613	39.55310	9/11/2012	10/10/2019	7.08	0	0.20	high	OPEN	Stable	1
Leland Harris	1066	P	inactive	-113.88598	39.56025	9/11/2012	6/25/2018	5.79	0		high		Flooding	3
Leland Harris	1067	P	active	-113.89622	39.55302	9/11/2012	4/30/2020	7.63	1465	-0.02	moderate	DISP	Stable	5
Leland Harris	1068	P	active	-113.88974	39.55455	10/31/2014	4/30/2020	5.50	0	-0.01	moderate	JUNC	Stable	5
Leland Harris	1069	P	active	-113.88361	39.56200	9/11/2012	10/10/2019	7.08	185	-0.07	high	OPEN	Stable	1
Miller Spring	10012	S	active	-113.86499	39.58009	5/4/2010	12/10/2019	9.60	0	0.01				
Miller Spring	1001	P	active	-113.86541	39.58142	3/29/2010	10/10/2019	9.53	0	-0.02	high	ELEO	Stable	6
Miller Spring	1002	P	active	-113.86534	39.58121	3/29/2010	4/30/2020	10.09	0		high	DISP	Stable	7
Miller Spring	1003	P	active	-113.86528	39.58169	9/15/2010	4/30/2020	9.62	183	0.01	high	SCAM	Stable	2
Miller Spring	1004	P	active	-113.86534	39.58058	3/29/2010	4/30/2020	10.09	0		high	JUNC	Stable	6
Miller Spring	1005	P	inactive	-113.86542	39.58350	3/29/2010	4/17/2019	9.05	0	-0.02	low		Stable	7
Miller Spring	1006	P	active	-113.86563	39.58349	11/11/2009	4/30/2020	10.47	387	0.02	high	ELEO	Stable	5
Miller Spring	1007	P	retired	-113.86582	39.58354	3/29/2010	10/17/2018	8.55	253	0.01	high		Stable	3
Miller Spring	1008	P	active	-113.86582	39.58497	3/29/2010	4/30/2020	10.09	0	-0.01	high	ELEO	Stable	5
Miller Spring	1009	P	inactive	-113.86568	39.58500	3/29/2010	4/17/2019	9.05	92	-0.07	low		Drying	4
Miller Spring	1010	P	active	-113.86619	39.58503	3/29/2010	4/30/2020	10.09	183	-0.01	moderate	DISP	Stable	7
N. Gandy Salt Marsh	65	W	active	-113.91753	39.48503	7/15/2009	3/4/2020	10.64	126	-0.06				
N. Gandy Salt Marsh	66	W	active	-113.91752	39.48505	8/20/2009	3/4/2020	10.54	455	-0.03				
N. Gandy Salt Marsh	67	W	active	-113.91750	39.48512	9/16/2009	3/4/2020	10.46	546	-0.03				
N. Gandy Salt Marsh	1027	P	retired	-113.91612	39.48537	3/29/2010	10/30/2014	4.59	0		low			8
N. Gandy Salt Marsh	1028	P	active	-113.91625	39.48523	3/29/2010	4/30/2020	10.09	115	0.04	high	ELEO	Stable	5
N. Gandy Salt Marsh	1029	P	active	-113.91616	39.48488	3/29/2010	4/30/2020	10.09	0	-0.04	high	JUNC	Stable	6
N. Gandy Salt Marsh	1030	P	active	-113.91522	39.48446	3/29/2010	4/30/2020	10.09	0	-0.01	moderate	SCAC	Stable	4
N. Gandy Salt Marsh	1031	P	inactive	-113.91525	39.48345	3/29/2010	6/11/2019	9.20	32	-0.03	low		Stable	5
N. Gandy Salt Marsh	1032	P	retired	-113.91742	39.48144	3/29/2010	10/30/2014	4.59	0	0.16	low			7
N. Gandy Salt Marsh	1033	P	active	-113.91784	39.48146	3/9/2011	4/30/2020	9.14	0	-0.01	high	DISP	Drying	5
N. Gandy Salt Marsh	1034	P	retired	-113.91802	39.48138	3/29/2010	10/30/2014	4.59	0		low			5
N. Gandy Salt Marsh	1035	P	active	-113.91920	39.48193	3/29/2010	4/30/2020	10.09	32	0.01	high	DISP	Drying	5
N. Gandy Salt Marsh	1036	P	active	-113.91915	39.48386	3/29/2010	4/30/2020	10.09	0	-0.04	moderate	DISP	Stable	7
N. Gandy Salt Marsh	1090	P	inactive	-113.92380	39.47908	8/10/2013	10/16/2017	4.18	243		low		Stable	2
N. Gandy Salt Marsh	1091	P	retired	-113.92279	39.47786	10/29/2014	10/19/2018	3.97	0	-0.15	low			5
N. Gandy Salt Marsh	1092	P	active	-113.92641	39.47670	11/1/2014	4/30/2020	5.49	350	-0.02	high	ELEO	Stable	3
Salt Marsh Range	1079	P	active	-113.88479	39.53202	5/29/2013	4/30/2020	6.92	203	0.00	high	ELEO	Stable	4
Salt Marsh Range	1080	P	active	-113.89289	39.51379	5/29/2013	4/30/2020	6.92	203	0.02	high	DISP	Stable	7
S. Gandy Salt Marsh	1093	P	inactive	-113.92466	39.46835	10/31/2014	4/17/2019	4.46	200	-0.08	low		Stable	5

Table 2. *Continued.*

Wetland System	Location ID	Feature Type[1]	Location Status[2]	X Coord (Long)	Y Coord (Lat)	Measure Begin Date	Most Recent Measure in DB	Years of Record	Data Gaps (days)	Mann-Kendall Water Level Trend[3]	Piezometer Priority[4]	2020 Vegetation Community[5]	Vegetation Trend	Hydro-period[6]
S. Gandy Salt Marsh	1094	P	inactive	-113.92621	39.46693	5/21/2015	4/17/2019	3.91	0		low		Stable	3
S. Gandy Salt Marsh	1095	P	active	-113.92543	39.46522	5/21/2015	4/29/2020	4.94	0		moderate	ELEO	Stable	5
S. Gandy Salt Marsh	1096	P	active	-113.92381	39.45882	10/30/2014	4/29/2020	5.50	0		high	SCAM	Flooding	2
S. Gandy Salt Marsh	1097	P	active	-113.92192	39.45952	10/30/2014	4/29/2020	5.50	0	0.18	moderate	JUNC	Stable	5
S. Gandy Salt Marsh	1098	P	retired	-113.92723	39.46478	10/31/2014	4/18/2018	3.46	0	-0.15	high		Stable	6
Twin Springs	58	W	active	-113.86311	39.40352	2/10/2009	3/3/2020	11.06	91					
Twin Springs	59	W	active	-113.86309	39.40351	2/10/2009	3/3/2020	11.06	364	0.09				
Twin Springs	60	W	active	-113.86301	39.40348	2/10/2009	3/3/2020	11.06	0	0.04				
Twin Springs	1047	P	active	-113.87513	39.40720	11/30/2010	4/29/2020	9.41	119	0.02	high	TYPH	Stable	3
Twin Springs	1052	P	active	-113.87276	39.40604	3/30/2010	4/29/2020	10.08	25	0.02	high	TYPH	Flooding	3
Twin Springs	1053	P	inactive	-113.87264	39.40561	3/30/2010	4/16/2019	9.05	0	0.01	low		Stable	1
Twin Springs	1054	P	retired	-113.87145	39.40466	3/30/2010	4/16/2019	9.05	0		moderate		Stable	5
Twin Springs	1055	P	active	-113.86882	39.40351	3/30/2010	10/11/2019	9.53	0	-0.01	moderate	SCAM	Stable	2
Twin Springs	1056	P	active	-113.86689	39.40373	3/30/2010	4/29/2020	10.08	0	0.03	high	JUNC	Stable	6
Twin Springs	1057	P	active	-113.86646	39.40364	3/30/2010	4/28/2020	10.08	0	0.03	high	SCAM	Flooding	4
Twin Springs	10008	S	active	-113.86281	39.40299	5/26/2010	12/8/2019	9.54	0	0.003				
Twin Springs	10009	S	active	-113.86385	39.40369	12/22/2009	12/3/2019	9.95	0	0.01				

[1] Feature types include piezometers (P), wells (W), and spring gauges (S).
[2] Location status includes “retired” for features that have been physically removed, “inactive” for features that are still present in the field without a transducer, and “active” for features with active monitoring.
[3] Mann-Kendall water-level trend shows the slope of change for features with a significant trend or left blank if indeterminate; trends <0.01 ft/yr are displayed as 0.0 Units of slope are in feet per year for wells and piezometers and cubic feet per second per year for spring gauges.
[4] Piezometer priorities are assigned to piezometers based on feedback from hydrogeologists and native aquatic biologists in 2019.
[5] Vegetation community is the dominant species in an area approximately 1 m^2 around each piezometer. Species include *Carex* spp. (CARX), *Distichlis spicata* (DISP), *Eleocharis* spp. (ELEO), *Juncus* spp. (JUNC), open water (OPEN), *Schoenoplectus acutus* (SCAC), *Schoenoplectus americanus* (SCAM), and *Typha* spp. (TYPH).
[6] Hydroperiod definitions are given in table 3.

Water Level Trends

To quantify and statistically verify long-term trends, we conducted a Mann-Kendall analysis on data from each wetland piezometer, spring gauge, and well near Snake Valley wetland sites using the pyMannKendall (Hussain and Mahmud, 2019) Python library. The data display significant serial autocorrelation (Inkenbrandt, 2020) and would not be suitable for a traditional Mann-Kendall test, so we applied two modified Mann-Kendall tests: a trend-free pre-whitening method (Yue and Wang, 2002) and a seasonal Mann-Kendall test (Hirsch and others, 1982). Both tests have different ways of removing periodicities in the data that cause serial autocorrelation. We used an alpha value of 0.01 for both tests. When results of both the seasonal and pre-whitening tests agreed and were both significant, we retained and reported the result and the slope from the seasonal test, but if the tests were not congruent, then the results were reported as indeterminate. Significant Mann-Kendall test results are interpreted to mean that water levels had substantially decreased or increased over the period of record.

The largest decline in water level was at wetland piezometer 1076 in Big Springs, which displayed the Mann-Kendall slope value of -1.36 feet per year (ft/yr), indicating a water level decline of -1.36 ft/yr. However, this piezometer was only measured for about three years, between 2013 and 2016. All locations at the Big Spring site display declining (or indeterminate) water levels with rates between -1.36 ft/yr and -0.113 ft/yr (appendix B). Wells and piezometers at Burbank Meadows, spatially adjacent to Big Springs, also show declining water levels with rates ranging from -1.11 to -0.03 ft/yr (table 2). Clay Spring has a decline in spring flow of -0.01 cfs/yr, but nearby piezometers 1048 and 1049 show increases of 0.1 and 0.166 ft/yr, respectively. While these sites are near Clay Spring, they may be more closely related to the Pruess Lake system. Wetland piezometer 1070, nearer to the spring, shows a significant decline in water level of -0.1 ft/yr.

The greatest increase in water level was at wetland piezometer 1062 in Leland Harris (Mann-Kendall slope of 0.45 ft/yr). However, this piezometer was only active for a short period from 2013 to 2016 and 8 of 13 piezometers and all four wells at Leland Harris have declining water levels. Similarly, North Gandy Salt Marsh had declining water levels in 7 of 13 piezometers and all three wells. All monitoring locations at Central Spring and Twin Springs, except for wetland piezometer 1055, show an increase in water levels over time or, less often, an indeterminate pattern, with increases ranging from 0.01 to 0.15 ft/yr.

The Mann-Kendall test is sensitive to the measurement period. For example, if a period of significant increase is excluded, it could significantly change the results of the analysis. The 2019 water year (Oct. 2018–Sept. 2019) was especially wet, resulting in higher measured water levels in many of the piezometers. Not all of the piezometers have records that are over the same time period, and a more in-depth examination of the trends may be warranted for answering specific questions regarding water levels at specific sites.

Of the 52 piezometers having at least eight years of data, 18 had their minimum recorded water level in 2010 and 9 piezometers each had minimum levels in 2013, 2016, and 2018. Minimum levels are typically recorded between July and September with about half occurring in August. Most piezometers at North Gandy Salt Marsh had their lowest years in 2016 and 2018. Piezometers with minimum water levels in 2013 were mostly from Miller Spring or Twin Springs and no piezometers at either location recorded minimum levels in 2016 or 2018. Of the same 52 piezometers, 30 recorded their maximum water levels in 2013 or 2014, typically in January or February. At least 75% of the piezometers at Leland Harris, Miller Spring, and North Gandy Salt Marsh recorded maximum water levels in 2013 or 2014. Piezometers at other complexes recorded maximum water levels across a wider range of years.

Piezometer Hydroperiod and Vegetation

We examined water level plots and assigned each piezometer to one of nine hydroperiods by visually assessing seasonal fluctuations, the presence of surface water, and the depth to saturated soil (table 3). We then compared hydroperiods with vegetation community data collected in a 1-m^2 area surrounding each piezometer during surveys in fall 2019 (table 4). Most vegetation communities were associated with several different hydroperiods and most hydroperiods supported multiple vegetation communities. Drastically different vegetation communities (for example, salt grass and cattails) were found in areas with distinctly different hydroperiods, but more similar vegetation communities (salt grass and mountain rush or hardstem bulrush and chairmaker's bulrush) were found in areas with overlapping hydroperiods.

Using vegetation data collected during 2010, 2012, 2013, 2017, and 2019 by various individuals and organizations, we were able to track vegetation communities at 74 wetland piezometers during at least two points in time and identified 12 piezometers where vegetation communities shifted over time. At these twelve locations, six of the vegetation community shifts indicated that the piezometer was experiencing wetter hydroperiods (i.e., a shift from mountain rush to open water) and the other six indicated a drying hydroperiod (i.e., a shift from hardstem bulrush to spikerush). The remaining 62 piezometers had vegetation communities that remained stable, did not experience a drastic change in dominant species, or experienced a shift between spike rush and mountain rush communities, the latter of which we viewed with low confidence. Grazing and lack of distinguishing vegetative features complicated the identification of these two species, and our confidence in past observations was too low to identify a vegetation community shift based solely on these species.

Five of the six piezometers with a drying vegetation trend also had a declining water level trend based on the Mann-Kendall test and four of the six piezometers with a wetter vegetation trend also had increasing water levels based on the Mann-Kendall test; the remaining piezometers in both cases were indeterminate. However, piezometers experiencing large changes in water level (>0.05 ft/yr) did not always experience a shift in vegetation communities, and vegetation communities occasionally shifted independently of piezometer trends. An assumed relationship between changing vegetation communities and changing water levels may be complicated by (1) lagged vegetation response to changing water levels, (2) inability to distinguish subtle vegetation community changes (ecotonal shifts and spikerush/mountain rush confusion), (3) inconsistently collected vegetation data, (4) different time periods assessed in some cases for the water trends and the vegetation trends, and (5) many vegetation communities occur in multiple hydroperiods.

Table 3. *Descriptions of hydroperiods assigned to piezometers based on visual examination of seasonal fluctuations, the presence of surface water, and the depth to saturated soil in plots.*

Hydroperiod	Description
1	Seasonally fluctuating surface water levels. Surface water present throughout most years.
2	Stable surface water, generally less than 6 inches deep.
3	Seasonal fluctuations between surface water and surface saturation.
4	Stable surface water or near surface saturation.
5	Seasonally fluctuates between surface water and a saturation zone 1 to 2 feet below the surface.
6	Seasonally fluctuates between surface saturation and a deeper saturation zone 1 to 2 feet below the surface. Surface water is occasionally present some years.
7	Seasonally fluctuates between surface saturation and a deeper saturation zone 1 to 2 feet below the surface. Surface water is absent all years.
8	Seasonally fluctuates between a deep saturation zone 1 to 2 feet below the surface and unsaturated conditions with saturation zones 2 to 5 feet below the surface.
9	Stable, deep saturation zone 1 to 2 feet below the surface

Table 4. *Number of piezometers in each vegetation community and hydroperiod.*

Vegetation Communities	Hydroperiod[1]									Sum
	1	2	3	4	5	6	7	8	9[2]	
Open water	2[3]	1	0	0	0	0	0	0	0	*3*
Schoenoplectus americanus	0	6	1	2	1	0	0	0	0	*10*
Typha latifolia	0	0	2	0	0	0	0	0	0	*2*
Schoenoplectus acutus	0	0	2	1	1	0	0	0	0	*4*
***Eleocharis* spp.**	0	0	1	1	5	1	0	0	0	*8*
***Carex* spp.**	0	0	0	0	0	1	0	0	0	*1*
Juncus arcticus	0	0	0	1	3	7	1	0	0	*12*
Distichlis spicata	0	0	0	0	2	0	3	2	0	*7*
Sum	*2*	*7*	*6*	*5*	*12*	*9*	*4*	*2*	*0*	

[1] Hydroperiod definitions are given in table 3.
[2] Only active piezometers surveyed for vegetation data in 2019 are included in the table and did not include any sites with the #9 hydroperiod.
[3] Fields with values greater than 0 are shaded gray.

Climate Data

We downloaded climate data from four regional climate stations and two SNOTEL stations and aggregated them into yearly data to find long-term trends in water availability. The climate stations are located at Great Basin National Park headquarters (Baker, Nevada), Callao, Eskdale, and Partoun, and the two SNOTEL sites are near Wheeler Peak in the southern Snake Mountains and Red Mountain in the Deep Creek Range (figure 1, table 5). Data were aggregated by water year (Oct. 1–Sept. 30) because most precipitation in the Snake Valley drainage basin occurs as snowfall. We examined precipitation (rain), snowfall, and reference evapotranspiration data from water years 2005 to 2019 for stations that were selected based on location and completeness of record. For the SNOTEL stations, we only examined the maximum snow-water equivalent (SWE). The relevant data for each station are summarized in figure 2.

Precipitation data shows similar trends for all of the stations we examined. Relative to other stations, Great Basin National Park shows higher precipitation for water year 2014 and lower relative precipitation for water year 2015. The lowest years for precipitation were 2006 to 2008. Years 2010, 2012, 2015, and 2018 were also below average. The highest precipitation years were 2005, 2011, and 2019. Water years 2009, 2013, 2014, and 2016 had precipitation greater than or close to average for all stations.

Snowfall and reference evapotranspiration are less congruent for the stations we examined. Snowfall was low during water years 2006, 2007, and 2015 and high during water year 2011 for all stations. Snowfall during water year 2019 was above average for all stations except for Partoun. Reference evapotranspiration was above average for water years 2006, 2007, 2012, and 2018 for all stations except for Partoun, which deviates from the other stations for all years except 2018. Reference evapotranspiration was low or near average for water years 2010, 2011, and 2019 for all stations except Partoun. Average reference evapotranspiration across all stations was higher than usual from 2015 to 2018.

Based on yearly precipitation, snowfall, and evapotranspiration records, the wettest water year was 2011. Water years 2013, 2014 and 2019 were relatively high, and 2019 had high precipitation. Relatively dry water years were 2006, 2007, 2012, 2015, and 2018, and 2007 was the driest (figure 2).

None of the climate stations showed significant long-term trends in climate variables when data were aggregated by water year for the years 2000 to present, based on the Mann-Kendall pre-whitening method (table 6). Using daily data and the seasonal Mann-Kendall method, Eskdale and Partoun had significant increasing trends in maximum and minimum temperature. Partoun also had a decreasing trend in precipitation and increasing trend in reference evapotranspiration. Data from the climate station at Great Basin National Park showed an increasing trend in minimum temperatures and increasing reference evapotranspiration.

Species Data

Least Chub

Least Chub data are collected annually at Leland Harris, Gandy, and Bishop Springs using minnow traps to capture fish from designated monitoring locations at each site, typically in late summer or early fall when water levels are low and Least Chub are congregated into deeper areas. All captured species are identified and counted, and measurements are made of approximately the first 100 Least Chub captured in each trap. These data are used to calculate metrics including mean length, percent juvenile (<33 mm total length), percent Least Chub versus other species, trap hours, and catch per unit effort (CPUE). Distributional monitoring is conducted once every three to five years and involves sampling a larger number of designated sites throughout the wetland complex. Both the annual and distributional monitoring data have been collected since before the installation of the wetland piezometers, dating back to 2004 or earlier. CPUE values at Gandy and Bishop Springs in years where distributional

Table 5. *Regional climate stations used for this review.*

Station ID	Station Name	Latitude	Longitude	Elevation (ft)	State
USC00422607	ESKDALE	39.1078	-113.953	4980	UT
USC00421144	CALLAO	39.8997	-113.713	4342	UT
USC00426708	PARTOUN	39.6308	-113.886	4780	UT
USC00263340	GREAT BASIN NP	39.0056	-114.221	6850	NV
SNOTEL-1147	WHEELER PK	39.02	-114.32	10,060	NV
SNOTEL-1247	TAKKA WIIYA	39.74	-113.98	9122	UT

Table 6. Trend in climate parameters based on daily data and data aggregated by water year.

Station Name	Start Date	End Date	Number of Measurements	Min	Min Date	Daily Data (2004–present)		Aggregated by Water Year (2000–present)	
						MK[1] Seas. Trend	MK Seas. Slope	MK PRWH[2] Trend	MK PRWH Slope
Maximum Temperature									
GREAT BASIN NP	8/1/1987	5/9/2020	11,221	-18.9	12/22/1990	no trend		no trend	
CALLAO	5/17/1962	5/9/2020	20,780	-17.2	1/6/2013	no trend		no trend	
ESKDALE	3/27/1966	5/9/2020	18,911	-15.6	12/23/1990	increasing	0.0000	no trend	
PARTOUN	3/19/1906	5/9/2020	25,355	-18.9	1/12/1963	increasing	0.0500	no trend	
Minimum Temperature									
GREAT BASIN NP	8/1/1987	5/9/2020	11,058	-28.3	12/22/1990	increasing	0.0600	no trend	
CALLAO	4/5/1952	5/9/2020	20,488	-31.1	1/12/1963	no trend		no trend	
ESKDALE	3/27/1966	5/9/2020	19,064	-35	2/6/1989	increasing	0.0417	no trend	
PARTOUN	3/19/1906	5/9/2020	25,394	-33.9	2/6/1989	increasing	0.0455	no trend	
Precipitation									
GREAT BASIN NP	8/1/1987	5/1/2020	10,630	0	8/1/1987	no trend		no trend	
CALLAO	6/14/1938	5/3/2020	28,432	0	7/1/1938	no trend		no trend	
ESKDALE	3/27/1966	5/7/2020	18,209	0	3/27/1966	no trend		no trend	
PARTOUN	3/19/1906	5/9/2020	24,582	0	3/19/1906	decreasing	0.0000	no trend	
Reference Evapotranspiration									
GREAT BASIN NP	8/1/1987	5/9/2020	11,120	-0.23607	12/22/1990	increasing	0.0049	no trend	
CALLAO	5/17/1962	5/9/2020	20,731	-0.29167	1/12/1963	no trend		no trend	
ESKDALE	3/27/1966	5/9/2020	19,112	-0.58057	2/7/1989	no trend		no trend	
PARTOUN	3/19/1906	5/9/2020	25,381	-0.37846	2/7/1989	increasing	0.0070	no trend	
Snow Fall									
GREAT BASIN NP	8/1/1987	5/1/2020	10,795	0	8/1/1987	no trend		no trend	
CALLAO	7/1/1938	5/1/2020	27,441	0	7/1/1938	no trend		no trend	
ESKDALE	3/27/1966	5/7/2020	18,104	0	3/27/1966	no trend		no trend	
PARTOUN	10/1/1906	5/9/2020	22,695	0	10/1/1906	no trend		no trend	

[1] MK = Mann-Kendall
[2] PRWH = Pre-whitening modification test from Yue and Wang (2002)

surveys were not conducted may be skewed by sample site selection because in those years biologists usually sampled only a few sites where they thought they could trap 100 fish with little effort; both sites were sampled with distributional surveys from 2007 to 2009, after which distributional sampling occurred at each site every three years.

We compiled CPUE data from the three Snake Valley locations, including data from 2007 through 2019 for Gandy and Bishop Springs and data from 2004 through 2019 at Leland Harris (table 7). Within the range of available data, 2008 through 2010 had the highest CPUE values at Gandy and Bishop Springs. Otherwise, there was no consistency in which years had high or low values across sites. The change from distributional to more targeted monitoring may impact CPUE values; the lowest CPUE values between 2010 and 2019 at Gandy occurred during years with distributional monitoring, though this pattern was not seen at Bishop Springs, where only one of three low values occurred in a year with distributional monitoring. We ran the Yue and Wang (2002) modified Mann-Kendall test on the Least Chub CPUE values for time periods with continuous years of species data. Bishop and Gandy showed decreasing trends for the years 2007 to 2019 and Leland Harris showed no significant trend for 2009 to 2019 (table 8).

Mark Grover, former aquatic biologist with the UDWR, collected extensive data at the Leland Harris spring complex between October 2012 and August 2014, including a bathymetric survey, visual fish surveys and surface water level measurements at 47 points at 15 sampling occasions, and demographic monitoring using minnow traps from mid-August to late September of 2012 to 2014 (Grover, 2019). He used the data to demonstrate differing habitat preferences for adults and juveniles that change over time and seasonal fragmentation of Least Chub habitats within Leland Harris. Shallow ponds are used by spawning adults and juveniles in the spring and early summer and then both age classes migrate to deep springs as ponds start to dry in the summer and fall. In August when water levels are lowest, Least Chub are found in ten distinct isolated patches of water that are no longer connected due to low water levels.

Table 7. *Least Chub and Columbia Spotted Frog monitoring data, including catch per unit effort (CPUE) for Least Chub and egg mass counts for Columbia Spotted Frog.*

Year	Least Chub CPUE			Columbia Spotted Frog Egg Mass Counts				
	Gandy Marsh	Bishop Springs	Leland Harris	Kell (a.k.a. Beck)	Bishop	Gandy	Leland Harris	Miller
1996							936	
1997						406	352	557
1998					275[1]	489[1]	528	1626
1999					274	672	436	1630
2000					241	784	613	1274
2001					201	585	804	1154
2002					357	90	687	1178
2003					615	115	588	262
2004			12.2		214	132	389	357
2005			44.4		325	155	567	183
2006			57.4	89	425	205	428	279
2007	11.1	27.8	20.3	82	891	114	241	246
2008	11.6	35.5	20	120	715	128	165	246
2009	15.1	33.3	26.3	156	704	121	271	164
2010	11.3	**46.0**[2]	48.8	141	511	185	626	232
2011	**10.4**	17.8	18.4	305	745	256	1033	980
2012	**7.2**	**9.4**	19.8	304	1111	528	2902	1276
2013	3.0	**8.9**	39.1	462	1125	473		
2014	**9.8**	8.5	83	301	1430	374		
2015	**9.8**	**0.3**	138.5	130	1327	302	991	
2016	0.6	**7.5**	44.8	316	1030	325	1043	2319
2017	**7.5**	0.2	23.4	163	979	282		
2018	**7.5**	**0.2**	36.7	239	648	152		
2019	4.8	**9.6**	50	277	459	141	240	2728

[1] Values highlighted in blue and red are in the top or bottom 20% of values for the site, respectively.
[2] Values in bold for Least Chub at Gandy and Bishop Springs indicate years when distributional monitoring did not occur.

Table 8. *Trend in species data for Least Chub and Columbia Spotted Frog (CSF), based on the modified Mann-Kendall test (Yue and Wang, 2002).*

Site	Species	Begin Year	End Year	Trend[1]	Slope[2]
Kell (a.k.a. Beck)	CSF	2007	2019	no trend	
Bishop	CSF	1998	2019	increasing	43.41
Gandy	CSF	1998	2019	no trend	
Leland Harris	CSF	1997	2012	no trend	
Miller	CSF	1997	2012	no trend	
Gandy	Least Chub	2007	2019	decreasing	-0.55
Bishop	Least Chub	2007	2019	decreasing	-2.77
Leland Harris	Least Chub	2007	2019	no trend	

[1] Sites with significant trends highlighted in gray.
[2] Slope presented as change in egg masses or catch per unit effort per year.

Columbia Spotted Frog

Columbia Spotted Frog habitat in Snake Valley exists within two different UDWR regions and surveys are managed by the Central and Southern regional offices. Columbia Spotted Frog surveys occur approximately once per week throughout the breeding season (approximately March to early April) to count egg masses, record their location, and chart their development through four egg classes from initial egg laying through hatching. Annual data (1998 through 2019) are available at the Southern region sites—Bishop Springs Complex and Gandy Springs—whereas data were not collected at Central region sites—Miller and Leland Harris Springs—in some years starting in 2013 (table 7). Habitat data for the Southern region are 10 to 15 years old and were not digitized, whereas recent data for the Central region include water depth, temperature, distance to shore, pH, and conductivity at locations where egg masses were found (though not all parameters were collected in all years).

We compiled annual egg mass count data from Kell (a.k.a. Beck), Bishop, Gandy, Leland Harris, and Miller Springs, which included years 1996 through 2019 with some data gaps. The years with the highest number of egg masses were 2000 for Gandy, 2012 for Leland Harris, 2013 for Kell, 2014 for Bishop, and 2019 for Miller. The years with the lowest counts were 2001 for Bishop, 2002 for Gandy, 2006 for Kell, 2008 for Leland Harris, and 2009 for Miller (table 7). All five sites (except Kell in 2011) showed large increases in egg mass numbers in 2011 and 2012 and all three sites with data available showed large decreases in egg mass numbers in 2017. The Yue and Wang (2002) modified Mann-Kendall test showed an increasing trend of egg mass numbers at Bishop Springs between 1998 and 2019; none of the other sites showed significant trends (table 8).

Mollusks

Survey data have been collected for each Snake Valley sensitive mollusk species between two and five times since 2001, except for Cloaked Physa (table 9). Cloaked Physa has only been documented once in Snake Valley (Taylor, 1988) and was not found during a later attempt to collect specimens from the sole historical occurrence in Snake Valley (Hovingh, 2018), so its presence in Snake Valley is questionable. Mollusk surveys have been conducted by a variety of agencies using different methods. The most recent mollusk surveys in Snake Valley were focused on the three springsnails (genus *Pyrgulopsis*) and were conducted by UDWR. Survey data sometime include density estimates, though methods vary across years. The population of Longitudinal Gland Pyrg at Clay Spring has the most years of density data, with density estimates from 2009, 2012, 2016, and 2019, though methods differed between the first two and last two years of surveys. Habitat variables including water temperature, dissolved oxygen, pH, conductivity, patch size, spring discharge, water depth, and wetted channel width have sometimes been collected during mollusk surveys. Population trend data are not available for any of the mollusk species since survey methods have differed across years and few years of data are available. However, evidence suggests that Sub-globose Snake Pyrg has declined. The species was previously considered common or abundant, observed with a density of 343 snails per square meter by Vinson (2002). Surveys in May 2019 found 21 live snails despite an intensive survey effort; repeat surveys in August 2019 found only 4 live snails.

Relationships Between Climate, Water Level, and Species

We categorized years between 2005 and 2019 into climate, water level, and species classes to preliminarily review relationships between factors (table 10). For climate, we classified years as driest, wettest, dry, wet, or no class based on overall trends in climate variables from all four climate stations. For water levels, we determined which years had the most piezometers that reached their lowest and highest water levels in particular years and categorized those years as low or high, accordingly. The year 2013 was notable because it had both a large number of piezometers with high water levels in the winter and a large number with low water levels in the summer. Piezometer data are only available starting in fall 2009. For the species data, we classified years as "low count" if the year had a value in the bottom 20% of egg mass counts or CPUE values for the site between 2005 and 2019 and "high count" if they were in the top 20%. We then determined how many sites were classified as low or high count for each year.

Egg mass counts were low at two or three of the five Columbia Spotted Frog sites in every year between 2005 and 2009, and each site had between two and three low egg mass years during this period (table 10). Egg mass counts were high at 25% or more of surveyed sites each year between 2011 and 2016, and egg mass counts were high for each site in half the surveyed years during this period, except for Miller Spring, which had one high year out of the three surveyed. Least chub CPUE values were less consistent. Three years had high Least Chub CPUE values at two of three sites—2008 through 2010. Otherwise, no two sites had high or low count years in the same year. One site had low CPUE values in every year from 2011 through 2019 except 2014.

The period with low Columbia Spotted Frog egg mass counts and high Least Chub CPUE values, 2005 through 2010, includes the two driest years in the period of interest (2006 and 2007) and no particularly wet years. Piezometer data are not available for most of the period, though water levels were at their lowest for many piezometers in 2010. The period from 2011 to 2016

Table 9. *Species and habitat data for the five sensitive mollusk species in the Snake Valley region of Utah.*

Species	Site	Timeframe	Species Data	Habitat Data	References
Anodonta nuttalliana (Winged Floated)	Pruess Lake	2001, 2012, 2014, 2018	2001 efforts were to collect specimens for genetics work (Mock and others, 2004). Mussel counts are available for 2012, 2014, and 2018 (UDWR field report).	General description for UT: reservoirs and low gradient streams.	Mock and others, 2004; UDWR field reports[1]
Pyrgulopsis anguina (Longitudinal Gland Pyrg)	Stateline Springs	2016, 2019	Catch per unit effort data for 2016 surveys (Sada, 2017). Springsnail counts from kitchen sieve scoops are available from 2019 surveys (UDWR field report).	Water depth, discharge, velocity recorded for each spring during 2016 surveys. Discharge, average water depth and width, temperature, and conductivity for each spring are available from UDWR for 2019 surveys.	Sada, 2017; UDWR field report
	Clay Spring	2005, 2009, 2012, 2016, 2019	Surveys in 2005 by Golden (2007) and 2009 (Jones and Wilson, 2009) provided mostly presence data. Three density estimates from 100 cm^2 plots in 2009 and 2012 (UDWR field reports). Density from kitchen sieve scoops in 2016 and 2019 (UDWR field reports).	General habitat parameters (size, water quality, and vegetation) for the spring are provided in Golden (2007). Water depth and wetted channel width recorded at plot/scoop locations (UDWR field reports).	Golden, 2007; Jones and Wilson, 2009; Sada, 2017; UDWR field reports
P. hamlinensis (Hamlin Valley Pyrg)	White Rock Cabin Springs	2009, 2010, 2012, 2019	Three density estimates in 2012 from 100 cm2 plots in 2012. No density data for 2019 (snow made for difficult sampling; UDWR field report). Surveys were conducted in 2009 and 2010 by UDWR but data in these reports are limited to documenting presence.	This species is endemic to a spring complex with sedge, watercress, and duckweed. The substrate is mostly gravel. Water temperature is 16˚C and conductivity is 160 µmmho/cm (Jones and Wilson 2009). Water depth and wetted channel width recorded at scoop locations (UDWR field reports).	Jones and Wilson, 2009; UDWR field reports
P. saxatilis (Sub-globose Snake Pyrg)	Gandy Warm Springs	2002, 2009, 2012, May 2019, August 2019	Quantitative density data from 5 sites that were sampled twice per year for 2 years (Vinson, 2002). Three density estimates from 100 m2 plots in 2012 (UDWR field report). Some density data for 2019 UDWR surveys. UDWR survey in 2009 documented presence.	This species is endemic to the Gandy Warm Springs complex. Discharge and general water quality are provided in Jones and Wilson (2009). Discharge, temperature, and conductivity are available for the springhead pool; water depth and channel wetted width are available for each plot/scoop (2012–2019 UDWR field reports).	Vinson, 2002; Jones and Wilson, 2009; UDWR field reports
Physa megalochlamys (Cloaked Physa)	Bishop Springs	1988	No abundance data exists for UT.	No habitat data exists for UT.	Taylor, 1988

[1] All UDWR field reports were written by Kevin Wheeler.

Table 10. Comparison of climate, piezometer, and sensitive species trends.

Year	Columbia Spotted Frog		Least Chub		Climate[4]	Piezometer Water Levels[4]
	Low Count[1]	High Count[1]	Low CPUE[2,3]	High CPUE[3]		
2005	2 of 4	0 of 4	0 of 1	0 of 1		No data
2006	2 of 5	0 of 5	0 of 1	1 of 1	driest	No data
2007	3 of 5	0 of 5	0 of 3	0 of 3	driest	No data
2008	3 of 5	0 of 5	1 of 3	2 of 3		No data
2009	2 of 5	0 of 5	0 of 3	2 of 3		Minimal data
2010	0 of 5	0 of 5	0 of 3	2 of 3		lowest
2011	0 of 5	2 of 5	1 of 3	0 of 3	wettest	
2012	0 of 5	2 of 5	1 of 3	0 of 3	dry	
2013	0 of 3	3 of 3	1 of 3	0 of 3	wet	high to low
2014	0 of 3	2 of 3	0 of 3	1 of 3	wet	high
2015	0 of 4	1 of 4	1 of 3	1 of 3	dry	
2016	0 of 5	3 of 5	1 of 3	0 of 3		low
2017	0 of 3	0 of 3	1 of 3	0 of 3		
2018	0 of 3	0 of 3	1 of 3	0 of 1	dry	low
2019	2 of 5	1 of 5	1 of 3	0 of 3	wet	

[1] Values in the Columbia Spotted Frog low- and high-count fields indicate the number of sites out of the number of surveyed sites that had egg mass counts within the bottom or top 20% for the site, respectively.
[2] CPUE = Catch per unit effort
[3] Values in the Least Chub low and high CPUE fields indicate the number of sites out of the number of surveyed sites that had CPUE values within the bottom or top 20% for the site, respectively.
[4] Values indicating drier climate, lower water levels, and lower species counts are colored red and values indicating wetter climate, higher water levels, and higher species counts are colored blue; one year with both high and low water levels is colored yellow.

had high egg mass counts and low CPUE values; this period includes three wetter than usual years and two dry years, and many piezometers had their highest water levels during this period. There appears to be a positive association between wet years and egg mass counts for Columbia Spotted Frog, and egg mass numbers appear to be affected for several years after a series of wet or dry years. For example, three of the four years between 2011 and 2014 were wetter than normal; these years all had elevated egg mass counts as well as 2015 and 2016, despite 2015 being a drier year. In contrast, Least Chub CPUE values tend to be higher in drier periods of time and lower in wetter periods, though the relationship is weak at best. Least Chub may become more concentrated in a few pools when water levels are low, leading to a higher trapping rate in those years. However, it is worth exploring whether there are other metrics collected on an annual basis that may be more informative than CPUE.

FUTURE STUDY RECOMMENDATIONS

The objective of this work is to determine how changes in groundwater extraction, climate patterns, and hydrology impact sensitive species in Snake Valley. To achieve the objective, we will connect hydrologic data, wetland habitat metrics, and species population parameters to predict changes to sensitive species and their habitats. The UGS has collected a substantial amount of hydrologic data in Snake Valley. In this section, we first discuss life stages and habitat variables that are likely important to sensitive species and potential studies that could be conducted to better understand population dynamics and how they might relate to water levels. Next, we discuss aerial imagery analysis and hydrology studies that could be conducted to develop a better understanding of how conditions change over time and the controls on those changes. Last, we discuss an overall approach for working with existing and new data to aid in achieving the objective of this work.

Sensitive Species

Least Chub

We conducted a literature review to summarize the following information for Least Chub in Snake Valley: (1) population dynamics and demographics, (2) key habitat parameters, and (3) sensitive life stages (appendix A). We identified spawning (approximately April to late June), summer refuge (early July to mid-September), and overwintering (approximately early

November to late February) as time periods when Least Chub may be particularly sensitive to fluctuating water levels or other disturbances. Potential hydrologic metrics that could be used to assess habitat conditions at each time period are listed in table 11.

Metrics related to the extent, depth, and period of surface water within the wetland are directly relatable to sensitive periods in the Least Chub life cycle. Areas of relatively deep, permanent surface water connected to springs or other groundwater discharge areas are essential refuge habitat during seasonally low water levels experienced in late summer (Least Chub Conservation Team, 2014; Saenz, 2014) and provide thermally protected overwintering habitat (Grover, 2019). Shallow seasonally flooded areas provide crucial spawning habitat with egg mass attachment opportunities and warmer temperatures nearer the optimum reported in Wagner and others (2005) for larval growth and development. We assume greater amounts of overwintering, summer refuge and spawning habitat would increase juvenile recruitment and adult survival.

Habitat connectivity metrics assessing surface water connections between spawning areas and refuge habitats may help determine the extent of Least Chub habitat within a wetland complex. Surface water levels within a marsh complex are dynamic and surface water connectivity between Least Chub habitats changes over the growing season (Grover, 2019). Grover (2019) identified eight seasonally isolated refuge areas within the Leland Harris wetland complex that became functionally isolated during late summer. Seasonally flooded areas within Leland Harris and other wetland complexes may be crucial in connecting isolated refuge areas and maintaining a viable Least Chub population within a wetland.

Two other habitat quality metrics may be important in considering Least Chub habitat in Snake Valley—cattail/bulrush encroachment and water temperature. Dense emergent vegetation has been shown to restrict Least Chub mobility between refuge areas (Grover, 2019) and shade the water surface, reducing algae production and limiting a key food source during the summer and fall months (Sáenz, 2014). Determining the extent of cattail/bulrush encroachment into refuge habitats may be useful in de-

Table 11. *Key hydrologic metrics important for Least Chub at different life stages.*

Metric	Effect to Least Chub	Notes/Difficulties
Spawning (April 1 to June 30)		
Area of shallow water (<30 cm)	Egg masses are deposited throughout the spawning season in shallow water. Reduction of available spawning habitat may shorten the season or reduce spawning output.	Could be analyzed with hypsometric curves constructed from lidar or bathymetry data.
Groundwater depth	Groundwater depth likely correlates to overall water levels in Snake Valley wetlands, which could serve as a proxy for area of shallow water.	Groundwater wells in Leland Harris correlate well with surface water levels (Grover, 2019); need to investigate in other locations. May want to use regional wells instead of UGS wells to capture long-term trends.
Connectivity to deep-water habitats	Areas of shallow water lacking a surface water connection to deep water refuge habitat are not viable spawning habitats.	Would require hypsometric curves and spatial knowledge of refuge spring or pond habitats.
Summer refuge (July 1 to September 14)		
Area of deep water (>30 cm)	Post-spawning adults return to deep-water habitats with lower temperatures, greater levels of dissolved oxygen, and permanent surface water.	Could be analyzed with hypsometric curves constructed from lidar or bathymetry data.
Water temperature in refuge pools and springheads	Increased water temperature, salinity, and decreased levels of dissolved oxygen are stressors for Least Chub.	Would require locating known refuge areas. May also require installation of temperature monitoring stations.
Groundwater depth	Groundwater depth likely correlate to overall water levels in Snake Valley wetlands, which could serve as a proxy for area of deep water.	Groundwater wells in Leland Harris correlate well with surface water levels (Grover, 2019); need to investigate in other locations. May want to use regional wells instead of UGS wells to capture long-term trends.
Connectivity to other deep-water habitats	Seasonally low water levels during late summer may fragment deep water habitats and isolate populations.	Would require bathymetry data and locating known refuge habitats.
Overwintering (November 1 to February 28)		
Area of deep water (>30 cm) near springheads and groundwater discharge areas	Adults and juveniles overwinter in springheads and deeper, groundwater fed pools. Reduced extent of overwintering habitat could limit survival.	Would require hypsometric curves and locating springheads and discharge areas.

scribing population trends that appear independent of hydrology metrics. Least Chub are generalists capable of tolerating large swings in temperature and dissolved oxygen but are not immune to extreme swings and temperature-related mortality (Sáenz, 2014). Larval and juvenile development are also temperature-dependent with optimal temperatures for development exceeding those found in typical refuge habitats (Crawford, 1979).

To evaluate habitat connectivity, we would need to (1) locate the refuge areas that Least Chub utilize as summer refuges and for overwintering to survive through the summer and winter and (2) collect fine-scale bathymetric or elevation data during a low water period. Winter and summer refuge area location and bathymetry data have been collected at the Leland Harris wetland complex by Grover in 2019. Sáenz (2014) conducted trap sampling at numerous locations within the two other wetland complexes within Snake Valley known to support Least Chub (Gandy Salt Marsh and Bishop Springs) but did not explicitly identify which locations would be suitable refuge habitat. Repeat field surveys to evaluate the presence/absence of Least Chub at the locations sampled by Sáenz may be helpful in determining which areas within Gandy Salt Marsh and Bishop Springs function as refuge habitats for Least Chub. These presence/absence surveys would need to be combined with detailed elevation profile data to accurately relate changing water levels to extent and depth of surface water and ultimately evaluate habitat connectivity.

Least Chub population dynamics within Snake Valley are poorly understood and attempts to conduct standard mark-recapture studies are stymied by Least Chub's relatively small body size. Novel marking techniques using injected polymers may be a feasible option that would allow a mark-recapture study to be conducted. Such a study could provide a rough sense of individual movements within a marsh complex as well as a much more detailed demographic picture leading to more accurate estimates of population size and cohort survival through sensitive periods. Population estimates derived from this study could be compared against several variables such as climate data, regional groundwater levels, or site-specific observations of vegetation encroachment and water depth. These comparisons could identify other biotic or abiotic factors that affect Least Chub in Snake Valley.

A similar analysis could be conducted using CPUE data from previous studies—Grover (2019), Sáenz (2014), and UDWR monitoring—where CPUE could be used as a proxy for more robust population estimates. The comparisons against historical climate data or regional groundwater levels could illuminate Least Chub response to changing water levels. The same CPUE data could also be used in a time-series analysis to determine if Least Chub populations experience positive or negative feedback from their own densities, e.g., if increased reproductive output and recruitment from a previous year promotes even greater growth the next year.

Information from all of these studies could support management actions aimed at improving habitats, understanding key biotic and abiotic factors, and developing strategies to maintain long-term population viability.

Columbia Spotted Frog

We conducted a literature review to summarize information about the following for Columbia Spotted Frog in Snake Valley: 1) population dynamics and demographics, 2) key habitat parameters at different life stages, and 3) sensitive times during breeding, development and dispersal (appendix A). We identified several time periods when Columbia Spotted Frogs may be particularly sensitive to fluctuating water levels or other disturbances. These periods include breeding (approximately March to mid-April), larval development (usually mid-March to mid-August, but possibly extending to mid-October), and dispersal (mid-March to late April for breeding adults and late August to mid-October for juveniles). Potential hydrologic metrics that could be used to assess habitat conditions for Columbia Spotted Frogs at each time period are listed in table 12.

Some metrics, particularly those related to hydrologic regime or extent of water within the wetland, would be directly relatable to sensitive periods in the Columbia Spotted Frog life cycle. Shallow surface water that persists through the breeding period and into the larvae development period is imperative for egg mass survival (UDWR, 2006) and beneficial for larvae development into juvenile frogs. More extensive surface water during the larval development period would reduce larvae densities (Patchett and others, 2018) and pond desiccation stress (Richter-Boix and others, 2011); both factors are linked to reduced body mass at metamorphosis and reduced juvenile survival rates. Temperature has been linked to accelerated metamorphosis (Morris and Tanner, 1969), but the effects on body mass have not been studied in Columbia Spotted Frogs. Permanent water has been identified as a strong predictor of Columbia Spotted Frog occupancy (Arkle and Pilliod, 2015) and dispersing adults and juveniles would likely migrate to areas of permanent water; we are assuming greater amounts of permanent water would reduce mortality during the dispersal period.

Habitat connectivity metrics such as the connection between breeding sites and permanent water or potential dispersal corridors may help gauge survival rates of dispersing adults and juveniles. Cohort survival studies of Columbia Spotted Frogs and the closely related Oregon Spotted Frogs found high mortality rates for juveniles between metamorphosis and their second year (Meyer, 2011) and for adult males dispersing from breeding sites (Chelgren and others, 2006). When dispersing, frogs risk greater predation as well as desiccation. Dumas (1966) found exposure to relative humidity at or below 65 percent and temperatures equal to or exceeding 25°C lethal to Columbia Spotted Frogs for any period longer than two hours. Frogs mitigate desiccation by dispersing during the evening, following rain storms, or through riparian and wetland habitat (Lingo, 2013). In arid Snake Valley, frogs may be restricted to dispersing through flooded or saturated wetland habitats, and their ability to safely disperse from breeding sites may be severely limited at some points in the year.

Table 12. *Key hydrologic metrics important for Columbia Spotted Frog at different life stages.*

Metric	Effect to Columbia Spotted Frog	Notes/Difficulties
Breeding (March 1 to April 15)		
Area of shallow water (<20 cm)	Egg masses deposited in shallow water that must persist for at least 12 to 21 days for larvae to hatch. Areas of shallow water that dry out before mid-April would destroy egg masses.	Would require hypsometric curve data; water depth of interest close to margin of error in piezometer data.
Water level stability	Egg masses typically laid along pond margins, and rapidly changing water levels may strand egg masses at the edge.	Could be measured as standard deviation over time period or difference between maximum and minimum.
Groundwater depth	Groundwater depth likely correlates to overall water levels in Snake Valley wetlands, which could serve as a proxy for area of shallow water.	Groundwater wells in Leland Harris correlate well with surface water levels (Grover, 2019); need to investigate in other locations. May want to use regional wells instead of UGS wells to capture long-term trends.
Larvae development (March 15 to August 15)		
Area of shallow water (<20 cm)	Metamorphosis accelerated by stressors like increasing larvae density or decreasing water depth. Accelerated metamorphosis often results in smaller juvenile frogs with lower survival rates.	Would require hypsometric curve data; water depth of interest close to margin of error in piezometer data, would need to identify areas of permanent surface water.
Connectivity to permanent waters	Larvae fully aquatic until metamorphosis is complete (122 to 209 days). Shallow, seasonally flooded areas used as egg deposition sites must be connected to permanent water throughout the summer if larvae are to survive through metamorphosis.	Water depth of interest close to margin of error in piezometer data, would need to identify areas of permanent surface water and areas repeatedly used as breeding sites.
Groundwater depth	Groundwater depth likely correlated to overall water levels in Snake Valley wetlands, which could serve as a proxy for habitat extent.	Groundwater wells in Leland Harris correlate well with surface water levels (Grover, 2019); need to investigate in other locations. May want to use regional wells instead of UGS wells to capture long-term trends.
Water temperature in larval development pools	Temperature affects growth rates and metamorphosis timing. Juvenile size following metamorphosis has been strongly linked to survival rates and abnormal temperature swings may adversely affect development.	Would require locating known breeding sites/development pools. May also require instillation of temperature monitoring stations.
Cattail and bulrush encroachment into open water habitats	Anecdotal evidence and broad habitat requirements suggest that extensive encroachment of dense, tall emergent vegetation limits habitat suitability for larval and adult frogs.	Would require locating known breeding sites and tracking vegetation across several years.
Dispersal (March 15 to April 30 for breeding adults and August 15 to October 15 for juveniles)		
Areas of permanent water	Adults and juveniles remain mostly aquatic and require water throughout the year for foraging and overwintering. Reduced extent of permanent water could limit adult survival.	Would require hypsometric curve data, would need to identify areas of permanent surface water, would need to consider vegetation density as well.
Saturated dispersal corridors	Juveniles and adults face a high risk of desiccation (65% humidity at 25°C is lethal after two hours) and dispersal to summer feeding and overwintering areas likely occurs through areas of relatively higher humidity. Reduced extent of saturated dispersal areas could increase mortality during dispersal periods.	Like the other connectivity metrics, would require identifying areas consistently used as breeding sites and permanent waters used as overwintering habitats. Would also require a more detailed understanding of frog movement patterns and dispersal distances.

Two other habitat quality metrics may be important in considering Columbia Spotted Frog habitat in Snake Valley—cattail/bulrush encroachment and water temperature. Columbia Spotted Frogs avoid areas of dense, tall emergent vegetation (Morris and Tanner, 1969; Arkle and Pilliod, 2015) and anecdotal evidence links pond succession and the loss of open water habitat to declining Oregon Spotted Frog numbers at one reintroduction site (Ramsayer, 2008). Determining the extent of cattail/bulrush encroachment into open, ponded areas or areas with shorter-stature vegetation favored for egg mass deposition may be useful for describing population trends that appear independent of hydrology variables. Water temperature also affects population dynamics by determining when adult frogs emerge from hibernation (Morris and Tanner, 1969) and the duration of the breeding period (Hovingh, 1993), and by influencing larval growth rates (Morris and Tanner, 1969). Water temperature effects on larval growth rates may be the most relevant as delayed growth or reduced body mass at metamorphosis decrease juvenile survival rates (Richter-Boix and others, 2011; Patchett and others, 2018).

Evaluating any habitat connectivity or quality metric hinges on locating known breeding sites. Columbia Spotted Frogs prefer breeding sites that have shallow water (depths less than 20 centimeters), solar heating, and presence of emergent vegetation like spikerushes (*Eleocharis* spp.), sedges (*Carex* spp.), or rushes (*Juncus* spp.), and show some site fidelity across multiple years (Bull, 2005; Davis and Verrell, 2005; Pearl and others, 2007). A spatial analysis of egg mass locations and counts from the UDWR egg mass surveys may be helpful in locating frequently used breeding sites. If there is strong fidelity to a few locations, those may be good locations for additional monitoring such as photo points for tracking changes in vegetation over time or deployment of temperature probes. This spatial analysis could be expanded to evaluate any spatial or elevational changes in egg mass distribution in wet versus dry years and to assess the degree of flexibility in breeding site selection. The data for this analysis already exist—there are weekly egg mass count data from the breeding season available with UTM coordinates for Bishop and Gandy from 1998 to 2019 and weekly count data from Leland Harris and Miller from most years between 1996 and 2019.

Several other analyses could be conducted with the UDWR egg mass survey data that may illuminate factors affecting Columbia Spotted Frog populations in Snake Valley. Preliminary evaluation of egg mass data from the southern UDWR region suggests that sites close to one another experience good and bad years independently, which may mean that site-specific demographic or habitat variables strongly affect populations rather than changes being driven by climate. Studies by Bull (2005) in eastern Oregon found similar trends, with egg mass counts varying between years and sites. Bull (2005) noted a significant uptick of egg mass numbers two years after an unseasonably warm summer, but did not observe that uptick in all sites studied. The UDWR egg mass survey data could be subjected to a time-series analysis of egg mass numbers to determine whether there are any significant lag periods of responsiveness to increases or decreases in eggs based on the assumed one to two-year delay between a boom or bust reproduction year and the recruitment of that cohort into the breeding population. A time series analysis could include climate data or groundwater levels from regional monitoring wells to determine if wetter, cooler conditions or elevated regional groundwater levels (and presumably surface water levels in Snake Valley wetlands) corresponded to increased egg mass counts. A more complex model could be built that would consider several of the hydrologic metrics identified in table 12 as predictors of yearly egg mass counts to evaluate population responses to changing climate and water levels. The data for this analysis already exist. Egg mass count data are available from Bishop and Gandy from 1998 through 2019 and additional data from Kell (a.k.a. Beck) Spring and spring complexes in Tule Valley for varying numbers of years which could be used to look for general lag periods for the species. A time series analysis looking at the full set up of data would have to use regional groundwater wells that have been in operation through all of the egg mass surveys, rather than local UGS wells that have been in place since about 2009.

A mark-recapture study may be very useful in understanding Columbia Spotted Frogs in Snake Valley. Such a study could provide a more detailed demographic picture leading to revised male to female sex ratios, more accurate population estimates, and a better understanding of cohort survival through sensitive periods. All of this information could support management actions aimed at improving habitats, survival rates of juvenile and breeding adults, and long-term population viability. The results of a mark-recapture study could also improve analysis of hydrologic data. More accurate population estimates could be used to investigate the relationship between egg mass deposition, adult population size, and hydrologic conditions, which may help determine the extent to which hydrologic conditions versus the number of breeding frogs controls egg deposition. Furthermore, identification of cohort survival at different sensitive periods could help determine the most important life stages (and corresponding hydrologic metrics) to evaluate.

Mollusks

We conducted a literature review for the three springsnail species known from Snake Valley, but not for Winged Floater or Cloaked Physa, focusing on parameters that may affect core springhead habitat rather than identifying sensitive lifestages or unique habitats within the Snake Valley springs and wetland complexes. Potential metrics to track environmental variables that may affect springsnails are listed in table 13.

The Species Status Assessment for 14 Springsnails in Nevada and Utah concluded that there are four main physical and biological needs for springsnails: 1) sufficient water quality, 2) adequate substrate and vegetation, 3) free-flowing water, and 4) adequate spring discharge (U.S. Fish and Wildlife Service, 2017). Groundwater depletion and groundwater development (e.g., diversion) are considered threats to springsnails in the Conservation Strategy for Springsnails in Nevada and Utah (Museum of Northern Arizona Spring Stewardship Institute, 2020). Therefore, spring discharge or water levels are among the most valuable hydrologic parameters that the UGS can monitor to contribute to springsnail and other aquatic mollusk conservation in Snake Valley and throughout Utah.

Springsnails and the other sensitive mollusks in Snake Valley are obligate aquatic species, and complete dewatering of their habitat would result in extinction. However, even slight decreases in discharge may impact these mollusks in complex ways that are not yet clear. In-stream habitat parameters, including wetted channel width, water depth, and water velocity, were altered in a springbrook after a 10% decrease in discharge (Morrison and others, 2013). Reduced spring discharge has also been found to cause greater swings in daily minimum and maximum water temperatures (Morrison and others, 2013). Many springsnails appear to require specific habitat conditions (Hershler, 1998; Mladenka and Minshall, 2001; Grasby and Lepitzki, 2002; Sada, 2008), so changes to these conditions may contribute to population declines for some springsnail species (Grasby and Lepitzki, 2002; Morrison and others, 2013; Sada, 2017). Additionally, decreased discharge may alter the microbial community's distribution and abundance (food resources for some springsnails) in a spring, which in turn may affect the distribution and abundance of springsnails (Grasby and Lepitzki, 2002; Lepitzki, 2002). Decreased water levels at Pruess Lake could reduce the amount of available habitat for Winged Floaters and the fish that serve as hosts for the larval mussels. Reduced water levels could also alter water quality and chemistry and create an environment that is less suitable for the mussels and their fish hosts.

Research examining how decreased discharge and water levels impact mollusk density, abundance, and distribution is limited, especially for western Utah. Preliminary monitoring of spring habitats and macroinvertebrate communities were conducted in 2009 and 2010 in Spring Valley and Snake Valley (Sada, 2014) and continued monitoring of these habitats and communities is recommended to better establish a relationship between water availability and mollusk populations. Further research on this topic will be critical to the long-term management and persistence of these and other aquatic mollusk species throughout Utah.

Spring-specific monitoring could also be expanded by installing water level or discharge monitoring equipment on springs supporting sensitive springsnails that are outside of the UGS monitoring network. In Snake and Hamlin Valleys, these springs include White Rock Cabin Springs about 40 miles south of Big Springs and Gandy Warm Springs near Gandy, Utah. The USGS maintained a gauge on Warm Creek downstream of Gandy Warm Springs from 2006 to 2019, but no longer collects data at that site. Expanding the UGS surface and groundwater monitoring networks to these springs could provide additional information for ongoing springsnail monitoring efforts.

The UDWR has recently developed a Conservation Agreement and Strategy for Sub-globose Snake Pyrg aimed at restoring the population and distribution of this species at Gandy Warm Springs. A key part of this effort involves understanding how past or present hydrologic changes impact the population. This could be achieved by comparing springsnail densities against groundwater models specific to Gandy Warm Springs built from the USGS Warm Creek gauge data and data from regional and local groundwater monitoring wells. Sub-globose Snake Pyrg populations may be too low to effectively observe any density changes and other springsnail species may need to be used as a proxy. A better understanding of the relationship between water availability and springsnail populations is crucial to UDWR efforts to preserve Sub-globose Snake Pyrg.

Table 13. *Key hydrologic metrics important for springsnails.*

Metric	Effect to Springsnails	Notes/Difficulties
Spring discharge	Decreased spring flows have been linked to reduced habitat by affecting channel width, water depth and velocity, and ability to buffer temperature (Morrison and others, 2013), but may also affect food abundance (Lepitzki, 2002). Drastic decreases in discharge may ultimately result in total dewatering and population loss.	UGS maintains flow gages at several of the springs known to support these species including: Twin Springs, Foote Spring, Clay Spring, and several of the Stateline Springs
Groundwater depth	Groundwater levels and spring discharge are positively correlated (Masbruch and Brooks, 2016) and could serve as a proxy for spring flow for springs lacking a UGS gage.	May need to use regional UGS groundwater monitoring wells to capture-long term trends and groundwater levels for springs on the periphery of Snake Valley.
Water levels	Water depth affects dissolved oxygen, temperature, and amount of habitat (Morrison and others, 2013).	Changes in water levels affecting springsnail populations may be within the margin of error for transducers; many of the springs supporting these species exist outside the wetland piezometer monitoring network.

Aerial Imagery

Aerial photographs can be used to estimate the extent of two variables important for sensitive species—vegetation cover and surface water extent—as well as trends in those variables over time. Landsat data provide aerial images at 30-m resolution at least monthly with data extending back to at least 1984. Landsat data have been used to relate groundwater declines to declining NDVI (a measure of plant health that can be used to identify wetland vegetation and vigor) in a small spring system in Snake Valley (Huntington and others, 2016) and to estimate surface water extent in the western United States and globally (Donnelly and others, 2020; https://global-surface-water.appspot.com). The coarse resolution of the data makes it challenging to detect smaller pools of water or water under vegetation, though constrained spectral mixture analysis can obtain proportional estimates of water in each pixel to provide more accurate estimates of surface water in areas with interspersed vegetation or turbid water (Donnelly and others, 2020. Google Earth Engine and ESRI Living Atlas provide preprocessed NDVI data derived from Landsat data. Landsat data can be used to detect larger-scale trends in surface water and wetland vegetation over time, but may not be as useful for examining patterns of interspersion between open water and vegetation or estimating the full extent of surface water due to issues with resolution and dense vegetation obstructing images. Variations in inundated and vegetated areas could be compared to historical climate records qualitatively and statistically to evaluate climatic controls on surface water and vegetation over many years.

Higher resolution aerial photographs are available from Sentinel, HRO, Google Earth, Hexagon, and NAIP, though these data generally have poorer temporal resolution, with photographs captured yearly or less frequently. The UGS also maintains historical aerial photographs in its database, which may be useful for assessing long-term changes. Higher resolution aerial imagery could be used in conjunction with hypsometric curves (discussed below, used for estimating surface water extent at different groundwater elevations) and detailed elevation data to understand the extent of open and vegetated water at varying depths within wetland complexes.

New imagery could supplement existing layers or even be used as a new method for conducting annual monitoring of vegetation and surface water. The Utah Department of Natural Resources (DNR) currently operates numerous unmanned aircraft systems (UAS), colloquially referred to as drones. The UAS at the DNR can currently collect multi-band imagery, which is useful for vegetation and saturation mapping. The UAS can also create digital elevation models using overlapping photographs and GPS ground control with a process known as structure from motion (photogrammetry). However, DEMs created using structure from motion cannot penetrate vegetation and therefore cannot measure bare earth elevation.

Hydrologic Studies

Hydrology determines habitat suitability for sensitive species. Area of inundation (water extent), water depth, and water temperature are key metrics controlling habitat suitability for Least Chub and Columbia Spotted Frogs. Understanding how these metrics change over time and the relative contribution of different drivers (climate, anthropogenic activities) and predicting these metrics under different scenarios could help predict the fate and impact of sensitive species in the region.

Some work has linked groundwater extraction to changes in the Snake Valley wetland systems. The U.S. Geological Survey has completed groundwater models that simulate impact of groundwater pumping on the spring discharge that supports Snake Valley wetland systems (Halford and Plume, 2011; Masbruch and Gardner, 2014; Masbruch and Brooks, 2017; Masbruch, 2019). Grover (2019) closely examined the relationship between groundwater depths, surface water depths, and Least Chub populations in Leland Harris. Grover (2019) found that groundwater levels explained 97% of the temporal variation in surface water levels, and groundwater levels were best predicted by evapotranspiration rates from the previous three months, as well as a small but significant relationship with the current month's precipitation. A 1.33-ft reduction in groundwater levels, such as that which occurred between February and August of 2013, led to an 81% loss of water volume. Two pending applications for withdrawal within 5 miles of Leland Harris are predicted to result in a 1.17-ft reduction in shallow groundwater levels within five years, according to simulation modeling by Masbruch (2016).

Hypsometric curves show the relationship between water level elevation and area of inundation, which can then be used to show how the amount of available flooded habitat changes with changing groundwater levels (Inkenbrandt, 2020). Hypsometric curves are built using detailed elevation data. Lidar elevation data at 1-meter resolution, flown in summer of 2009, exists for most Snake Valley wetland areas. The available lidar includes elevation details of areas that are typically submerged in the spring, though it does not have data for deeper pools and other areas that were flooded when the lidar was flown. In the near future, the DNR proposes equipping a UAS with basic lidar instrumentation to allow for calculation of bare earth elevations, which could be compared with existing lidar data. The UAS could collect lidar data during the next low-water year to obtain elevation data for areas that were submerged in 2009. Bathymetry data, information on the shape and elevation of underwater terrain, would also provide the elevation data necessary for developing hypsometric curves. Bathymetry data could be obtained by collecting water depth across transects in flooded parts of wetlands. Aggregated water level elevation data from the wetland piezometers can provide mean values for the time periods of interest to calibrate the hypsometric curves. The hypsometric curves can be checked using the surface water extent data calculated from aerial imagery analysis, described above.

Many wetland complexes in Snake Valley have multiple areas of discrete and diffuse discharge, and pools can become disconnected from flow during periods of low water, so multiple measurement points are needed to develop good hydrologic estimates. Surface water extent estimates derived from hypsometric curves can be specific to life stages and habitat important to sensitive species, such as the extent of shallow water during the Columbia Spotted Frog breeding season.

Once hypsometric curves are developed, we could conduct a time series regression analysis. Data from water elevation in individual piezometers, complex-wide estimates from hypsometric curves, and aerial imagery analysis could be related to climate and pumping data. Using an approach similar to Masbruch and others(2016a), we could quantify major shifts in climate and hydrology over time, examining temperature data as well. Masbruch and others(2016b) used annual PRISM and SNOTEL data with water level data from selected wells to measure the frequency and effect of higher-than-average precipitation events on groundwater level fluctuations. We can use well and piezometer data to conduct a similar analysis, looking at the impacts of both years with higher- and lower-than-average precipitation events. The extreme years would be the domains that bracket regression analysis, regressing the time series in between major shifts. We would identify each year where a major shift in groundwater level or temperature occurred and examine the amount and rate of change associated with that shift. The resulting output of such analysis would be the time intervals of significant recharge events, rate of change between each shift, and an estimate of the magnitude of recharge volume contribution.

Time periods between major recharge events can be closely examined by performing regressions on climate and water levels. To relate climate to water levels, previous studies used regional climate data, including four valley stations (Callao, Partoun, Eskdale, Great Basin National Park) and two SNOTEL stations (Wheeler Peak and Takka Wiiya) (table 5). Hurlow and Inkenbrandt (2016) and Hurlow (2014) found that water years having precipitation that greatly exceeded the mean precipitation caused a step change in groundwater levels in many of the Snake Valley monitoring network wells. Examining the groundwater response to extreme variations in precipitation and temperature could allow for more accurate predictions and better understanding of the relationship between climate and groundwater levels and may provide insight into the relationships among climate, groundwater, spring discharge, surface water, habitat, and species populations. The most challenging parts of this analysis may be isolating the primary environmental variables that influence sensitive species populations and accounting for possible time-lags between cause and effect (e.g., whether a particularly wet winter season supports beneficial habitat and spring discharge beyond that water year).

Part of the hydrologic examination could include a comparison of vertical hydraulic gradients in spring-gradient wells (i.e., the magnitudes and changes in relative water level elevations in adjacent wells that are open to the aquifer at different discrete depth ranges) and how they relate to flows. Vertical hydraulic gradient controls groundwater flow to springs and is determined by the groundwater potential at different depths in the aquifer. The vertical hydraulic gradient can change as a result of climatic or anthropogenic influence. Spring-gradient wells are a proxy to spring flow where flows are diffuse or hard to measure. Spring-gradient wells are currently located at the Leland Harris, North Gandy Salt Marsh, and Twin Springs complexes; additional wells could be added to other complexes such as South Gandy Salt Marsh, Central Spring, and the southern part of Leland Harris.

With the changes observed in piezometers, wells, and surface flow sites as a check, we could then use existing MODFLOW model outputs (table 14) to quantify predicted hydrologic changes in spring systems. The MODFLOW model has been run for different pumping scenarios, and climate could be adjusted for varying climate scenarios. We could check the current conditions against the predictions from various scenarios to see which scenario best matches the current conditions.

The model data, climate data, hydrologic data, and hypsometric curves could then be used to establish predictive models to determine how changes in precipitation, groundwater pumping, and evapotranspiration drive changes in hydrology (Inkenbrandt, 2020).

By building on existing efforts to examine these data (Hurlow and Inkenbrandt, 2016; Grover, 2019; Inkenbrandt, 2020), we can establish a link between species, climate signal, and water levels using time-series statistical analysis. We would split hydrographs into segments based on major recharge events and regress to evaluate trends for each segment. Some links can be established by comparing trend analyses of different datasets for specific time intervals. The temperature data, which have yet to be examined in great detail, could also be used, as previous studies have shown that water temperature affects sensitive species populations.

Table 14. Simulated drawdowns and declines in flow based on MODFLOW simulations conducted by the USGS.

Site Name	Discharge Type[1]	Steady-State OFR 2019-1083[2] Scenario E				Transient OFR 2017-1026[2] Scenario 3			
		Simulated Pre-development Level	Projection of Existing Water Rights	Simulated Pre-development Flow	Existing Water Rights	30 yr Simulation		100 yr Simulation	
		Simulated Groundwater Elevation (ft amsl)	Simulated Decline (ft)	Simulated Discharge (ac-ft/yr)	Simulated Decline (%)	Simulated Capture (ac-ft/yr)	Simulated Capture (%)	Simulated Capture (ac-ft/yr)	Simulated Capture (%)
Big Springs	Spring	5576	6	7,063	39	-142	-2	-302	-4
Clay Spring	Spring	5359	15	281	100	46	19	78	32
Dearden Springs	Spring	5436	7	4,626	69	-118	-2	-181	-3
Foote Reservoir Spring	Spring	4803	2			25	1	111	5
Gandy Salt Marsh Lake Spring Complex	ETg	4776	2	623	5	0	0	0	0
Gandy Salt Marsh Seep	ETg	4753	1	115	17	0	0	0	0
Leland Harris Spring Complex	ETg	4753	11	201	65	0	0	0	0
Miller Spring	Spring	4732	21	261	100	155	51	260	86
Snake Valley North Spring Complex	ETg	4,700	38	46	100	7	39	13	70
Snake Valley South Spring Complex	ETg	4705	27	100	100	7	30	12	55
Springs feeding Gandy Salt Marsh Lake	ETg	4772	2	623	5	0	0	0	0
Twin Springs	Spring	4802	2	3,640	19	13	<1	71	4

[1] ETg = groundwater evapotranspiration

[2] OFR 2019-1083 (Masbruch, 2019) is steady-state, which is the equilibrium that the system would come to over an indeterminate amount of time, and OFR 2017-1026 (Masbruch and Brooks, 2017) is transient, meaning that time brackets are defined. Both models assume consistent climatic conditions over the duration of the model run and are based on approved water rights, whether or not they are currently developed.

Approach

We suggest leveraging the available existing data to better understand how climate, hydrology, sensitive species counts, and vegetation change over time. Aerial photography, lidar, hourly water level and temperature measurements, climate station measurements, wetland maps, amphibian egg mass counts, fish counts, and limited springsnail density data all exist for the region. In combination, these data can be used to predict the impacts of hydrologic changes on sensitive species populations in the region.

We have discussed in detail a number of potential studies above and outlined them in table 15. Most studies could be completed with existing data, though many would be improved by the results of other studies listed in the table. For example, hypsometric curves could be constructed with existing lidar data, but would be improved by the collection of more detailed elevation data either from bathymetric measurements or lidar flown in an extremely dry summer. Species regression models predicting egg mass or Least Chub counts could be modeled using simple water level elevations or more detailed surface water extent estimates from hypsometric curves or aerial imagery analysis. Studies could be completed in a number of ways. The UGS has the technical expertise to conduct hydrology and aerial imagery studies as well as some of the data analysis for sensitive species. Studies that require field surveys for sensitive species would be best carried out by the BLM, UDWR, and graduate student collaborations.

We suggest first conducting aerial imagery analysis with existing surface water extent and NDVI data, checking results against high resolution imagery when available to determine how well the coarse resolution data captures on-the-ground trends. Next, we recommend developing species regression models to look for basic relationships between habitat parameters and species success using readily available hydrologic and climate variables. As an example, a model of egg mass numbers in a wetland complex may include mean springtime water elevation from a nearby well, mean springtime air temperature, open water cover from aerial imagery analysis, and egg mass numbers from the previous one or two years. This initial modeling effort would be improved on in future iterations with improved surface water estimates from hydrologic analysis, water temperature data, and additional years of species data, but would be a useful first exploration to look for initial relationships between variables.

Next, we suggest focusing on hydrologic studies, first developing hypsometric curves to predict surface water extent based on groundwater elevation. Next, we could conduct spring-gradient studies to quantify how gradient and flow to the springs changes over time. Regression and step-change analysis will provide insight of how climatic factors influence wetland hydrology, and existing MODFLOW predictions are our best approach to understand how pumping does and will influence wetland hydrology. Once a better understanding of hydrology is established, we will develop some understanding of periodicity of population trends in sensitive species. We will construct models and correlations between species data and habitat metrics of interest (e.g., wetland area, open water, vegetated shallow water, temperature). This analysis could potentially provide recommendations about more intensive or more years of data needed for Least Chub, Columbia Spotted Frog, and mollusk populations.

Most detailed species field data collection could occur concurrently with the studies discussed and be used to help identify important locations and pathways within wetland complexes and refine our understanding of habitat needs. Our limited understanding of mollusk habitat requirements stems from the scarcity of available data and would be greatly increased by collecting several consecutive years of density data and associated habitat parameters (e.g., water depth, flow, vegetation cover).

The suggested approach will help identify life stages and locations that are important for population persistence and create a better understanding of the relationship between population dynamics and habitat conditions. The work will provide better information about how wetland complexes have changed over time and how those changes are related to climate and hydrology. Finally, the work will allow us to determine the relationships between hydrology, habitat coverage, inundation area, and species counts, and to predict habitat availability, and thus species counts, under different climate and pumping scenarios (actual decrease in inches or surface area). A major limitation of this work will be uncertainty associated with making predictions beyond the observed range of climatic and hydrologic conditions, particularly in how adaptable species may be to major changes in habitat.

ESTIMATED COSTS AND FUNDING SOURCES

Maintaining the current Snake Valley monitoring network is expected to cost approximately $14,000 in Fiscal Year 2021 (FY21) in direct costs, excluding costs related to transducer replacement. These costs include personnel and travel costs associated with two surveys per year to download water level data from transducers from 50 piezometers, and data processing costs for converting transducer data to water elevation data, addressing data anomalies, and publishing water level data to the UGS

Table 15. *Summary of recommended studies.*

Name	Brief description	Input data	Output	Section Where discussed
Species regression models	Develop regression models to predict annual sensitive species metrics (egg mass or CPUE) based on predictors including hydrology, open water cover, temperature, and population metrics from previous years	Annual sensitive species data, hydrology data, open-water and vegetation estimates from imagery analysis, temperature data	Better understanding of relationship between sensitive species data and covariates, as well as lags in response to covariates.	Sensitive Species
CSF egg mass location analysis	Evaluate degree of fidelity of egg mass deposition locations and relationship with climate data	Egg mass count and location data; climate or groundwater level data	Identification of locations used consistently for breeding and changes in use based on wet versus dry years	Sensitive Species-CSF
CSF mark-recapture	Conduct mark-recapture study of CSF using pit tags	Several years of mark-recapture data on CSF and subsequent analysis	Revised male to female sex ratios, more accurate population estimates, and better understanding of cohort survival through sensitive periods	Sensitive Species-CSF
Least Chub refuge identification	Identify areas in wetland complexes used as summer and winter refuges by Least Chub	Data exist for Leland Harris (Grover 2019); field surveys in Gandy Salt Marsh and Bishop Springs during key time periods	Identification of areas used by Least Chub for summer and overwintering refuges	Sensitive Species-Least Chub
Least Chub habitat connectivity	Study to understand degree of connectivity between spawning and summer refuge habitats	Identification of refuge sites, detailed elevation data, and potentially Least Chub mark-recapture data	Better understanding of how changes in surface water levels may limit accessibility to key habitats	Sensitive Species-Least Chub
Least Chub mark-recapture	Conduct mark-recapture study of Least Chub using injected polymers or other technique over several years	Several years of mark-recapture data on Least Chub and subsequent analysis	Data on individual movement within marshes, more accurate estimates of population size and cohort survival	Sensitive Species-Least Chub
Springsnail population and habitat monitoring	Continued monitoring of habitats and macroinvertebrate communities at locations with sensitive mollusks	New data collection	Population trend data; data to examine relationship between mollusk densities and covariates including water availability	Sensitive Species-Mollusks
Spring monitoring	Establish new spring monitoring stations at springs supporting sensitive springsnails that are outside the UGS monitoring network	New water level or discharge monitoring stations established at White Rock Cabin Springs and Gandy Warm Springs	Data that could be used to evaluate changes in spring flow over time at key sites	Sensitive Species-Mollusks
Gandy Warm Springs springsnail study	Compare Sub-globose Snake Pyrg density data (or data from similar species) to hydrologic data	Springsnail density data, discharge estimates or groundwater model for Gandy Warm Springs built from USGS gauge data and data from regional and local monitoring wells	Better understanding of relationship between water availability and springsnail populations	Sensitive Species-Mollusks
Lidar data collection	Create new DEM for Snake Valley wetlands that captures low water periods	Lidar data collected with drone or airplane and processed to produce DEM	Improved elevation data for subsequent studies	Aerial imagery
Bathymetry	Develop elevation model for underwater areas	Collect precise elevation data along transects in areas that are consistently underwater	Improved bathymetry layer for use in subsequent studies	Hydrology
Cattail/bulrush encroachment and water cover	Use aerial imagery or Landsat data to map extent and interspersion of vegetation and open water over time	Aerial imagery and Landsat data	Annual (or less frequent) data on extent of wetland vegetation and open water	Aerial imagery
Hypsometric curves	Calculate relationship between area of surface water cover and surface water elevation	Existing or new lidar data	Charts and equations to determine area of surface water cover based on elevations from piezometers	Hydrology
Time series regression	Split hydrographs into segments based on major recharge events; regress trends for each segment	Aggregated piezometer, climate, egg mass count, and species count data	Correlation between time series trends observed for different data sets; tying species data to hydrology	Hydrology
Hydraulic gradient analysis	Compare groundwater elevations of nested piezometer for each spring gradient well over time	Time series of groundwater elevations; Spring gradient wells	Proxy of relative contribution of groundwater flow to spring systems	Hydrology
MODFLOW examination	Compare existing MODFLOW outputs and predictions to current conditions	Well and piezometer data	Estimate of current impacts by pumping; predictions of future impacts to spring systems	Hydrology

Groundwater Data Portal. Costs also include personnel time for UGS employees to attend meetings and present study results. These costs are expected to increase at a rate similar to inflation due to cost of living raises and increases in vehicle rental, vehicle mileage, and per diem rates. Increases or decreases in the number of active piezometers would increase or decrease costs to a minor extent. The largest decrease in costs would occur if enough piezometers were inactivated to require fewer days in the field each season to download data. Based on the age of the transducers and current number of spares, we estimate that transducer costs will be $14,000 between 2020 and 2030 or $1,400 per year to replace and refurbish transducers. The UGS has an approved indirect rate of 36.11% in FY21, but capped its indirect rate at 10% for the hydrologic monitoring work.

Funding for the Snake Valley work in FY21 was approximately 19% UGS, 23% BLM, and 58% Endangered Species Mitigation Fund (ESMF). However, each of these funders also contributed to maintenance of other wetland piezometer networks, in Tule Valley for the BLM and Mills and Mona for the UGS and ESMF, as part of the same contract. Although not necessary to the Snake Valley project, the additional networks contribute to the overall success of the Snake Valley project through increased efficiencies from shared activities such as preparing for field work, updating the database, and contacting the transducer manufacturer for transducer repair and replacement. The Tule Valley work provides funding for a second trip to the region each season, which makes it less expensive for the UGS to return to Snake Valley in the event that unforeseen circumstances prevent us from completing all downloads on the first trip to the area. Funding for work in all three areas in FY21 includes $10,000 from the BLM to support Tule Valley and Snake Valley piezometers and $10,534 from ESMF and $3,511 from the UGS to support Mills, Mona, and Snake Valley piezometers.

RECOMMENDATIONS AND CONCLUSIONS

Piezometer data are crucial to our understanding of Snake Valley wetland hydrology. Direct water level measurements over time are the best way to establish baseline information on hydrologic conditions under different climate scenarios. Baseline data are crucial for determining whether changes in water levels are due to climate change, drought, groundwater extraction, or a combination of factors. Hourly piezometer data can also serve as a proxy for key habitat metrics for sensitive species, such as March 1 to April 15 groundwater levels representing the extent of Columbia Spotted Frog breeding habitat. Piezometer data are also crucial inputs for developing hypsometric functions and modelling the relationship between climate and inundation using past data or forward modelling habitat changes that may occur from changing climate or groundwater pumping conditions. Inkenbrandt (2020) also demonstrated that piezometer data can be used to examine variations in wetland inundation, understand wetland trends, determine wetland hydroperiods, and estimate evapotranspiration and groundwater recharge rates. We also anticipate that data from the piezometer network may be used for future water rights application protests and to help with water rights administration.

We recommend maintaining the Snake Valley hydrologic monitoring network at its current size. The network has already been pared down to 50 active piezometers based on recommendations from stakeholders. Further minor reductions in the network would only result in a small amount of savings since much of the costs are related to travel to the region and travel between different groups of wells rather than the cost of downloading individual transducers. We have automated the transducer data processing and workflow to the UGS database, so reducing the number of active piezometers will not significantly affect data management time or efficiency. Furthermore, individual piezometers within a wetland complex can show different trends (e.g., five wells each within Foote Reservoir show increasing and decreasing water level trends); it is important to get adequate coverage within complexes to capture variation in effects and determine if there is an overall decline in water level or just shifting habitats.

We recommend maintaining the current distribution of active piezometers since prioritization was based on substantial input from stakeholders. The distribution could be reevaluated if future analysis finds inadequate coverage of sensitive species habitats or insufficient resolution for further hydrologic analyses. There are two known gaps in the current distribution where we lack detailed hydrologic data at key habitats. We recommend initiating monitoring at White Rock Cabin Springs in Hamlin Valley on the Utah-Nevada border and reestablishing the former USGS spring flow monitoring at Gandy Warm Springs near Gandy, Utah, to better monitor springsnail habitat at these springs which are the sole known habitats for Sub-globose Snake Pyrg and Hamlin Valley Pyrg.

Additional data collection in the region may make it easier to meet the project goal of connecting hydrologic conditions to species habitat and species population parameters. First, we recommend collecting species data on an annual basis to make it easier to analyze the effects of water levels on populations. Population measures in a given year are likely to be strongly tied to population numbers in previous years. For example, increased survivorship of juvenile Columbia Spotted Frogs may result in two or three years of increased populations, and thus increased egg mass counts, as this cohort matures and begins breeding. Annual surveys will allow understanding and control for these types of fluctuations to create a more robust analysis of the effects of water levels on populations. Columbia Spotted Frog and Least Chub have at least one site with 23 and 16 years of continuous year to year data, respectively, which will make a good starting place for analysis. Detailed springsnail data across different hydrologic conditions is lacking. More intensive studies of sensitive species could also benefit the project, as discussed above. Last, any analysis of the effects of hydrology on sensitive species should include data on important habitat covariates such as vegetation cover and water temperature. The former could be analyzed using existing or new aerial imagery or Landsat data. The latter could potentially be studied by deploying relatively inexpensive temperature loggers in key aquatic habitat locations and leveraging existing temperature data from weather stations.

The majority of studies proposed by this project could be done with existing data or with relatively minor inputs of new data. We recommend conducting some of the initial analysis that will allow us to look for relationships between hydrology, habitat, and sensitive species. The initial analysis will be helpful for determining whether simple relationships exist between habitat parameters and commonly collected sensitive species parameters or whether more detailed species data are needed to understand species' response to varying water levels. Initial analysis should also help determine the extent to which new lidar, imagery, or bathymetry data are needed to successfully conduct hydrologic analysis. Once initial analysis is complete, we could seek funding to fill any data needs and then complete a detailed hydrologic analysis for the region following the approach outlined above.

Funding for this work could come from multiple sources. A small increase in annual funding from the current project funders (BLM, ESMF, UGS) would allow us to conduct some preliminary analysis each year with existing data that could help push the project forward. Funding for intensive wildlife studies would likely need to be pursued by the UDWR and could come from the ESMF or from applicable grant programs such as the Desert Fish Habitat Partnership or State Wildlife Grants. Funding for more intensive hydrologic research could come from the ESMF, BLM, the Utah Division of Water Rights, annual legislative funding for hydrologic monitoring and analysis in Snake Valley, the Watershed Restoration Initiative, or other grant programs. We recommend conducting several years of preliminary analysis and then seeking funds to conduct a larger study. Last, we recommend evaluating all data and reevaluating the project as a whole again in another five to ten years.

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APPENDIX A

Species Accounts

SPECIES ACCOUNTS

Detailed species accounts for the seven sensitive species potentially occurring in springs and wetland complexes of Snake Valley were prepared by UDWR biologists, Drew Dittmer and Kate Holcomb. These accounts describe the distribution of each species, broadly and within Snake Valley, and broad habitat requirements. Where possible, these accounts summarize the best known information regarding specific habitat parameters, life history, and population demographics. The level of detail provided in each species account depends on the extent of available literature to review, with vastly greater bodies of literature existing for charismatic, broadly distributed species.

Least Chub

The Least Chub (*Iotichthys phlegethontis*) is a small fish having a known maximum length of 76 mm (Thompson and others, 2015). The species is sexually dimorphic with males being smaller than females, and during spawning, males show a bright reddish-gold band of coloration running the length of the body (Sigler and Sigler, 1996; Thompson and others, 2015). Least Chub are endemic to the Bonneville Basin, and all known populations occur in the state of Utah. Historically this fish occurred throughout the Bonneville Basin, in riverine backwaters of the Salt Lake City area, freshwater ponds and swamps around Great Salt Lake, and springs in western Utah (Hanks and Belk, 2004; Thompson and others, 2015). Due to landscape alterations, water diversions, and the introduction of nonnative fish species, the distribution of Least Chub has been greatly reduced. The species is only presently known from six extant populations: one south of Utah Lake in the Mona Springs area, two in the Sevier Drainage, and three in Utah's West Desert. Several refuge populations have also been established in suitable habitats in Utah, all within the historical range of the species.

In general, Least Chub are believed to prefer habitats that are characterized by slow flowing and lentic waters, and they can tolerate relatively high alkalinity levels. Detailed habitat descriptions are mostly from studies of Least Chub in the spring complexes of Utah's West Desert. In the more arid areas of their distribution, Least Chub spend much of the year in the deeper waters near spring heads. In the spring and summer, the fish often migrate to shallower seasonally flooded areas to spawn (Grover, 2019). The presence of some vegetation is important in these spawning habitats as the eggs of Least Chub are adhesive and attaching to aquatic plants allows for oxygenation of the eggs prior to hatching (Sáenz, 2014).

Least Chub are intermittent spawners, meaning that females carry eggs in varying stages of development and they can lay their eggs across a relatively long time span. Adults begin moving from their deeper-water habitats to shallow spawning habitats in late spring, and this movement is triggered by water temperatures at or exceeding 16°C. Spawning migrations can happen well into late summer if water temperatures and conditions are favorable. Spawning females may lay between 200 to 3000 eggs, approximately (Crawford, 1979). In addition to shallow habitats providing vegetation for egg attachment, the warmer temperatures of the shallow waters aid in a faster hatching time for eggs and increased growth rates of newly hatched Least Chub. Eggs have been documented to hatch in as little as two days at temperatures of 22°C (Crawford, 1979). The ideal temperature range for the growth rate of newly hatched Least Chub was determined to be between 20.7° and 24.4°C, and maximum growth occurred at 22.3°C (Wagner and others, 2005). Least Chub mature and are able to breed within one year of hatching (Sigler and Sigler, 1996).

While it is well documented that shallow-water habitats are important for breeding and early life-stage of Least Chub, relatively deep-water habitats are also critical to the persistence of the fish species. This is especially true in the most arid and isolated areas of the species' distribution where deeper-water habitats provide the fish with a refuge from temperature extremes, droughts, low-oxygen levels, and some protection from avian predators (Sáenz, 2014). Access to both seasonally available shallow water breeding habitat and deeper water refuge habitat is especially important for Least Chub populations in the Snake Valley region of western Utah. Fluctuating groundwater levels have been identified as a limiting factor to the seasonal connectivity of shallow-water and deep-water habitats that support Least Chub populations in the Snake Valley (Grover, 2019). In addition to fluctuating water levels, vegetation encroachment has also been identified as a source of habitat fragmentation that negatively impacts Least Chub by reducing the size and connectivity of open water habitats (Dittmer and others, in prep; Sáenz, 2014; Grover, 2019). The UDWR has used prescribed burns as a means to reduce vegetation encroachment and improve habitat connectivity for Least Chub. While UDWR considers improper grazing to be a threat to Least Chub habitats (Utah Wildlife Action Plan Joint Team, 2015), Sáenz (2014) observed that well managed cattle grazing can actually reduce vegetation encroachment and benefit Least Chub habitat.

Several conservation actions have been implemented to address the persistence of Least Chub populations. Mock and Miller (2005) recommended that three genetic management units be maintained to secure genetic diversity for the species. This recommendation was included in the Least Chub Conservation Agreement and Strategy (Least Chub Conservation Team, 2010; Least Chub Conservation Team, 2014) and applied by Thompson and others (2015) in the establishment of refuge populations to increase the redundancy of Least Chub populations on the landscape. However, studies assessing and analyzing how abiotic and biotic factors influence Least Chub population dynamics are still needed. Due to the relatively small size of this species, mark-recapture studies would be challenging. However, techniques using injected elastomers or neutral dyes have been applied to population studies of small fishes and tadpoles in arid environments (Frederick, 1997; Jung and others, 2002), and these methods may be useful for future population-level studies of Least Chub.

The Least Chub is often described as short lived and slow growing. Individual fish rarely live longer than three or four years, and it takes the bulk of that time for most individuals to grow larger than 50 mm in length (Sigler and Sigler, 1996; Sigler, 2016). While these life-history traits are typically adaptive for Least Chub, rapid anthropogenic changes to the species' habitat and introduction of non-native fishes threaten the future persistence of self-sustaining Least Chub populations. The Least Chub is identified as a species of greatest conservation need (SGCN) in Utah's Wildlife Action Plan (WAP, Utah Wildlife Action Plan Joint Team 2015). The WAP is the document that aids the Utah Division of Wildlife Resources in prioritizing conservation and management efforts for SGCNs. The WAP identifies eight threats to Least Chub. Groundwater pumping and droughts are considered to pose a high and very high threat, respectively. Other threats identified in the WAP, from highest to lowest threat, include non-native and invasive fish species (very high threat), small and isolated populations (high threat), unauthorized species introductions (high threat), improper grazing (medium threat), non-native and invasive plants (medium threat), and spring development (low threat). The Least Chub is currently not recognized as threatened or endangered by the U.S. Fish and Wildlife Service. However, between 1980 and 2014, the fish was petitioned for listing or considered a candidate species for listing multiple times.

Columbia Spotted Frog

Columbia Spotted Frogs (*Rana luteiventris*) are small frogs, 1.6 to 3.9 inches, in the family Ranidae. Their range spans southeastern Alaska to Alberta, Canada, and extends south through the Intermountain West with occurrences in Nevada and Utah representing the southernmost extent of the species (Dodd, 2013). The U.S. Fish and Wildlife Service recognizes three distinct population segments, Northern, Great Basin, and Utah, based on phylogenetic studies conducted by Funk and others (2008). Within Utah there are two recognized subclades which are distinct from the Deep Creek Range populations (Bos and Sites, 2001; Funk and others, 2008). This separation supports theories suggesting that Columbia Spotted Frog distributions in Utah are evidence of a range expansion from a single, relict population following the retreat of Lake Bonneville (Hovingh, 1997; Bos and Sites, 2001). As Lake Bonneville retreated, Columbia Spotted Frogs expanded north and east from a refugia population in Snake Valley (Bos and Sites, 2001) to establish populations along the Wasatch Front, Sevier River, and isolated springs and wetland complexes in the West Desert (Utah Division of Wildlife Resources, 2006). The wetland complexes in Snake Valley continue to support Columbia Spotted Frogs, and the species is known to occur at five locations within the Utah part of Snake Valley: Beck Springs, Miller Springs, Leland Harris spring complex, Gandy Saltmarsh, and Bishop Spring complex which includes the Foote Reservoir, Twin Springs, and Bishop Springs (Utah Division of Wildlife Resources, 2006).

Columbia Spotted Frogs are highly aquatic, and typical habitat in Utah includes permanent surface water such as spring pools, permanently ponded areas, or slow flowing, perennial streams (Utah Division of Wildlife Resources, 2006). Seasonally stable water temperatures, emergent vegetation density, water depths greater than one meter, and absence of predatory fish have been modeled as other important habitat factors (Welch and MacMahon, 2005; Arkle and Pilliod, 2015). Field observations from Idaho and Tule Valley, Utah, found active adult frogs in water temperatures ranging from 8° to 24 °C (Munger and others, 1996) and 17° to 29°C (Hovingh, 1993), respectively, and life history studies from Wasatch Front populations found them located in pools that were "continually spring fed" with a "temperature several degrees lower than other ponds in [the] specific area" (Morris and Tanner, 1969). Greater vegetation density and height have been shown to better predict occupancy, but Arkle and Pilliod (2015) identified an inflection point at roughly 40 percent shoreline cover (20 percent aerial cover); beyond this point, increasing vegetation density corresponded to decreasing likelihood of occupancy. Water depths greater than one meter may provide greater opportunities to escape from predators or overwinter below surface ice, but most likely indicate more permanent waterbodies (Arkle and Pilliod, 2015) as Morris and Tanner (1969) found frogs in shallow (50 to 80 centimeter), spring-fed pools along the Wasatch Front.

Breeding behavior varies within Utah and appears temperature dependent; starting earlier during warmer years, at lower elevations, more southerly latitudes, or in populations associated with thermal springs (Morris and Tanner, 1969; Hovingh, 1993). Tule Valley populations usually breed from early March to mid-April, but adults may emerge from hibernation in late February during warm years (Hovingh, 1993). Eggs are deposited shortly after adults emerge from hibernation but may be found in Tule Valley throughout the breeding season (Hovingh, 1993). Breeding and egg deposition occur in shallow pools with dense emergent vegetation; eggs are often communally deposited with many sites containing egg masses from several females. However, the number of eggs in a communal location can be highly variable from year to year (Hovingh, 1993; Dodd, 2013). Mature females lay a single clutch of eggs (Bull, 2005), with Utah populations typically depositing fewer eggs per mass (160 to 1200) than other populations (Morris and Tanner, 1969). Mature females in West Yellowstone typically breed every two to three years (Dodd 2013), but Bull (2005) observed most females breeding in consecutive years. Breeding behavior has not been explicitly studied in the Snake Valley populations. Oviposition studies from northeastern Oregon found oviposition sites were preferentially located in shallow water (mean depth of 13 centimeters), along the shoreline (mean distance from the shore of 1.10 meters), and in areas densely vegetated (>75% cover) by *Eleocharis*, *Carex*, *Glyceria* and other graminoid emergent species (Pearl and others, 2007). Pearl and others (2007) also found positive correlations between pond size and solar-warmed aspects to egg mass numbers. Adults may disperse from breeding ponds to suitable foraging and overwintering habitats (Bull and Hayes, 2001); dispersal distance and timing is condition-dependent with adults and fully-formed juveniles more likely to disperse at night, following rainstorms, or through covered habitats to reduce desiccation risk (Lingo, 2013). Eggs hatch within 12 to 21 days (Bull, 2005) and tadpoles may be found in Tule Valley wetlands from mid-March until early May (Hovingh, 1993). Development to fully formed juveniles with pointed snouts, absorbed tails, and rugose skin (Lingo, 2013) is greatly influenced by water temperatures but occurs throughout the summer and may last to mid-October (Morris and Tanner, 1969). Complete metamorphosis (Gosner Stage 46), independence from aquatic habitats, and possible overland dispersal occur in 122 to 209 days following egg deposition (Gosner, 1960; Morris and Tanner, 1969).

Columbia Spotted Frogs have strong fidelity toward breeding sites (Bull, 2005) and may be especially vulnerable to total reproductive loss during drought years (Davis and Verrell, 2005). Many ranids have developmental plasticity and are capable of accelerating development in response to decreasing water levels (Richter-Boix and others, 2011). The degree of plasticity varies by taxa, but ranids with similar life histories to Columbia Spotted Frogs—breeding in seasonal ponds, accelerated development at the cost of body mass—are capable of metamorphosing in roughly 80 percent of the optimum time (Richter-Boix and others, 2011; Patchett and others, 2018). Accelerated development and reduced body mass at metamorphosis are assumed to reduce juvenile survival during dispersal and into the next year (Chelgren and others, 2006; Patchett and others, 2018). Juvenile males studied in Oregon reached sexual maturity at 21 months and are capable of breeding following their second winter while females reached sexual maturity at 33 months following three winters (Bull, 2005). However, populations in central Nevada, and presumably Utah, reach sexual maturity earlier than Oregon populations, and males and females have been observed breeding after one and two winters, respectively (Bull, 2005). Columbia Spotted Frogs are sexually dimorphic, with mature females (greater than 2 years) significantly larger than mature males (Bull, 2005). Distinct size classes for both sexes also exist between 1-year-old frogs, 2-year-old frogs, and mature frogs (Bull, 2005).

Individuals have been aged to 12 years, but typical life span is shorter—3 to 8 years—and likely dependent on environment, population, and sex (U.S. Fish and Wildlife Service, 2015). Populations in cooler climates and females tend to survive longer than populations in warmer climates or males, respectively (Bull, 2005), with demographic studies in central Nevada determining the age of all captured males as three years or younger (Reaser, 2000). Size affects survivorship, with smaller adults at greater risk of desiccation and predation during dispersal and breeding (Patchett and others, 2018). Demographic studies of the closely related Oregon Spotted Frog (*Rana pretiosa*) (Chelgren and others, 2006) found different mortality rates between size classes, sex, and season, with small males during the breeding/post-breeding season (April to May) experiencing the greatest mortality. Females had greater overall survival rates than males, but experienced greater mortality during the summer (June to September) and fall redistribution (October) seasons. Males, regardless of size, experienced the greatest mortality during the breeding/post-breeding season. Males and females experienced the lowest mortality during the overwintering season (November to February). Demographic studies of Columbia Spotted Frog populations draw similar conclusions; mortality rates increase with decreased body size (Patchett and others, 2018) and females experience lower mortality rates (Reaser, 2000; Bull, 2005). These studies observed fluctuating rates of survivorship between sites and years, with populations—as determined by egg mass counts—varying by as much as an order of magnitude between years (Bull, 2005). These variations may be attributed to microclimate factors like persistence of water past the breeding season, unseasonably warm temperatures, and increased connectivity to other subpopulations (Bull, 2005; Reaser, 2000).

Mollusks

Five sensitive mollusk species are found in the Snake Valley region of Utah. One of these species is a mussel, Winged Floater (*Anodonta nuttaliana*); three species are springsnails, Longitudinal Gland Pyrg (*Pyrgulopsis anguina*), Hamlin Valley Pryg (*Pyrgulopsis hamlinensis*), and Sub-globose Snake Pyrg (*Pyrgulopsis saxatilis*); and one snail species whose presence in this area is questionable, Cloaked Physa (*Physa megalochlamys*). Cloaked Physa was historically collected from 13 sites in the Rio

Grande (Colorado), Snake Valley (Utah), Harney Basin (Oregon), and Upper Snake River (Idaho and Wyoming) by Taylor (1988). However, the species was not detected at the Snake Valley Site in Utah during subsequent survey efforts by Hovingh and Wu (Hovingh, 2018). Oliver and Bosworth (1999) include these mollusks in their literature review of rare mollusks of Utah.

Some of the species data collected during surveys are described as “density from kitchen sieve scoops.” In these situations, springsnail samples were collected following the UDWR’s mollusk protocols (Sada, 2011), which involves roiling substrate and vegetation for 3 seconds using a kitchen sieve (about 12 cm diameter with 1–1.5 mm mesh) in an area approximately 100 cm^2. Since a quadrat was not used it is difficult to ensure the 100 cm^2 area was consistently surveyed during each scoop; therefore, this should be taken into consideration when these density data are used in analyses.

In-stream habitat data (covariates) that can be quantitatively associated with density or abundance for these five mollusks are limited. Discharge is available from many of the springsnail surveys. Water temperature, DO, pH, and conductivity are also available for many of the springs, but they have not always been measured at each sample location. In some small springs (e.g., some of the Stateline Springs are <5 m long), these water quality measurements probably do not vary throughout the spring, but they are known to vary from the spring source to the terminus in larger spring systems like Clay Spring (Golden and others, 2007). Wetted channel width and water depth were collected at each scoop location in surveys by Kevin Wheeler (UDWR).

Future UDWR mollusk monitoring surveys in Snake Valley in fiscal year 2021 include Winged Floater at Pruess Lake and Longitudinal Gland Pyrg at Clay Spring. Surveys for Sub-globose Snake Pyrg at Gandy Warm Springs, Hamlin Valley Pyrg at White Rock Cabin Springs, and Cloaked Physa at Bishop Springs are planned for fiscal year 2022.

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APPENDIX B

Wetland Complex Maps

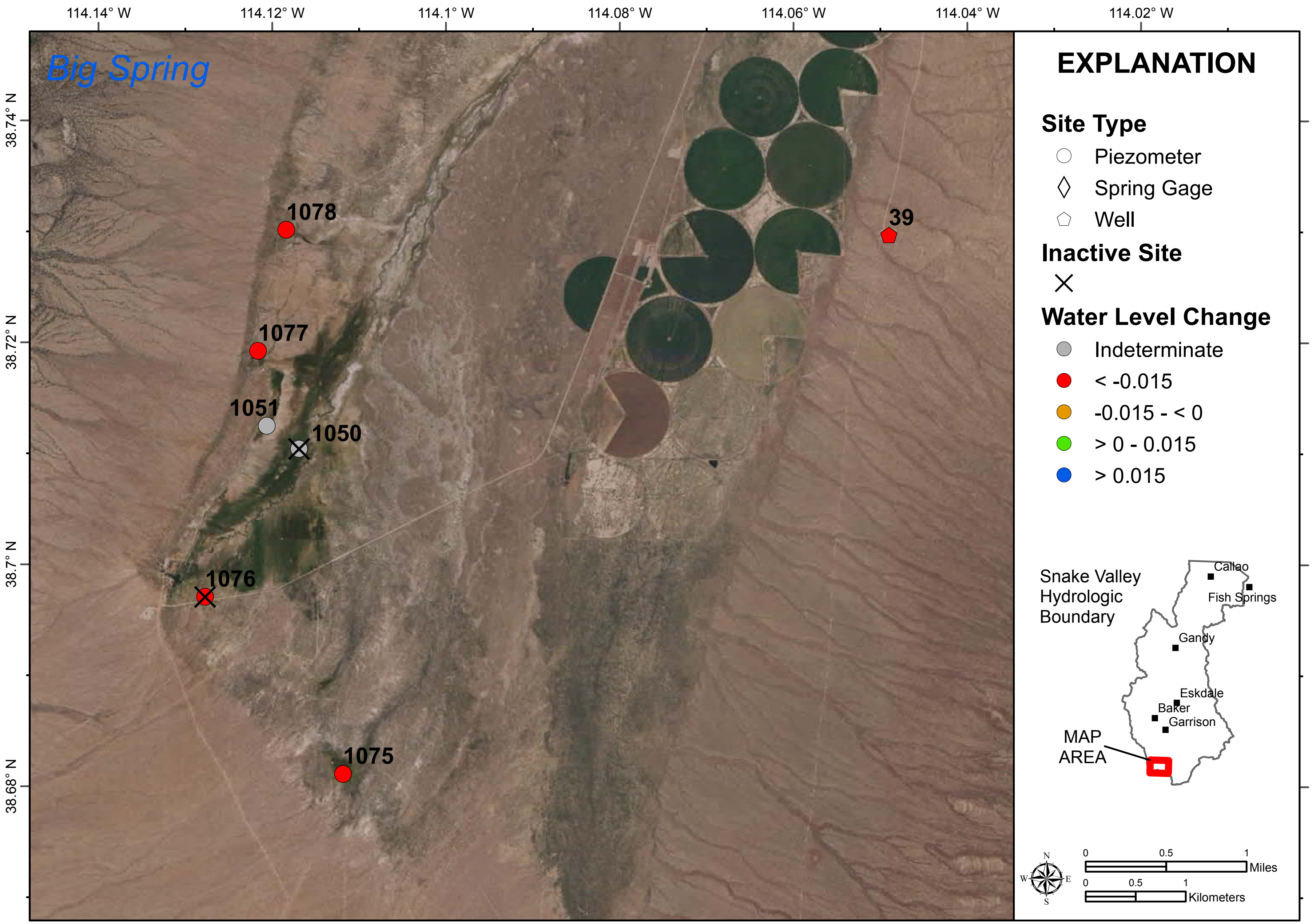

Figure B1. Hydrologic monitoring stations and associated trends at Big Spring. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

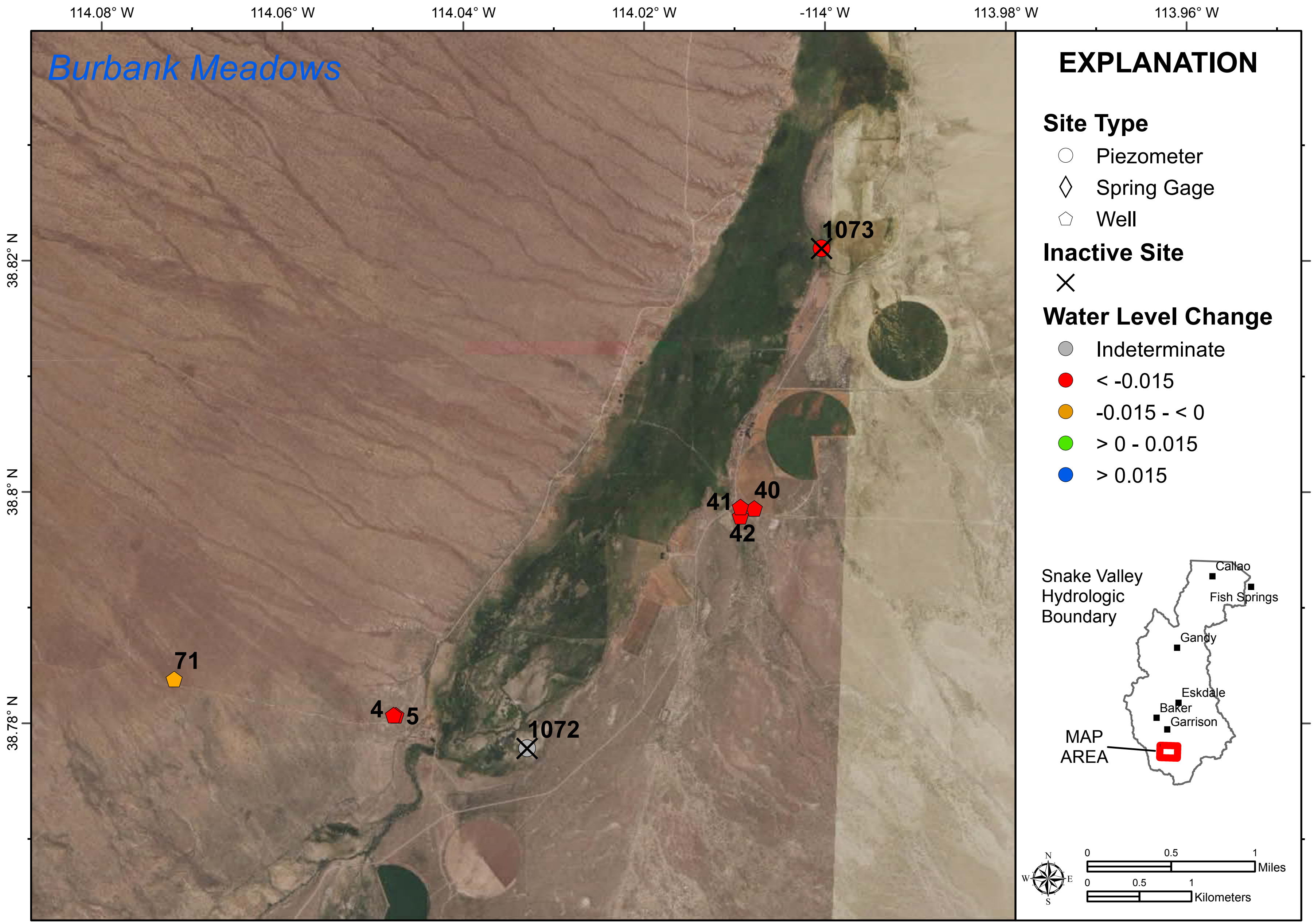

Figure B2. *Hydrologic monitoring stations and associated trends at Burbank Meadows. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".*

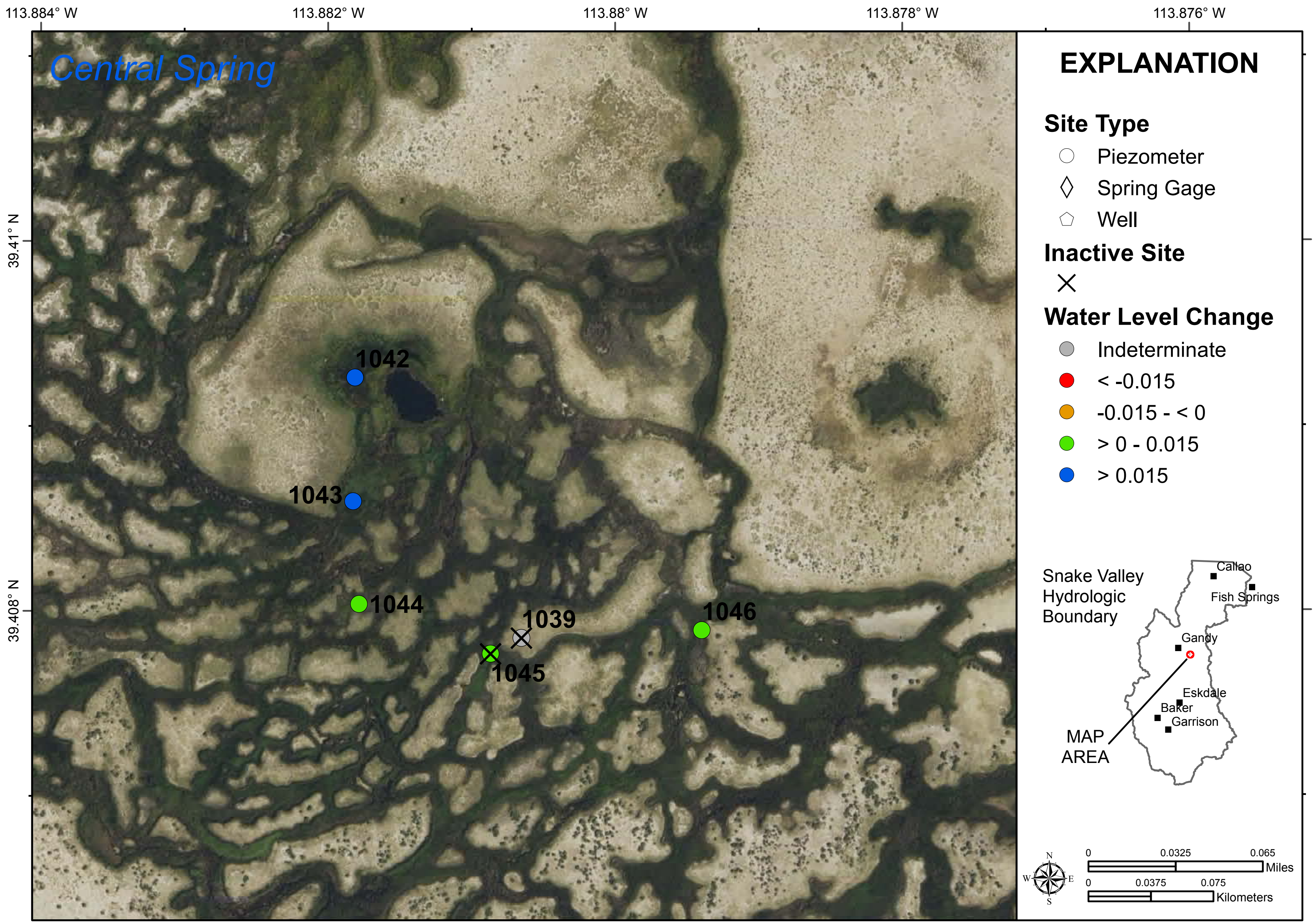

Figure B3. *Hydrologic monitoring stations and associated trends at Central Spring. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".*

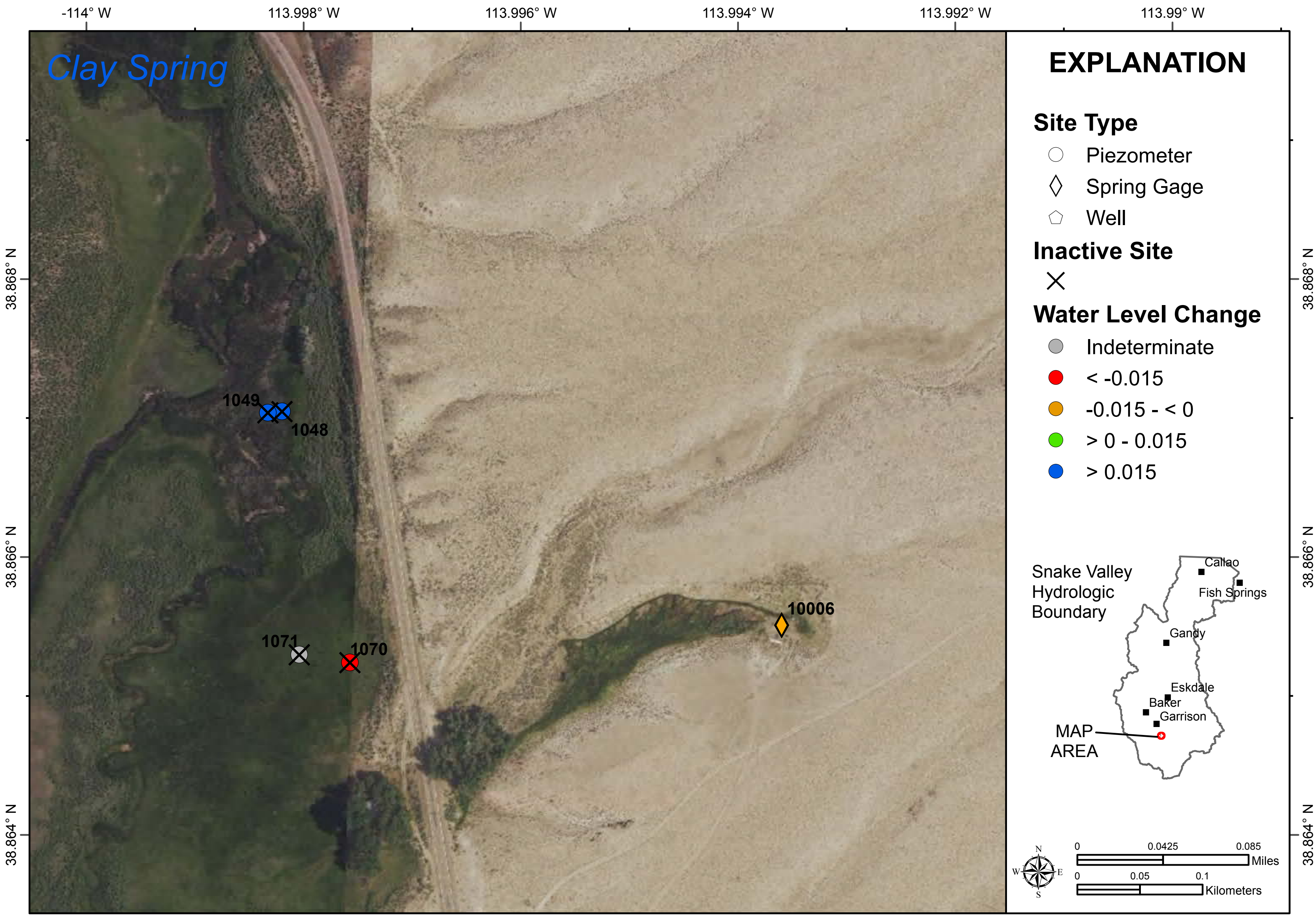

Figure B4. Hydrologic monitoring stations and associated trends at Clay Spring. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

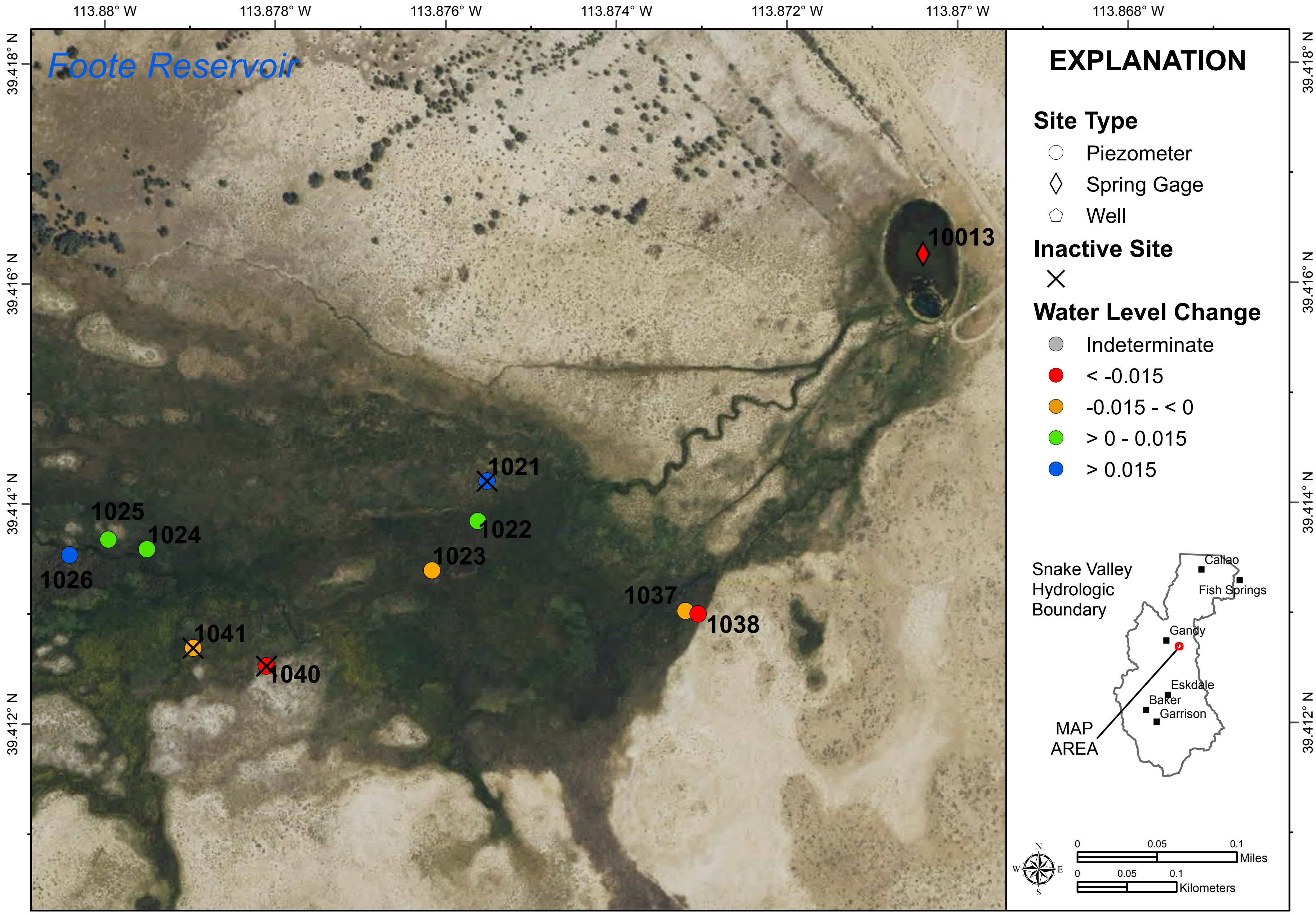

Figure B5. Hydrologic monitoring stations and associated trends at Foote Reservoir. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

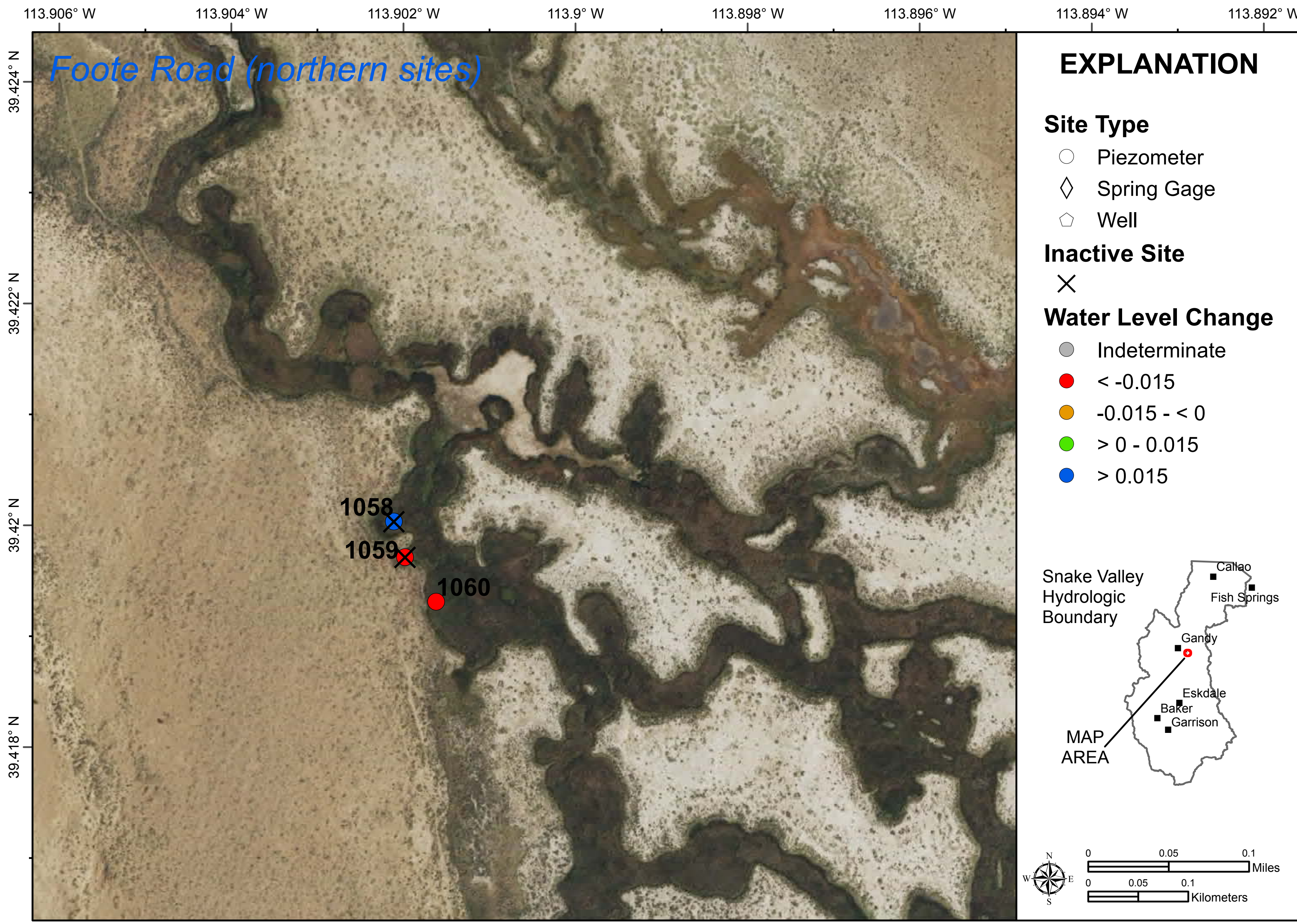

Figure B6. Hydrologic monitoring stations and associated trends at northern Foote Road sites. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

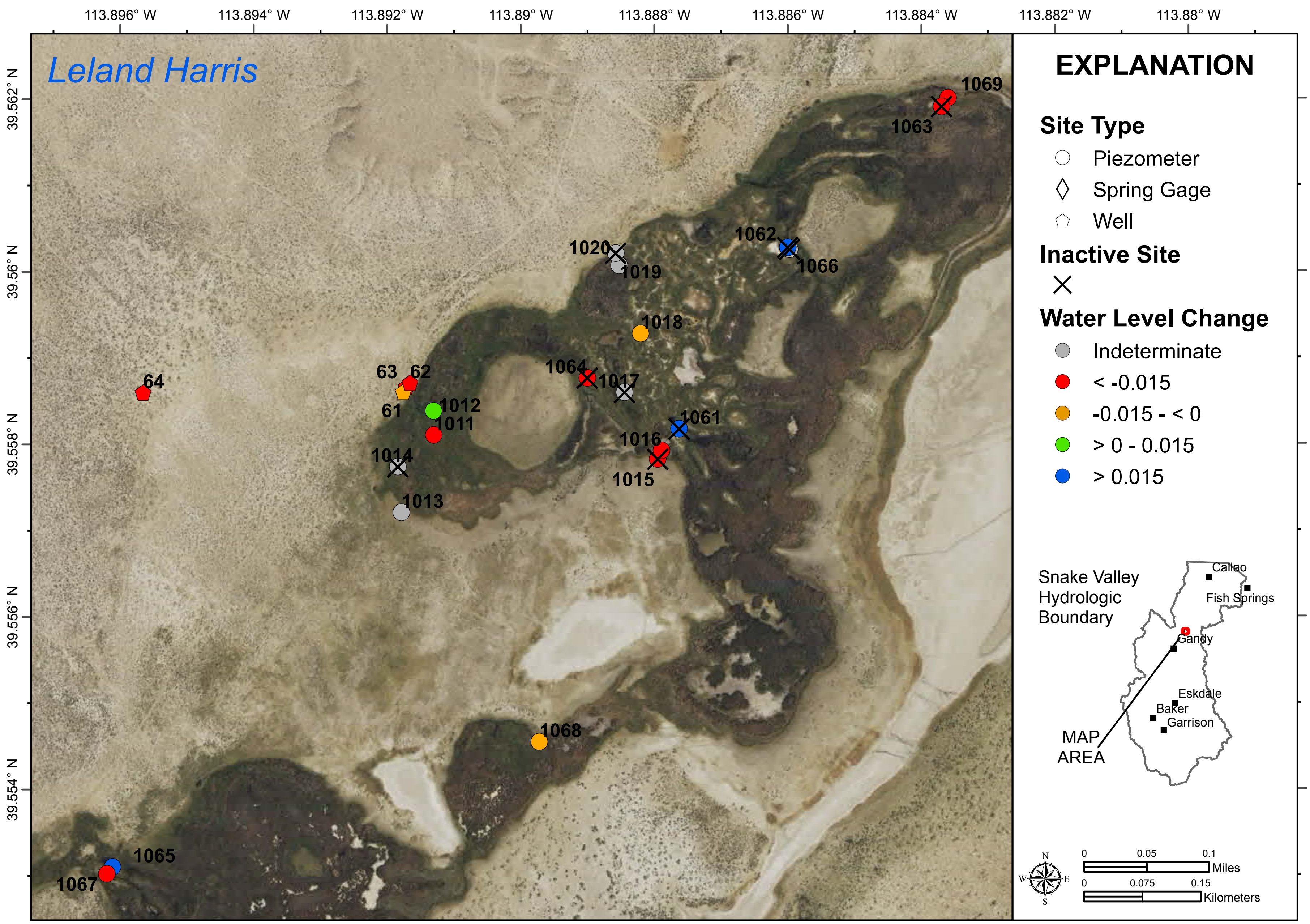

Figure B7. Hydrologic monitoring stations and associated trends at Leland Harris. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

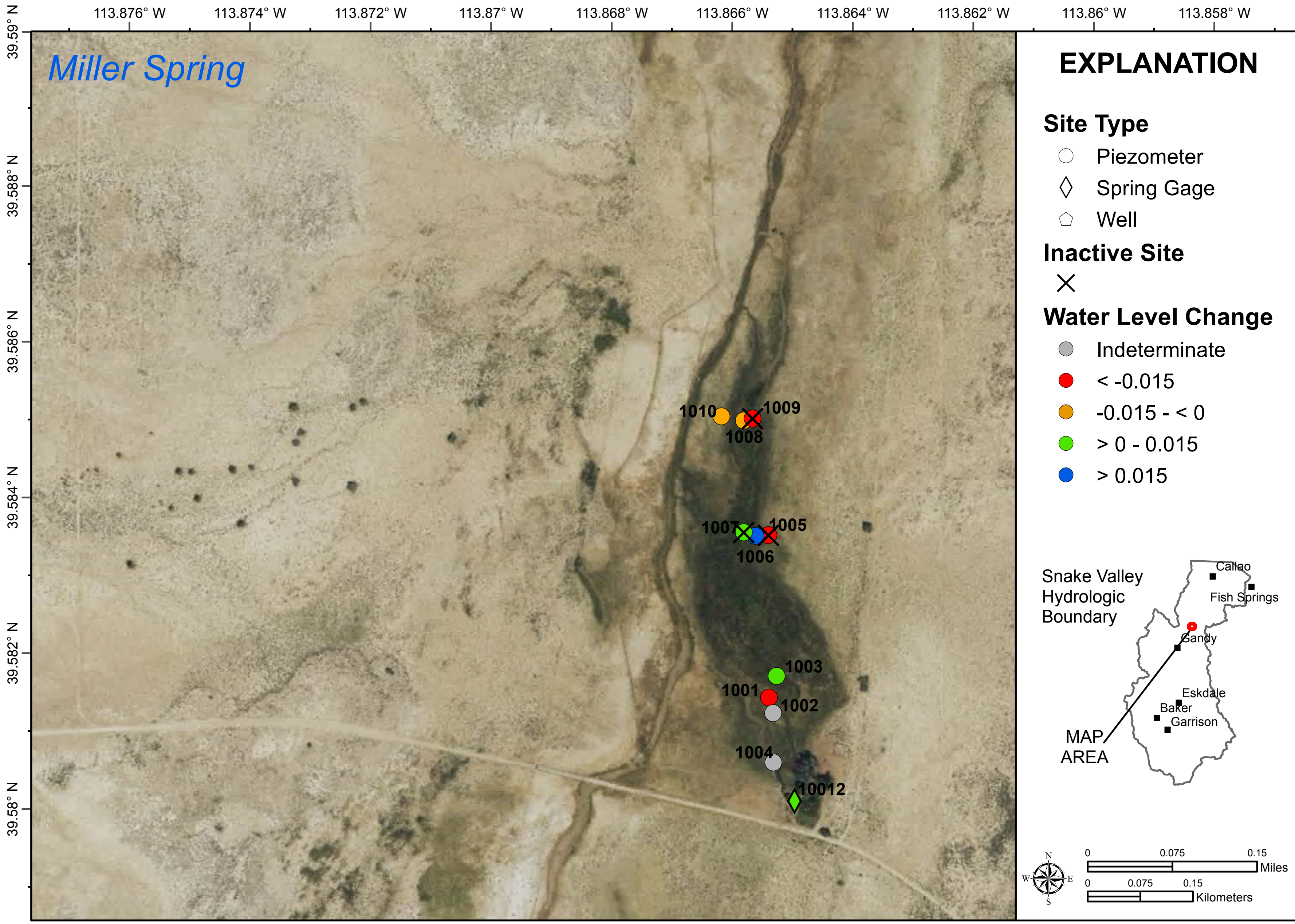

Figure B8. Hydrologic monitoring stations and associated trends at Miller Spring. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

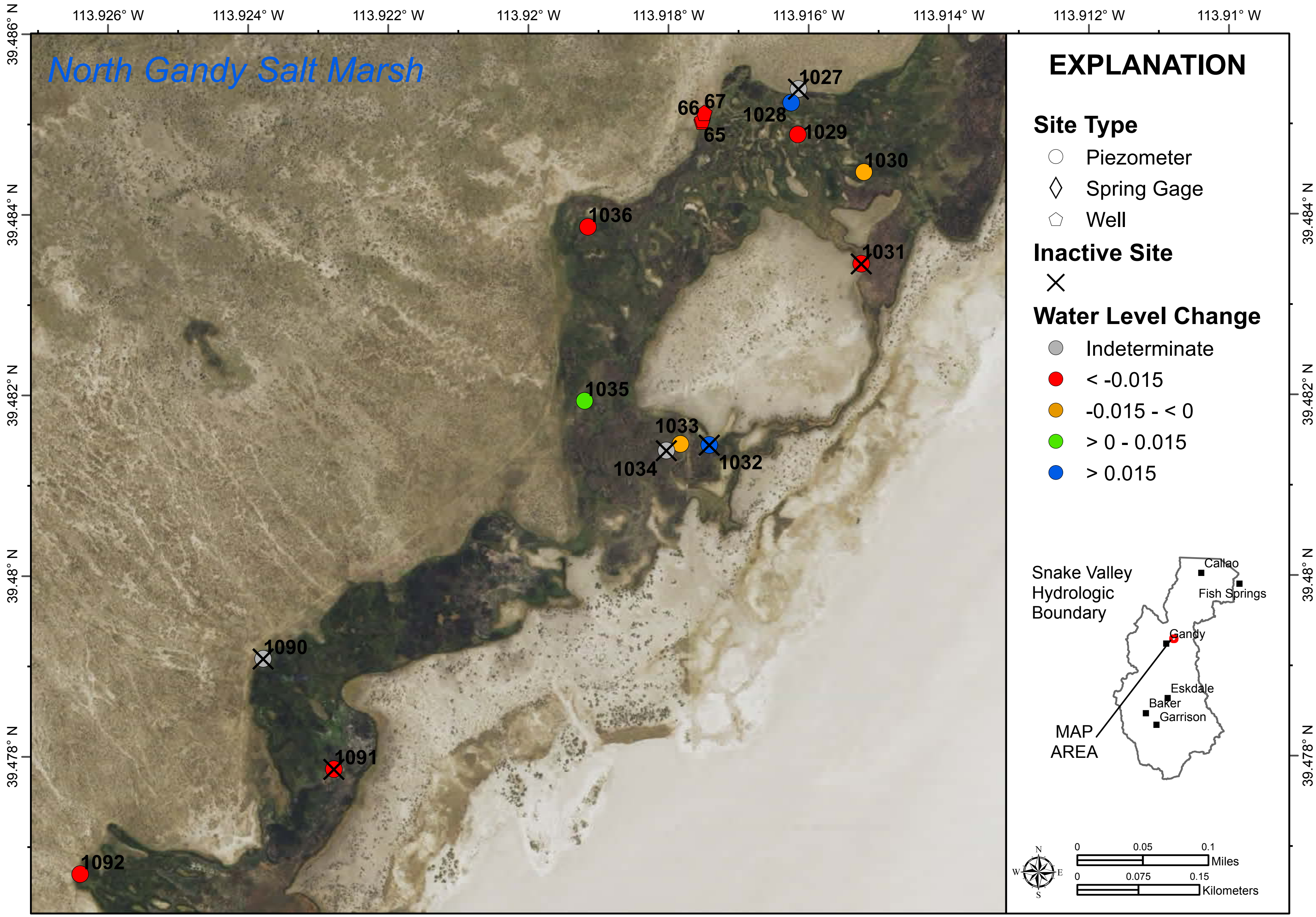

Figure B9. Hydrologic monitoring stations and associated trends at North Gandy Salt Marsh. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

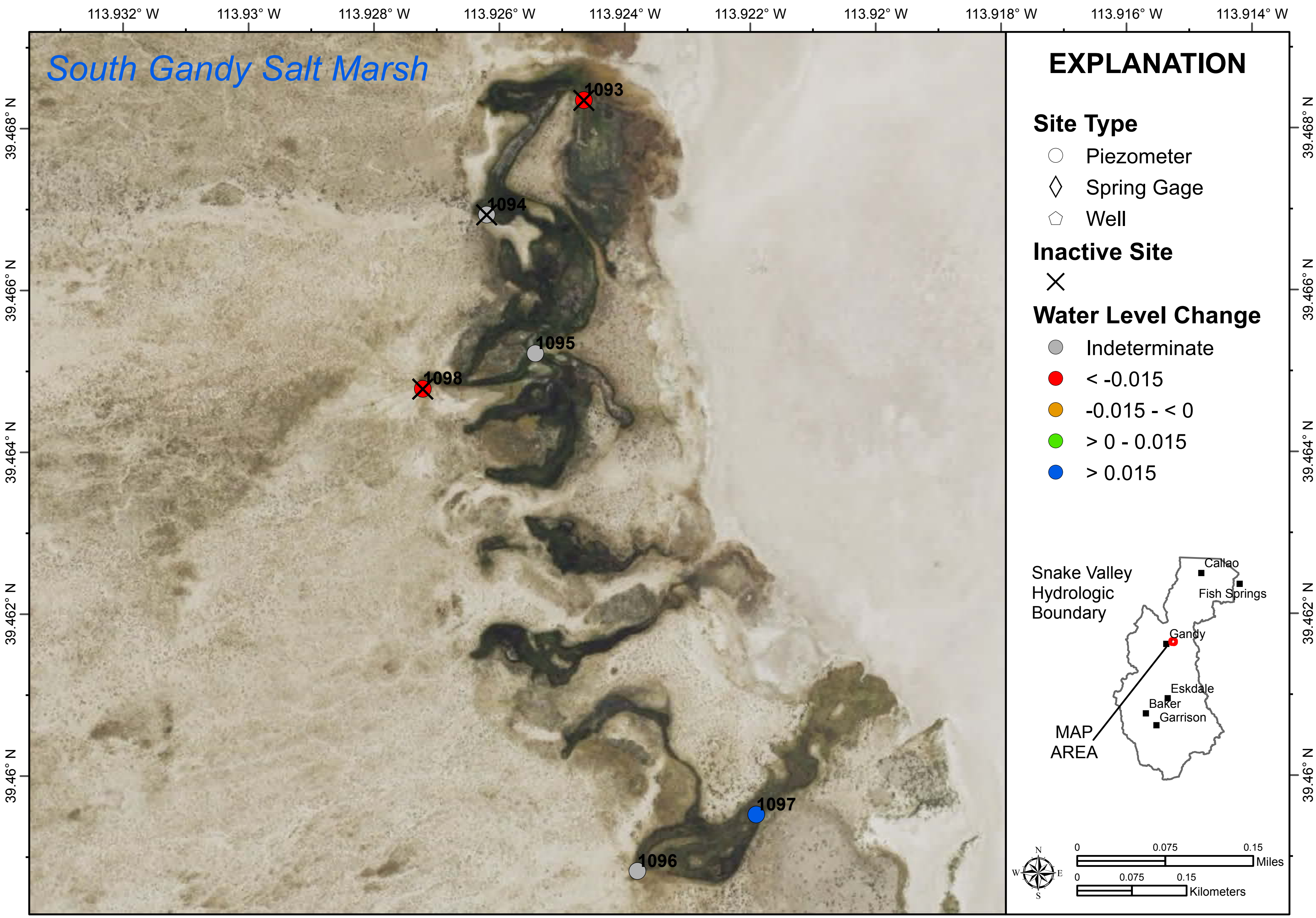

Figure B10. Hydrologic monitoring stations and associated trends at South Gandy Salt Marsh. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

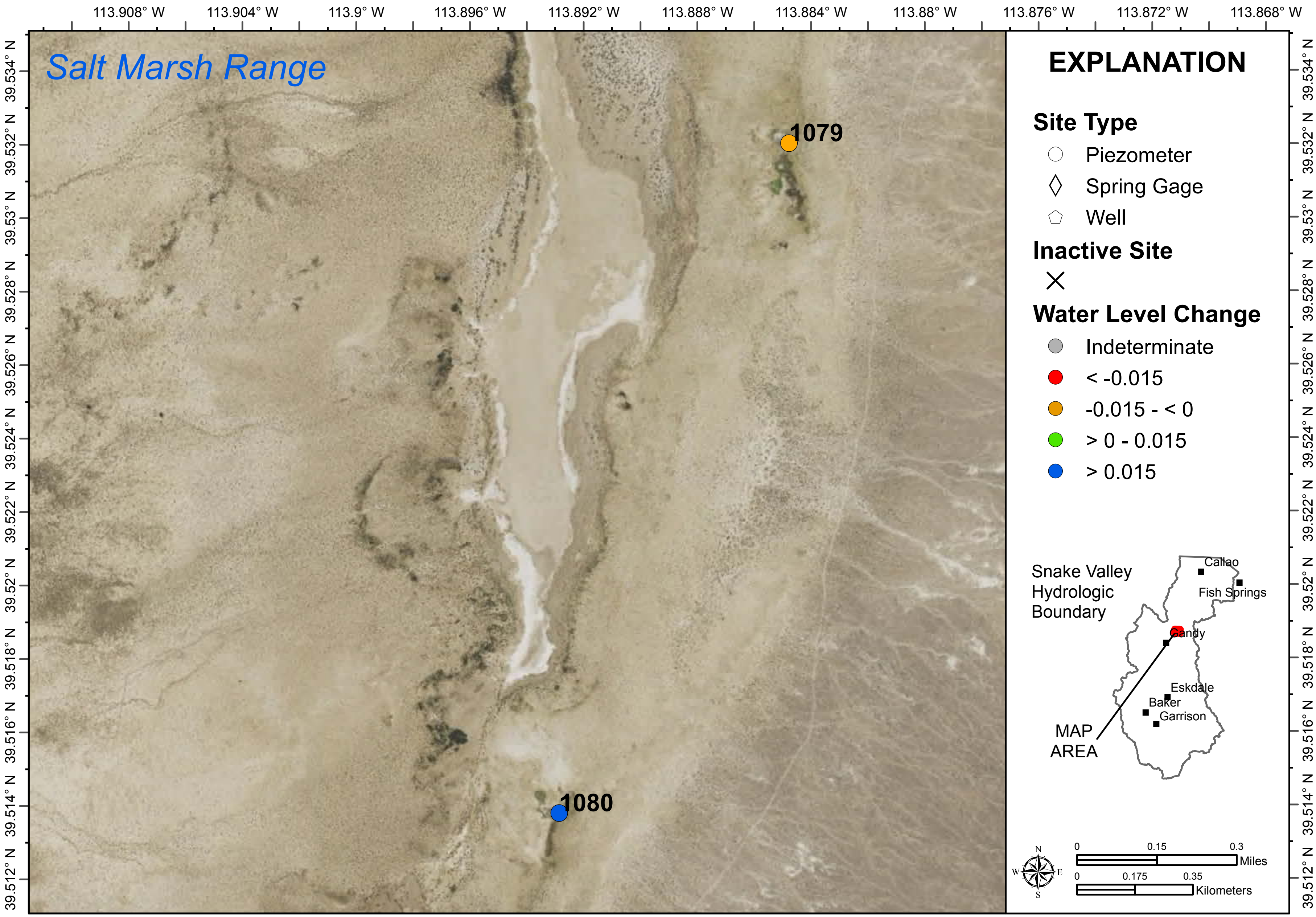

Figure B11. Hydrologic monitoring stations and associated trends at Salt Marsh Range. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".

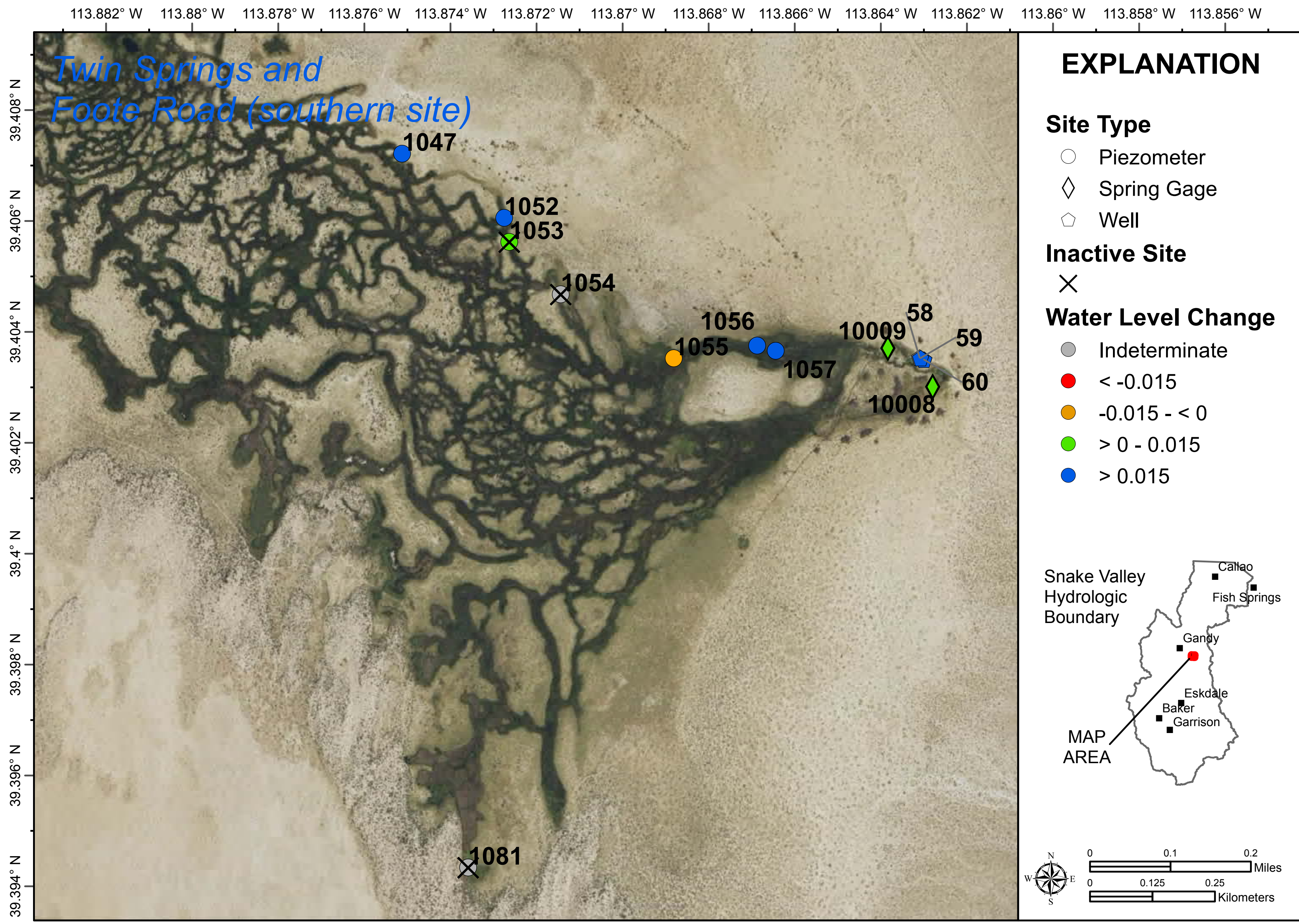

Figure B12. *Hydrologic monitoring stations and associated trends at Twin Springs and southern Foote Road. Slopes of hydrologic trends are in feet per year for piezometers and wells and cfs per year for spring gauges. Stations with no significant trend are listed as "indeterminate".*