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Status and Trends of Springs at Hovenweep National Monument, 1999–2021

Natural Resource Report NPS/NCPN/NRR—2023/2560



ON THE COVER

View from Square Tower Spring, Hovenweep National Monument. NPS/R. Weissinger.

Status and Trends of Springs at Hovenweep National Monument, 1999–2021

Natural Resource Report NPS/NCPN/NRR—2023/2560

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Executive Summary

Water is a scarce, but vital, resource at Hovenweep National Monument (NM). The National Park Service has prioritized long-term monitoring of water resources at the monument through a variety of programs and indicators since 1999. The purpose of this report is to evaluate water-quantity and water-quality data collected at long-term monitoring sites in Hovenweep NM from 1999 to 2021 for trends over time, and to summarize site-characterization data for currently monitored locations. Data are available for three active monitoring stations—Square Tower Spring, Hackberry Pool, and Goodman Point Spring—and three discontinued monitoring stations—Cajon Pool, Upper Hackberry Spring (Spring #4), and Horseshoe Spring.

Water resources at Hovenweep NM have exhibited many trends over the past two decades. Pool levels at both Square Tower Spring and Hackberry Pool went up, with a step increase shown in 2016 (after no sampling in 2014–2015). In contrast, flow decreased by more than half at Goodman Point Spring and ceased at Upper Hackberry Spring (Spring #4). Flow at Horseshoe Spring also decreased, although the period of record at this site was very short. Both Upper Hackberry Spring (Spring #4) and Horseshoe Spring were removed from the monitoring rotation because flows were increasingly absent or too low to measure. Pool-level dynamics and water chemistry at Cajon Pool are characteristic of precipitation-derived water rather than groundwater; this site was removed from the monitoring rotation because it was not a good indicator of groundwater conditions.

The water chemistry in both Square Tower Spring and Hackberry Pool changed significantly, but in opposite directions. Square Tower Spring had increasing total dissolved solids (TDS) and specific conductance, with all major ions showing increases over time. Hackberry Pool had decreases in TDS and most major ions through 2010, when water-chemistry lab analyses were suspended due to logistical constraints. Specific conductance continued to decrease at Hackberry Pool through 2021. The reasons for these changes are unknown. Increases in major ions at Square Tower Spring are unlikely to be related to oil and gas development in the region. Decreases in major ions at Hackberry Pool may reflect an increase in the amount of water that is entering the pool from rain and snowmelt rather than groundwater at this site. Water-quality parameters at Goodman Point Spring have remained stable.

While the causes of trends in water chemistry at these sites are likely natural, the small quantities of water and harsh water-quality conditions make these sites poor habitat for aquatic life. Groundwater is naturally low in dissolved oxygen—but the dissolved-oxygen concentrations in the two pools are persistently low, sometimes falling to near zero in the summer. Water temperatures also warm in conjunction with air temperatures, with temperatures as warm as 18°C in the pools and 19°C in Goodman Point Spring. Traditionally, Puebloan cultures would have managed these small water resources to promote infiltration and retention of precipitation and to remove sediment and debris.

Decreases in flow and increasing vegetation stress are likely tied to increasing air temperatures and long-term drought conditions across the region. The namesake hackberry trees at Hackberry Pool and nearby sites have shown increasing drought stress. Regionally, the underlying Dakota aquifer that feeds springs at the monument was relatively stable from 2008 to 2017, with decreasing levels from 2018 to 2021.

Overall, the most concerning trends observed at springs in Hovenweep NM are likely due to climate change. Increasing air temperature threatens springflow and spring-associated vegetation through increased evapotranspiration. While pool levels have increased, recent decreases in the regional Dakota aquifer raise concerns about the stability of pools in the future.

Managers could consider the potential benefits and risks of:

- Prioritizing protections and actions at Square Tower Spring, which has been the most resilient site at the monument in persistence of surface water and vegetation health during extreme drought.
- Implementing potential climate-adaptation actions that could improve groundwater infiltration upgradient of spring sites. This could include rehabilitating traditional structures to slow the flow of surface water.
- Implementing traditional management techniques that could increase dissolved-oxygen concentrations in the spring pools.
- Increasing invasive-plant removal efforts at Goodman Point Spring, which had the greatest number and cover of invasive-plant species of the three currently monitored locations.
- Developing interpretive stories about water-management techniques and the role of climate change in creating drought stress on iconic hackberry trees.

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1 Introduction

The overall mission of the National Park Service (NPS) is to preserve unimpaired the natural and cultural resources of the National Park System for the enjoyment of this and future generations. Hovenweep National Monument (NM) was established in 1923 to preserve examples of ancestral structures unique to the region. The monument protects 318 hectares (786 ac) of land in six discrete subunits scattered across southeastern Utah and southwestern Colorado, from west to east: Cajon, Square Tower, Holly, Hackberry/Horseshoe, Cutthroat, and Goodman Point (Figure 1-1). Many of the structures are clustered near springs or natural rainwater catchments that serve as the only sources of surface water in the area, making these water resources of significant cultural and natural importance. Because the protected area for each unit is small, water resources may be affected by surrounding land uses, and aquifer withdrawals and contamination are a management concern (Schelz and Moran 2006).

In 1999, administration of the monument transferred to the Southeast Utah Group (SEUG), which initiated long-term water-quality monitoring of the largest and sometimes only water resources in three park subunits: Cajon, Hackberry, and Square Tower springs. Water-quantity measurements were added in 2004 and expanded to include springs at Horseshoe and Goodman Point as well as a site adjacent to Hackberry Pool, Upper Hackberry Spring (Spring #4). In 2007, data management and reporting for the project were transferred to the Northern Colorado Plateau Network (NCPN) water-quality (Thoma et al. 2017) and springs (Weissinger et al. 2017) monitoring programs. Vegetation and site characterization was completed at several sites in 2020. The purposes of the programs can be framed with the following questions:

- What are the ranges in water-quantity and water-quality parameters for selected waters of NCPN parks?
- What are the current status and long-term trends in selected parameters at sites monitored in NCPN parks?

Previous evaluations of water-quality data at Hovenweep NM have compared subsets of data to state water-quality standards for Utah and Colorado, depending on the state where the unit is located (Schelz and Moran 2006; Van Grinsven et al. 2010; Hackbarth and Weissinger 2013; Hackbarth and Weissinger 2016). Sites have frequently not met water-quality standards for dissolved oxygen (Cajon, Square Tower, Hackberry), total dissolved solids (Square Tower), and aluminum (Cajon), and have exceeded an interim threshold for potential impairment for total phosphorus (Cajon, Square Tower, Hackberry). Low dissolved oxygen, in particular, indicates poor-quality habitat for aquatic life.

Analysis of water-quantity and water-quality trends can indicate whether conditions are changing in the water resources at Hovenweep NM, providing valuable information to park managers for use in management decisions. Long-term datasets can also document variability in aquatic systems.

1.1 Purpose and scope

The purpose of this report is to evaluate water-quantity and water-quality data collected at six long-term monitoring sites in Hovenweep NM from 1999 to 2021 for temporal trends, and to summarize site-characterization data collected at three sites in 2020.

This period was selected to provide an assessment of data since the beginning of the monitoring program. Not all parameters were collected at each site for the entire period, and the individual period of record for a single parameter and site combination ranges from 7 to 23 years. However, this period is useful as a status check for the program and as a means of highlighting the most significant management concerns.

Water-chemistry sampling was suspended at Hackberry Pool in 2010, and at Cajon Pool in 2013. Springflow sampling was suspended at Upper Hackberry Spring (Spring #4) and Horseshoe Spring in 2013, due to logistical constraints and lack of flow. In these cases, the report serves as a summary of the period of record and a baseline for any future work.

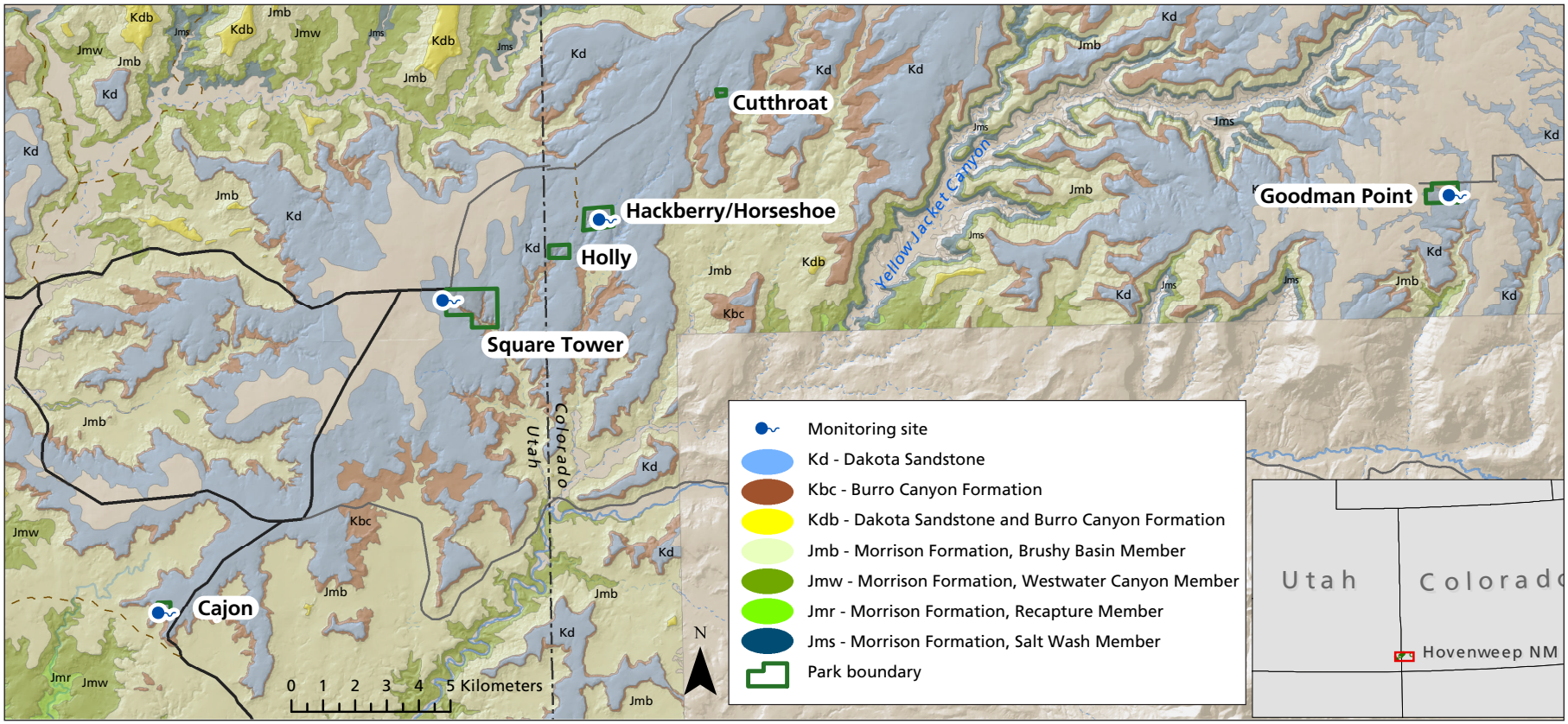


Figure 1-1. Location of Hovenweep National Monument and its subunits, with water-resource monitoring sites and geologic units.

Four monitoring locations were evaluated for core field parameters, such as relative pool water level or flow, dissolved oxygen, pH, specific conductance, and water temperature. Two locations had springflow measurements only. Three locations also included up to 28 laboratory parameters, including major ions, nutrients, and trace elements (Table 1-1).

Table 1-1. Monitoring parameters at water-resources monitoring locations in Hovenweep NM.

Sample type	Parameters
Core parameters	relative pool level, flow, dissolved oxygen, *Escherichia coli*, pH, specific conductance, water temperature
Major ions	alkalinity, calcium, chloride, magnesium, potassium, sodium, sulfate, total dissolved solids
Nutrients	total ammonia, dissolved and total nitrite plus nitrate, total dissolved nitrogen, dissolved and total phosphate
Trace elements	aluminum, arsenic, barium, boron, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, silver, zinc

1.2 Study area description

(adapted from Schelz and Moran 2006)

Hovenweep is on the dissected Cajon Mesa, which covers approximately 775 square kilometers (300 mi^2) on the Colorado–Utah border. Cajon Mesa extends from the base of the Southern Rockies southwest to the San Juan River. Elevation within the monument varies from 1,585 meters (5,200 ft) at the Cajon unit to 2,060 meters (6,760 ft) at the Goodman Point unit. Hovenweep has a semi-arid, temperate climate characterized by hot, dry summers sometimes punctuated by seasonal monsoon thunderstorms, and cold winters with precipitation patterns dominated by longer-duration Pacific stormfronts. For the National Weather Service Co-op weather station, Hovenweep NM (424100), located at the visitor center in the Square Tower unit of the park, the Western Regional Climate Center reported average annual precipitation of 27.4 centimeters (10.79 in) per year and an average snowfall of 45.2 centimeters (17.8 in) per year from 1957 to 2016. The average annual maximum temperature was 20.1°C (68.2°F), and the average minimum temperature was 2.0°C (35.6°F) (wrcc.dri.edu climate summary, accessed 11/04/2022).

All of the dissecting canyons in the monument have seasonally running streams that eventually flow into the San Juan River. Residual water is seasonally available, trapped in potholes or flowing in washes after rains or snowmelt. Rain-fed catchments were augmented by ancestral Puebloan residents using earthen dams to prolong surface water availability (Thornberry-Ehrlich 2004). Permanent, perennial water sources are limited to springs and seeps at canyonheads and along arroyos where the streambed contacts aquifer strata (Thornberry-Ehrlich 2004). The springs selected for monitoring are the only significant water sources in each subunit.

The primary geologic formation is Cretaceous-age Dakota Sandstone, which is also the spring-bearing aquifer in the park. Regionally, the Dakota aquifer is highly dissected and composed of perched local flow systems (Avery 1986). The water is primarily of calcium-bicarbonate type, with total dissolved solids of less than 500 mg/l. This suggests a local source of recharge—most likely, direct infiltration of precipitation into the aquifer (Avery 1986). High-sulfate waters noted in the vicinity of the Square Tower unit have been attributed to potential contact with gypsum (Avery 1986) or underlying shale layers (Whitfield et al. 1983). Hovenweep NM is situated on the southwest-dipping slope of the Blanding Basin (Thornberry-Ehrlich 2004).

Although the topography is fairly uniform, variations in rainfall, soil type, and plant associations occur through minor differences in elevation and drainage patterns. The northeastern half of Cajon Mesa is higher, cooler, and wetter, supporting a pinyon-juniper woodland. This part of the mesa is agriculturally productive, growing pinto beans, winter wheat, and alfalfa. Loamy soils in this region enhance groundwater infiltration that supplies Goodman Point Spring (WPI 2011). The Goodman Point unit supports fairly dense pinyon-juniper woodland, while the remaining Hovenweep units are mostly

juniper-sage and sage shrublands. Shallow-to-deep aeolian soils are found on the mesa tops, with shallow colluvium on the canyon slopes and shallow-to-deep alluvium in the canyon bottoms.

Water quality-related issues of management concern include potential waste contamination from unauthorized visitor use or trespass livestock, and potential spills or aquifer contamination from local oil and gas development (Schelz and Moran 2006). Visitation to Hovenweep remains relatively low, and park visitors are restricted to designated trails. However, given the dispersed nature of the units and limited staffing levels, off-trail hiking occurs. Likewise, all the units are surrounded by light livestock grazing, primarily of sheep and cattle, which may enter the monument when fences are compromised. The entire region overlies the Hermosa Group, a formation rich in oil and gas, and has seen extensive oil and gas development, including active wells in proximity to park boundaries (Figure 1-2). There is a soil bioremediation site for sludge from oil and gas development located about 2.5 kilometers (1.5 mi) northwest of the Square Tower unit (Martin 2000).

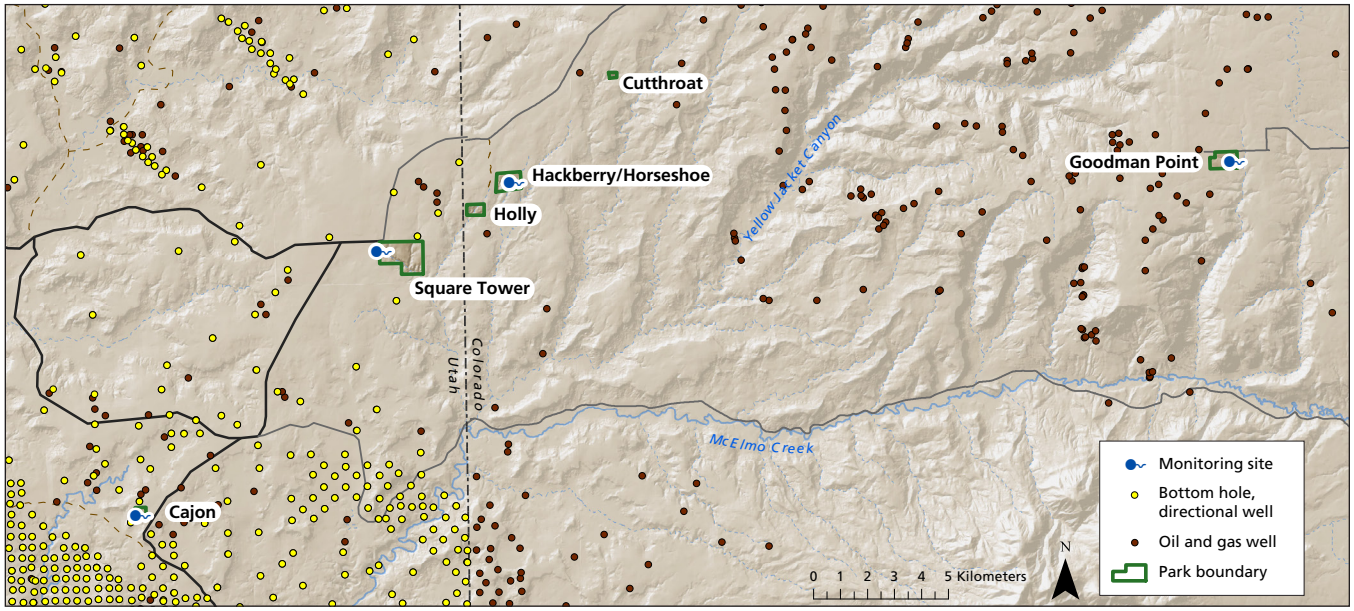


Figure 1-2. Locations of oil and gas wells in proximity to Hovenweep National Monument.

2 Methods

2.1 Field-data collection

Water-quality samples were collected quarterly beginning in 1999, then monthly starting in 2004, at the Cajon Pool, Hackberry Pool, and Square Tower Spring sites (Schelz and Moran 2006). Sites were generally visited on a two-year collection, two-year hiatus monitoring schedule. Water-quantity monitoring began in 2004 at Cajon Pool, Horseshoe Spring, Hackberry Pool, Upper Hackberry Spring (Spring #4), Square Tower Spring, and Goodman Point Spring.

Water-chemistry monitoring was suspended at Hackberry Pool after 2010, and Cajon Pool after 2013, due to logistical constraints on the Southeast Utah Group (SEUG) water-quality monitoring program (Hackbarth and Weissinger 2013). Springflow monitoring was also suspended at Horseshoe Spring and Upper Hackberry Spring (Spring #4) after 2013, due to the increasing frequency of visits with no measurable flow.

Site-characterization data were collected in 2020, including visual estimates of vegetation species cover.

Field-data collection methods followed standards outlined in the SEUG and NCPN water-quality monitoring protocols (Schelz and Moran 2006; Thoma et al. 2017), and the NCPN springs monitoring protocol (Weissinger et al. 2017). During each hydrologic sampling event, water temperature, pH, specific conductance, and dissolved oxygen were measured in the field using a calibrated multiparameter water-quality sonde. Pool-level measurements were collected by measuring the depth to pool surface from a permanent measuring point and then subtracting that value from an arbitrary datum of 1.5 meters. Flow measurements were collected by channeling flow with a temporary weir or plumber's putty and pipe and averaging 3–5 timed volumetric measurements.

Water samples were collected as surface grab samples. Each sample was processed into four aliquots: an unfiltered aliquot for major anions (unpreserved), an unfiltered and acidified (sulfuric-acid) aliquot for total nutrients, a 0.45-µm filtered and acidified (sulfuric-acid) aliquot for dissolved nutrients, and a 0.45-µm filtered and acidified (nitric-acid) aliquot for major cations and trace metals. Samples were kept on ice and delivered to the Utah Public Health Laboratory for analysis.

Site characterization involved measuring spring-associated geomorphic surfaces with a laser rangefinder and creating a sketch map to estimate the spring-associated area up to 50 meters from the spring orifice. A solar pathfinder was used to determine the potential solar radiation reaching the spring orifice for each month, and then totaled for the year and for the growing season (March–October). Vegetation species and ocular cover in cover classes were recorded for each species present within the spring-associated area.

2.2 Hydrologic analytic methods and quality assurance

Water-quality samples were analyzed for major ions, nutrients, and trace elements at the US Environmental Protection Agency (EPA)-certified Utah State Public Health Laboratory using EPA-approved methods. A list of analytical methods is presented in Appendix A. Field blanks were collected beginning in in October 2013, with periodic replicate samples added in October 2014. Quality-assurance methods are detailed in Weissinger (2016). Data were reviewed visually for anomalous results and by identifying outliers and calculating a charge balance for the sample. Anomalous results were reviewed for errors based on field datasheets, visit comments, and lab sheets. Charge balance could be calculated for 158 of 176 sample visits. Six of these had a charge balance of >15%; lab results from these visits were excluded from the analysis.

2.2.1 Bias

Laboratory proficiency-testing data were plotted over time and compared to EPA acceptance criteria to look for potential bias in results (see methods in Weissinger 2016). These data indicated a positive bias

for total dissolved solids (TDS) from 2011 to 2016, and a negative bias from 2017 to 2021. Chloride had increasing positive bias from 2015 to 2020 that stabilized at 2–6% in 2021. These analytical biases, although within the acceptable range for lab certification, could underlie reported trends over time for these parameters. In 2013, when the laboratory changed analytical methods for dissolved selenium, the method change corresponded to a drop in reported concentrations below reporting limits for independent sites across the NCPN. Selenium is not included in this report because the data from before and after this analytical-method change are not comparable.

Field blanks were submitted beginning in October 2013, including 59 blanks for major ions and nutrients and 34 blanks for trace elements. Field-blank detections were generally less than the long-term reporting limits and detected concentrations in source-water samples. The exceptions were dissolved and total phosphorus. In April 2011, the Utah state lab began reporting phosphorus at the minimum detection levels (MDL) rather than at the long-term reporting limits. Over 50% of field blanks had detections higher than the MDL of 0.003 mg/l from 2013 to 2021. Most of the field-blank phosphorus detections ranged from 0.003 to 0.01 mg/l. In source-water samples, 25 of 77 (33%) dissolved-phosphorus results, and 19 of 120 (16%) total-phosphorus results, were <0.01 mg/l—a considerable overlap with the concentrations reported for field blanks.

2.2.2 Variability

Variability was calculated as a Relative Percent Difference (RPD) between replicate and environmental samples using the formula:

$$RPD = \left[\frac{S_1 - S_2}{(S_1 + S_2) / 2} \right] \times 100$$

where S_1 is the concentration in the environmental sample and S_2 is the concentration in the replicate sample.

Major constituents were evaluated for an RPD of less than 15%. Trace elements and nutrients are often detected at very low concentrations, increasing uncertainty about precision and accuracy (Hem 1985). For this reason, trace elements and nutrients were evaluated for an RPD of less than 30% (Thoma et al. 2017). Measurements also were considered to be acceptable if replicate pairs both fell below the reporting limit (values censored), or if one measurement was below the reporting limit and the other was within three times the reporting limit. Programmatically, 215 of 217 (99%) of major ions, 368 of 378 (97%) of trace elements, and 160 of 172 (93%) of nutrients met data-quality goals during the period of record.

2.3 Hydrologic trend analysis

Data were summarized and evaluated to determine the number of samples available for each parameter-and-site combination (e.g., dissolved oxygen at Square Tower). Parameter-and-site combinations with fewer than 5 years or 20 observations were excluded from analysis due to the limited ability to detect trends in very short or small datasets (Schertz et al. 1991). Data summary and analysis were completed using the freeware R v.4.1.0 (R Core Team 2021).

Data were evaluated for linear trends using quantile regression at the median using the quantreg package for R (Koenker 2018). Quantile regression is a form of linear regression that estimates the conditional quantile—for example, the median or the 90th percentile, rather than the mean of the dataset (Koenker and Bassett 1978). It is especially useful when variability in the dataset changes over time, as in many ecological datasets. It is robust to outliers, missing data, and censored data, and has been previously used for water-quality analyses (Cade and Noon 2003, Cade 2017). Models were of the form:

Result ~ centered date + season

where "centered date" is the sampling date in decimal years centered around the median sampling date, and "season" is the day of the year/length of year in days.

Confidence intervals were estimated by bootstrapping with 10,000 iterations (Rogers

1992). When the 95% confidence interval (e.g., the interval between the lower confidence limit, and upper confidence limit) for the slope estimate for trend included zero, we concluded that there was no trend in the data. When the 95% confidence interval for the slope estimate does not include zero, a trend over time is very likely to exist. When this occurred, we concluded there was a trend over time. Total percent change over the period record was calculated as (trend slope × years of record) / median value × 100.

2.3.1 Reporting limits and data censoring

Some water-quality parameters, especially nutrients and trace elements, typically have very low concentrations that are close to the detection limitations of common analytical methods. Water samples without detectable levels of an analyte are reported as below the reporting limit (e.g., <10 mg/l for chloride) and are referred to as censored data because a cut-off, rather than a true value, is known. As analytical methods or laboratory practices change, the reporting limits can also change, so it is common for multiple reporting limits to apply to a single water-quality parameter over time. For example, for chloride, the reporting limit from the Utah Public Health Laboratory decreased from 10 mg/l in 2008 to 1 mg/l in 2011.

Censored data can affect quantile regression results, particularly as the amount of censoring approaches the quantile of interest—in this case, 50% of the data for estimating trends in the median values. For this study, we investigated each parameter with more than one reporting limit. For most such parameters, a majority of the data were censored, and the dataset was re-censored to the highest reporting limit for summary statistics. For total ammonia, dissolved nitrate plus nitrite, and dissolved phosphorus, the higher reporting limit corresponded to the beginning of the site's record, and all or most data were censored until the reporting limit was lowered. For these parameters, the earlier portion of the record was removed prior to data analysis. For datasets with >5% censored data, data were analyzed using censored quantile regression with the random censoring method of Portnoy (2003). Parameter-and-site combinations with >50% censored data are summarized in this report but were excluded from trend analysis due to the limited ability to detect trends in highly censored datasets.

2.3.2 Adjusting for water quantity

Many water-quality parameters change in concentration with changes in streamflow. Because water quantity changed at our monitoring locations over time, we investigated (when possible) whether trends in parameters were variable with changes in water quantity. The water-quantity relationship in datasets with more than 5% censored data is not reliably modelled (Schertz et al. 1991), so for uncensored datasets only, we included a water-quantity term of the form:

Result ~ centered date + season
+ centered pool level
(time trend plus seasonality plus pool-level model)
or
Result ~ centered date + season
+ centered flow
(time trend plus seasonality plus flow model)

where "centered pool level" is the measured pool level centered on the median pool level in the period of record and "centered flow" is measured flow centered on the median flow for the period of record. Trends from these models are reported as pool level-adjusted or flow-adjusted trends, respectively.

3 Results

3.1 Climate context

Climate summaries are provided using DAYMET gridded climate data for the park visitor-center location at the Square Tower unit (Thornton et al. 2018). Since 1980, Hovenweep NM has seen a gradual increase in both maximum and minimum air temperatures (Figure 3-1). Precipitation remains highly variable, although a LOESS smooth suggests a downward trend over the past 15 years (Figure 3-2). During the period of record for this report, annual average maximum and minimum temperatures were usually well above the 30-year climate normal (Figure 3-3A, B). Total annual precipitation and peak snow water equivalent (SWE) varied from well below to well above average, although the highest-snowpack years did not necessarily correspond to the years with the highest total precipitation (Figure 3-3C, D). SWE is an estimate of the total water that could instantaneously melt from a snowpack. It is used to predict potential runoff and groundwater recharge.

Water deficit represents the amount of water vegetation would use to meet its needs, if that water were available. It incorporates air temperature and antecedent moisture availability and is an ecologically relevant measure of drought stress (Thoma et al. 2020). Water deficit trended upward in major vegetation types at Hovenweep NM. The driest years in the 2000s were drier than any other years since 1980 (Figure 3-4).

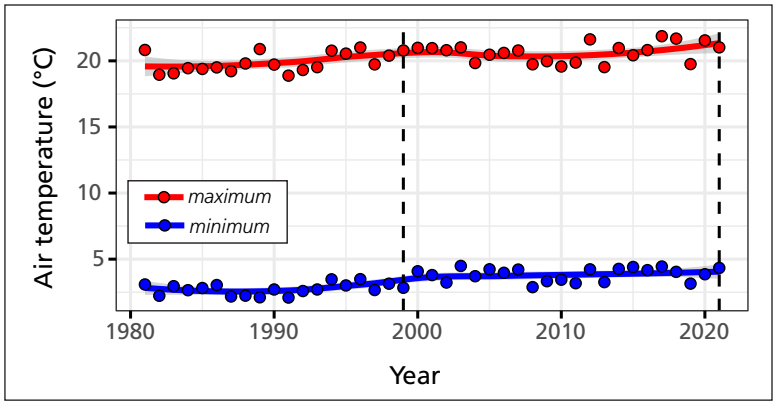


Figure 3-1. Annual average maximum and minimum air temperature for the Hovenweep NM visitor-center location, 1981–2021, with a LOESS smooth using DAYMET data. The period of interest for this report is shown with dashed lines at years 1999 and 2021.

3.1.1 Climate relationships to water quality and water temperature

Groundwater-fed systems, such as springs, are often considered highly stable, with relatively constant flow and temperature. However, comparisons of air temperature and water temperature at the monitoring locations in this report indicate that water temperatures at our monitoring sites rise as air temperatures rise (Figure 3-5). Higher air temperatures were also correlated with lower flow measurements at Goodman Point Spring (Figure 3-6), but the relationship of

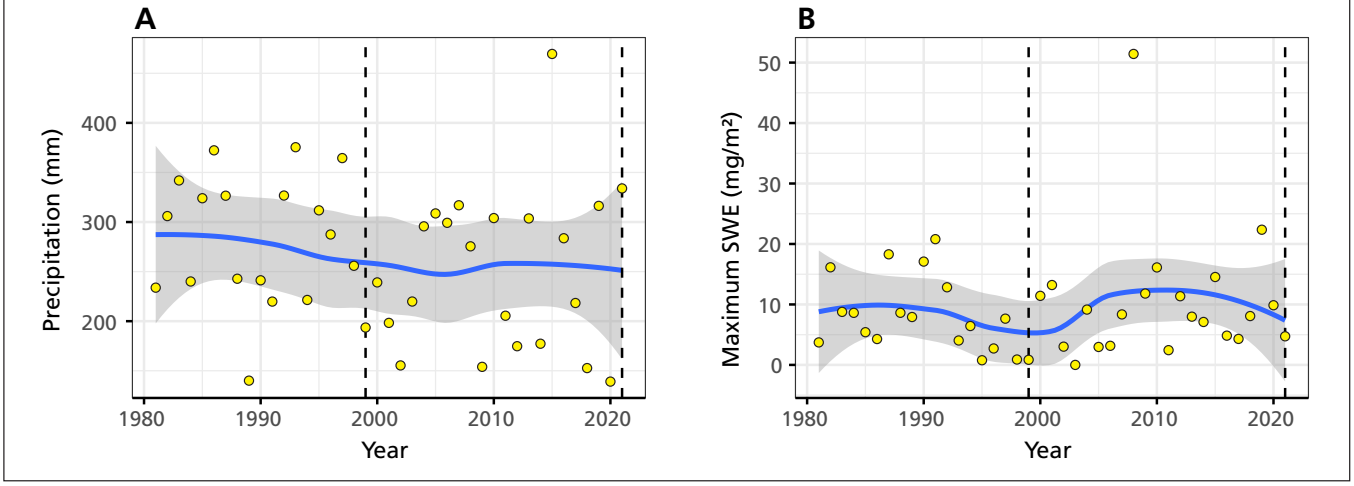


Figure 3-2. Annual average cumulative precipitation and maximum snow water equivalent for the Hovenweep NM visitor-center location, 1981–2021, with a LOESS smooth using DAYMET data. The period of interest for this report is shown with dashed lines at years 1999 and 2021.

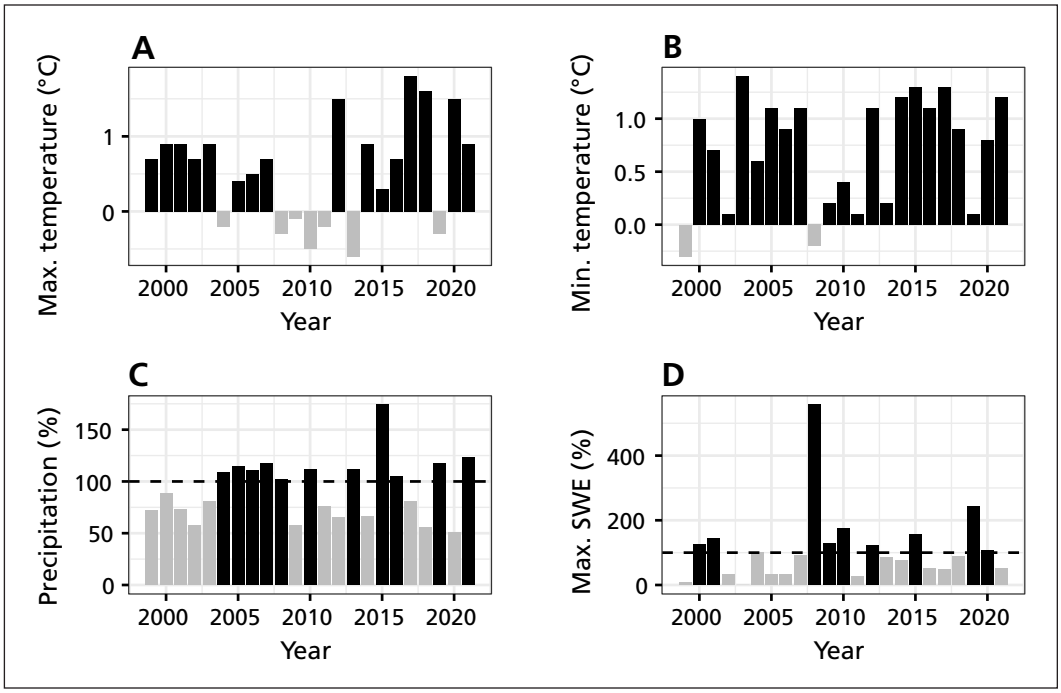


Figure 3-3. Annual departures from 30-year averages for the Hovenweep NM visitor-center location, 1999–2021, using DAYMET data, for (A) average maximum air temperature, (B) average minimum air temperature, (C) cumulative precipitation, and (D) annual maximum snow water equivalent.

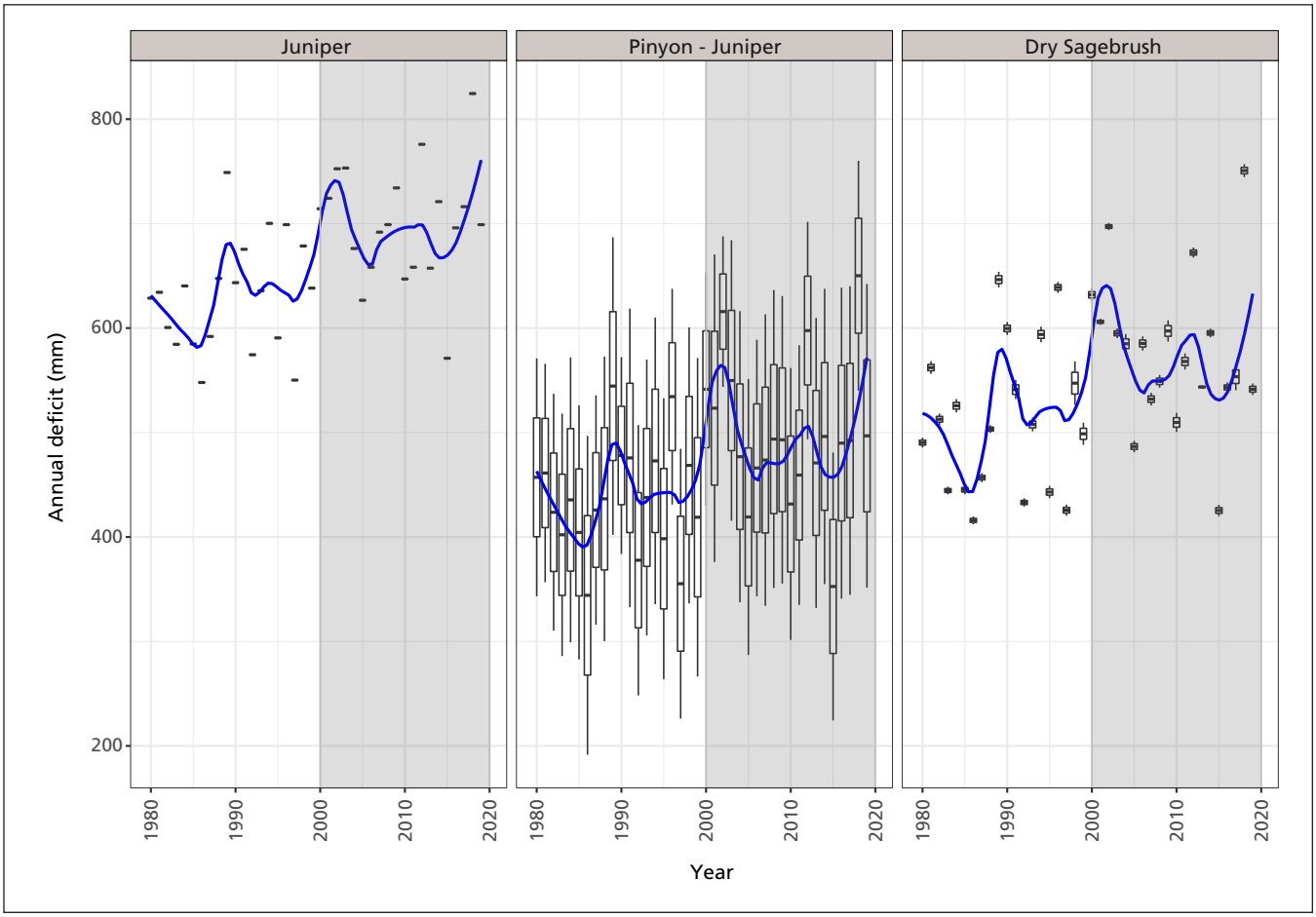


Figure 3-4. Annual water deficit, an indicator of drought stress, increased in all major vegetation types at Hovenweep NM over the period of record.

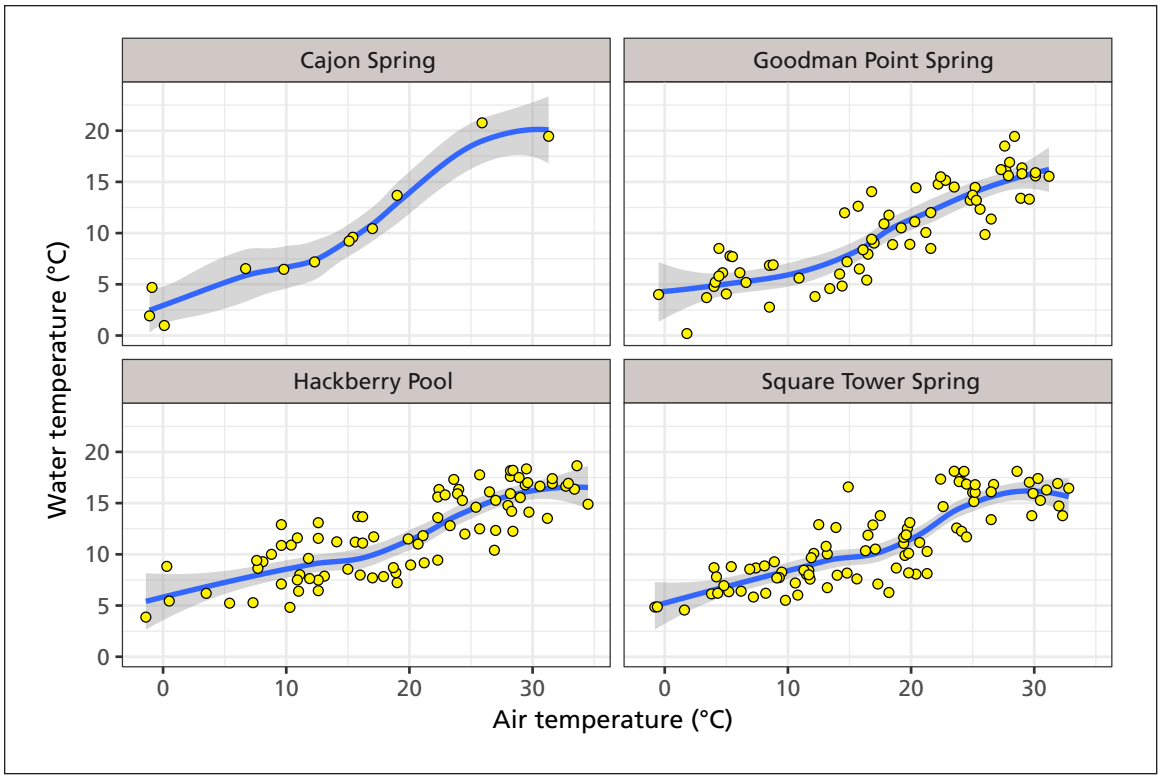


Figure 3-5. Relationships between air temperature and water temperature during sampling visits at four monitoring locations at Hovenweep NM, with a LOESS smooth and 95% confidence interval.

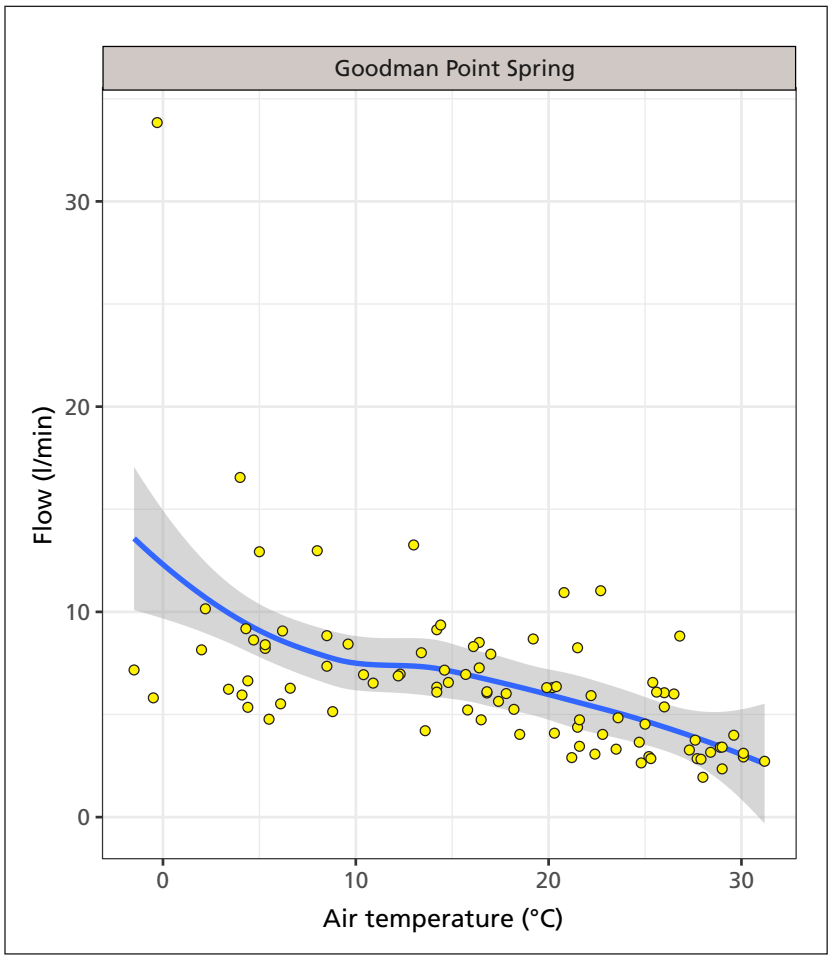


Figure 3-6. Relationship of measured air temperature to measured flow at Goodman Point Spring, with a LOESS smooth and 95% confidence interval.

air temperature to pool level was inconsistent (Figure 3-7). This suggests that even though we monitor at or near the emergence of groundwater at Square Tower, Hackberry, and Goodman Point, the available water has already been affected by weather conditions prior to measurement. At Goodman Point Spring, abundant plant life between the seep area and the monitoring station likely captures more of the available water as air temperatures rise, as has been shown in other springs regionally (Weissinger et al. 2016). For Hackberry Pool and Square Tower Spring, vegetation cover is low, and evaporation likely has a stronger effect than transpiration at air temperatures higher than about 20°C.

3.2 Currently monitored locations

3.2.1 Square Tower Spring

Square Tower Spring forms a small perennial pool, about 1.5 × 0.5 meters in surface area, below the overhanging canyon rim at the head of Square Tower Canyon. The ancestral Puebloan structure of Square Tower is located in the canyon roughly 25 meters downstream of the pool. Numerous other structures line the canyon rim above the spring. The pool is fed by subsurface perched groundwater from a buried contact zone. It was dug out and developed with stones on one side by the ancestral Puebloans (Figure 3-8). The pool is sufficiently protected by the overhanging pouroff that it does not receive water from overland flow events.

The spring-associated area for monitoring includes a narrow backwall in a shallow alcove (Figure 3-9). There are seeping sections of the backwall with moss and algae, but the colluvial slope and alcove floor are dry. The associated area also includes about 25 meters of a dry channel that is primarily a runoff channel from a notch at the head of the canyon above the spring. The channel includes fairly thick riparian vegetation to just past the Square Tower structure. Seven shallow-groundwater piezometers were installed in the vicinity of the structure in the late 1990s for a cultural-resource preservation project, and two shallow-groundwater piezometers located adjacent to one another in the channel at the base of the Square Tower structure had groundwater present after being rehabilitated in 2016. We present the data from piezometer #4. Data from the earlier project could not be found.

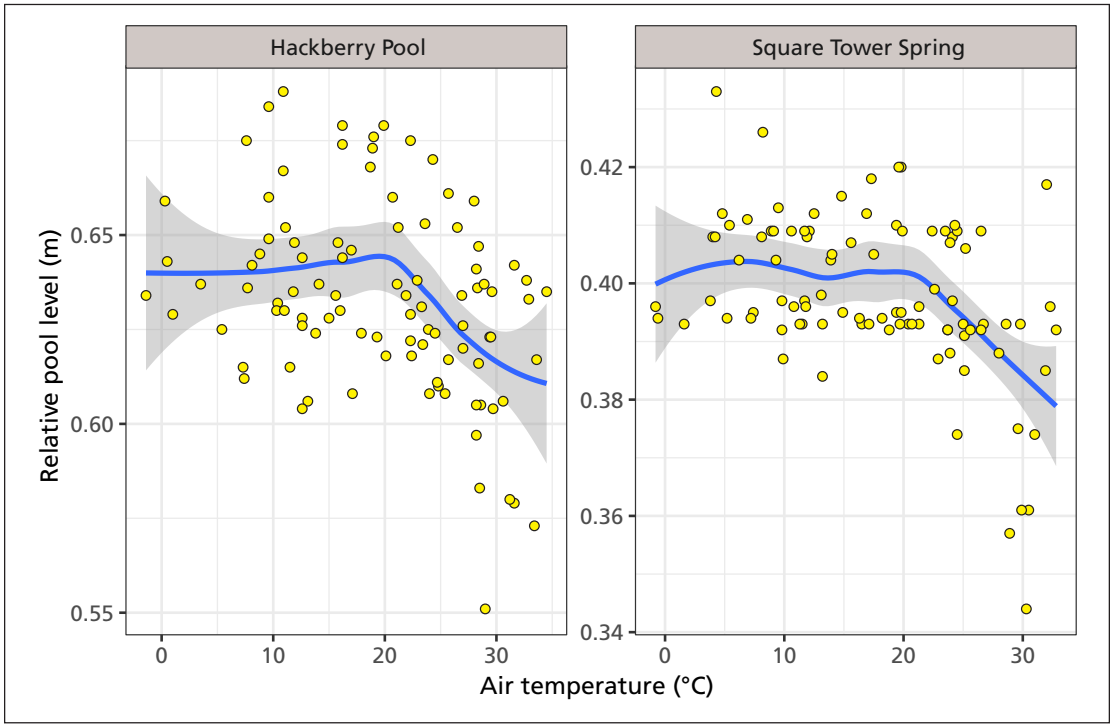


Figure 3-7. Relationship of measured air temperature to relative pool level during sampling events, with a LOESS smooth and 95% confidence interval.



Figure 3-8. Square Tower Spring water-quality and pool-level monitoring location, June 2017.

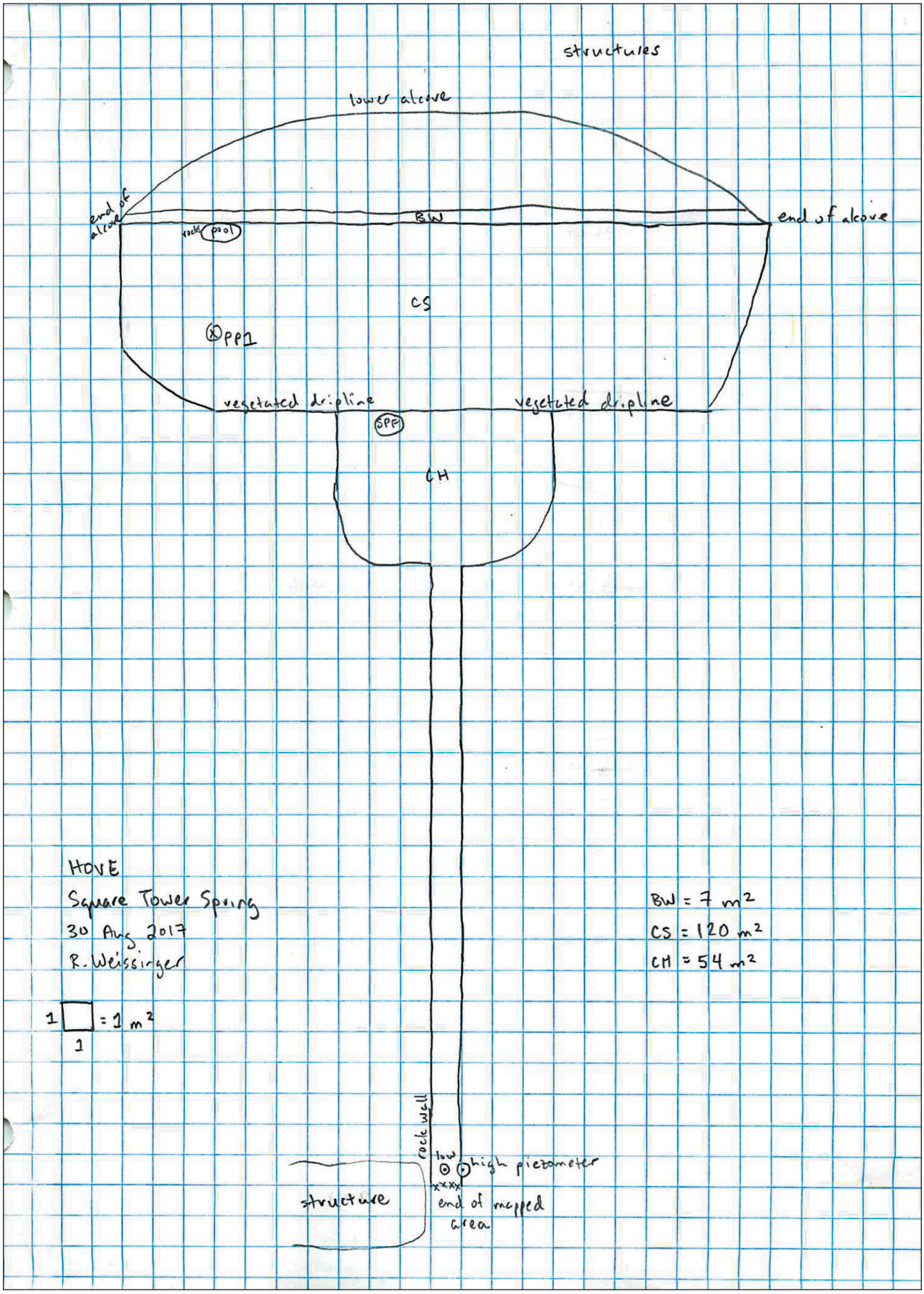


Figure 3-9. Sketch map of spring-associated area at Square Tower Spring.

3.2.1.1 Site characterization

The spring-associated area for monitoring is approximately 180 square meters. The spring orifice, partially shaded by the shallow alcove, receives about 73% of the annual potential solar radiation at the site and 66% of the potential growing-season solar radiation. In September 2020, 10 vegetation species were identified at the site, with 3 wetland species and 7 non-wetland species. Wetland vegetation cover was estimated at approximately 24%, while non-wetland cover was about 11%. Exotic species detected at the site included cheatgrass (*Bromus tectorum*) and horehound (*Marrubium vulgare*). A full species list for the site is available in Appendix A.

3.2.1.2 Hydrologic summary and trends

Square Tower Spring's pool level increased by an estimated 0.02 meters from 2004 to 2021, with a notable step increase in 2016 (Figure 3-10, Table 3-1). Water chemistry in the pool is characterized by relatively high and increasing specific conductance, major ions, and total dissolved solids (Table 3-1). Increasing trends remained even after adjusting for increasing pool levels, suggesting that the increases are not solely the result of changes in water quantity. Summary statistics and timeseries graphs for all parameters are presented in Tables 3-2 to 3-5 and Figures 3-11 to 3-14.

In 2016, NCPN began measuring groundwater depths in two piezometers downstream from the stream orifice that were previously installed for cultural-resource monitoring. These piezometers should reflect water availability in the runoff channel and are immediately next to one another. One is almost flush with the channel bottom, while the other protrudes several centimeters above the ground. Water depths in the two piezometers have fluctuated in tandem. From 2016 to 2021, depths fluctuated seasonally but remained within 30 centimeters of the ground surface (Figure 3-15).

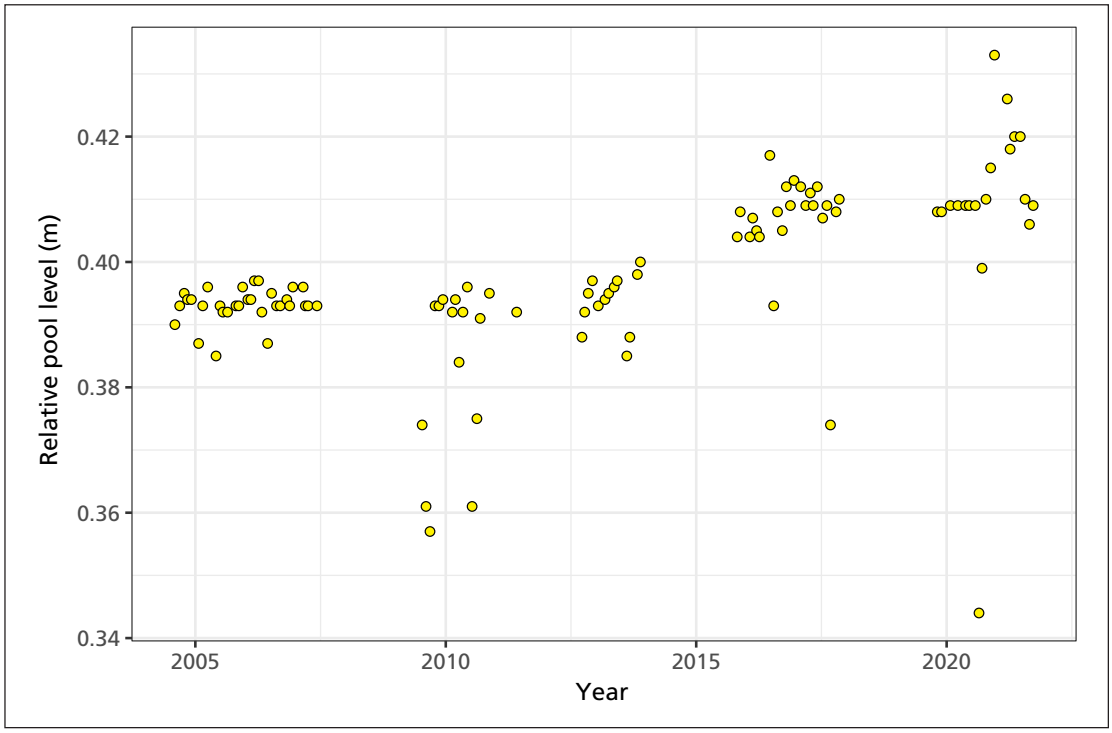


Figure 3-10. Relative pool level at Square Tower Spring, 2004–2021. Pool level increased over time.

Table 3-1. Trend results for parameters at Square Tower, with <50% censored data.

Parameter	Analysis type[1]	Period of record (yrs)	p-value	Ambient trend	Median concentration	Ambient change	Percent change	Pool level-adjusted measure	
								p-value	Trend
Dissolved oxygen (mg/l)	qr	23	0.263	none	5.26	–	–	<0.001	down
Escherichia coli (MPN/100 ml)	cqr	16	0.758	none	1	–	–	–	–
pH	qr	23	<0.001	up	7.57	0.30	4	0.025	up
Relative pool level (m)	qr	18	<0.001	up	0.40	0.02	5	–	–
Specific conductance (µs/cm)	qr	23	<0.001	up	1,626	422	26	<0.001	up
Water temperature (°C)	qr	23	0.355	none	10.0	–	–	0.009	up
Alkalinity (mg/l)	qr	23	0.002	up	463	37.9	8	0.645	none
Calcium (d) (mg/l)	qr	23	0.010	up	89.6	6.0	7	0.046	up
Chloride (mg/l)	qr	23	<0.001	up	15.4	3.8	25	<0.001	up
Magnesium (d) (mg/l)	qr	23	<0.001	up	130	33.0	25	<0.001	up
Potassium (d) (mg/l)	qr	23	<0.001	up	7.8	2.1	27	<0.001	up
Sodium (d) (mg/l)	qr	23	<0.001	up	105	44.4	42	<0.001	up
Sulfate as SO_4 (mg/l)	qr	23	<0.001	up	495	170	34	<0.001	up
Total dissolved solids (mg/l)	qr	23	<0.001	up	1,113	295	26	<0.001	up
Nitrate plus nitrite (d) (mg/l)	cqr	13	<0.001	down	<0.1	–0.14	–231	–	–
Nitrogen (d) (mg/l)	cqr	13	0.830	none	0.21	–	–	–	–
Phosphate as P(d) (mg/l)	cqr	13	0.770	none	<0.02	–	–	–	–
Total phosphate as P (mg/l)	cqr	23	0.269	none	<0.02	–	–	–	–
Boron (d) (µg/l)	qr	16	0.956	none	100	–	–	0.349	none
Chromium (d) (µg/l)	cqr	23	0.027	down	<5	–5.47	–149	–	–

[1]qr = uncensored quantile regression, cqr = censored quantile regression

Table 3-2. Summary statistics for core parameters at Square Tower Spring, 1999–2021.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Dissolved oxygen (mg/l)	2/19/1999	9/23/2021	17	106	0	0.97	5.26	9.24
Escherichia coli (MPN/100 ml)	10/30/2006	9/23/2021	12	70	28	<1	1	179
pH	2/19/1999	9/23/2021	17	108	0	7.34	7.57	7.80
Relative pool level (m)	8/5/2004	9/23/2021	15	102	0	0.39	0.40	0.41
Specific conductance (µs/cm)	2/19/1999	9/23/2021	17	110	0	1,434	1,626	1,841
Water level below ground (cm)	3/16/2016	9/23/2021	5	38	0	–25.2	–17.7	1.2
Water temperature (°C)	2/19/1999	9/23/2021	17	112	0	6.1	10.0	16.9

Table 3-3. Summary statistics for major ions at Square Tower Spring, 1999–2021.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Alkalinity (mg/l)	2/19/1999	9/23/2021	16	95	0	430	463	495
Calcium (d) (mg/l)	2/19/1999	9/23/2021	16	95	0	83.1	89.6	97.2
Chloride (mg/l)	2/19/1999	9/23/2021	16	94	2	12.6	15.4	17.6
Magnesium (d) (mg/l)	2/19/1999	9/23/2021	16	95	0	114	130	150
Potassium (d) (mg/l)	2/19/1999	9/23/2021	16	95	0	6.6	7.8	9.4
Sodium (d) (mg/l)	2/19/1999	9/23/2021	16	95	0	84.5	105	128
Sulfate as SO_4 (mg/l)	2/19/1999	9/23/2021	16	93	0	374	495	592
Total dissolved solids (mg/l)	2/19/1999	9/23/2021	16	92	0	1,000	1,113	1,326

Table 3-4. Summary statistics for nutrients at Square Tower Spring, 1999–2021.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Nitrate plus nitrite (d) (mg/l)	7/13/2009	9/23/2021	10	66	19	<0.1	<0.1	0.18
Nitrogen (d) (mg/l)	7/13/2009	9/23/2021	10	66	16	<0.2	0.21	0.79
Phosphate as P(d) (mg/l)	7/13/2009	9/23/2021	10	65	5	<0.02	<0.02	0.117
Total ammonia as N (mg/l)	7/13/2009	9/23/2021	10	65	51	<0.05	<0.05	0.19
Total nitrate plus nitrite (mg/l)	8/25/1999	9/23/2021	10	50	27	<0.1	<0.1	0.18
Total phosphate as P (mg/l)	2/19/1999	9/23/2021	16	95	25	<0.02	<0.02	0.09

Table 3-5. Summary statistics for trace elements at Square Tower Spring, 1999–2021.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Aluminum (d) (µg/l)	2/19/1999	7/26/2021	16	37	27	<30	<30	38
Arsenic (d) (µg/l)	2/19/1999	7/26/2021	16	38	38	<5	<5	<5
Barium (d) (µg/l)	2/19/1999	7/26/2021	16	38	23	<100	<100	<100
Boron (d) (µg/l)	7/11/2006	7/26/2021	12	37	1	69	100	122
Cadmium (d) (µg/l)	2/19/1999	7/26/2021	16	38	38	<1	<1	<1
Chromium (d) (µg/l)	2/19/1999	7/26/2021	16	38	16	<5	<5	9.7
Copper (d) (µg/l)	2/19/1999	7/26/2021	16	38	22	<12	<12	<12
Iron (d) (µg/l)	2/19/1999	7/26/2021	16	48	32	<30	<30	40.5
Lead (d) (µg/l)	2/19/1999	7/26/2021	16	37	36	<3	<3	<3
Manganese (d) (µg/l)	2/19/1999	7/26/2021	16	37	19	<5	<5	18.7
Mercury (d) (µg/l)	2/19/1999	7/26/2021	16	38	38	<0.2	<0.2	<0.2
Nickel (d) (µg/l)	7/11/2006	7/26/2021	12	26	26	<10	<10	<10
Silver (d) (µg/l)	2/19/1999	7/26/2021	16	38	38	<2	<2	<2
Zinc (d) (µg/l)	2/19/1999	7/26/2021	16	37	33	<30	<30	<30

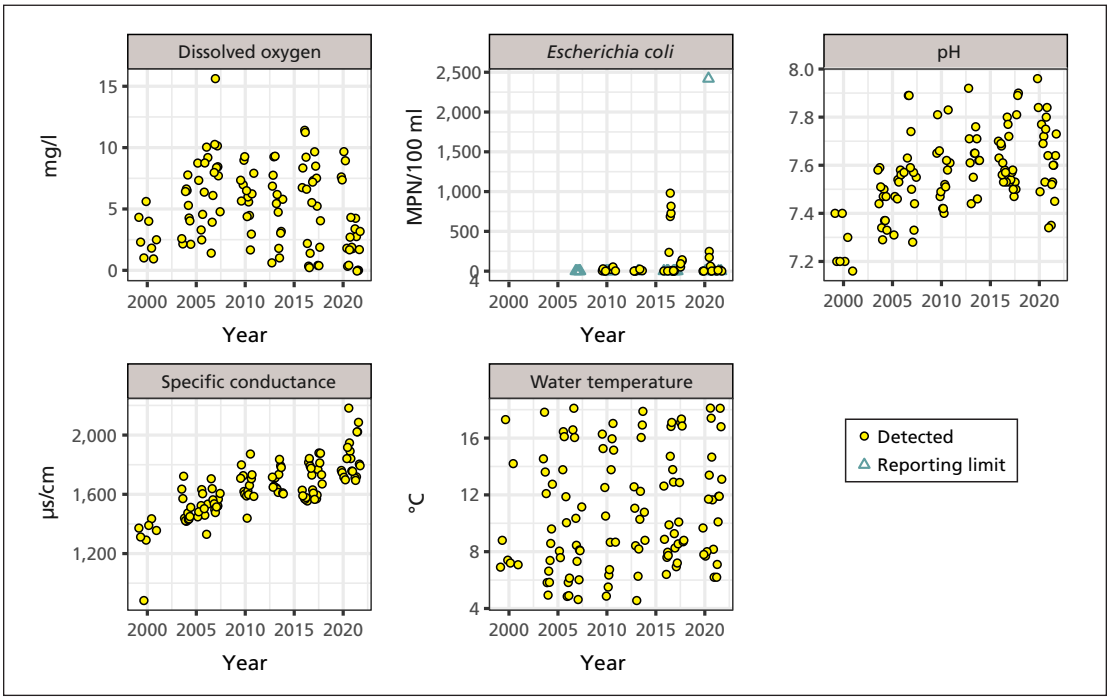


Figure 3-11. Core parameters at Square Tower Spring, 1999–2021. Specific conductance and pH increased, while there was no ambient trend in dissolved oxygen, *E. coli*, or water temperature. Values beyond the reporting limits were at levels too low or too high to be precisely measured, and are plotted at the reporting limits.

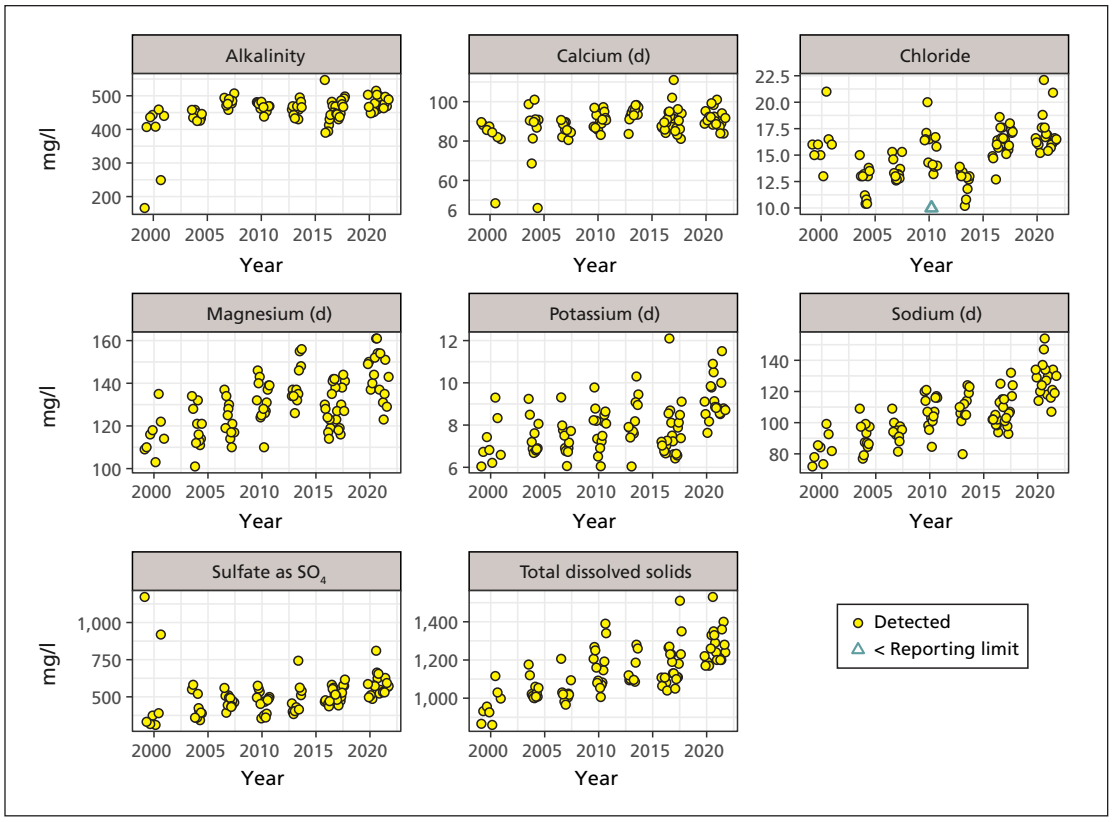


Figure 3-12. Major ions at Square Tower Spring, 1999–2021. There were increases in all major ions. Values below the reporting limit were at levels too low to be precisely measured, and are plotted at the reporting limit.

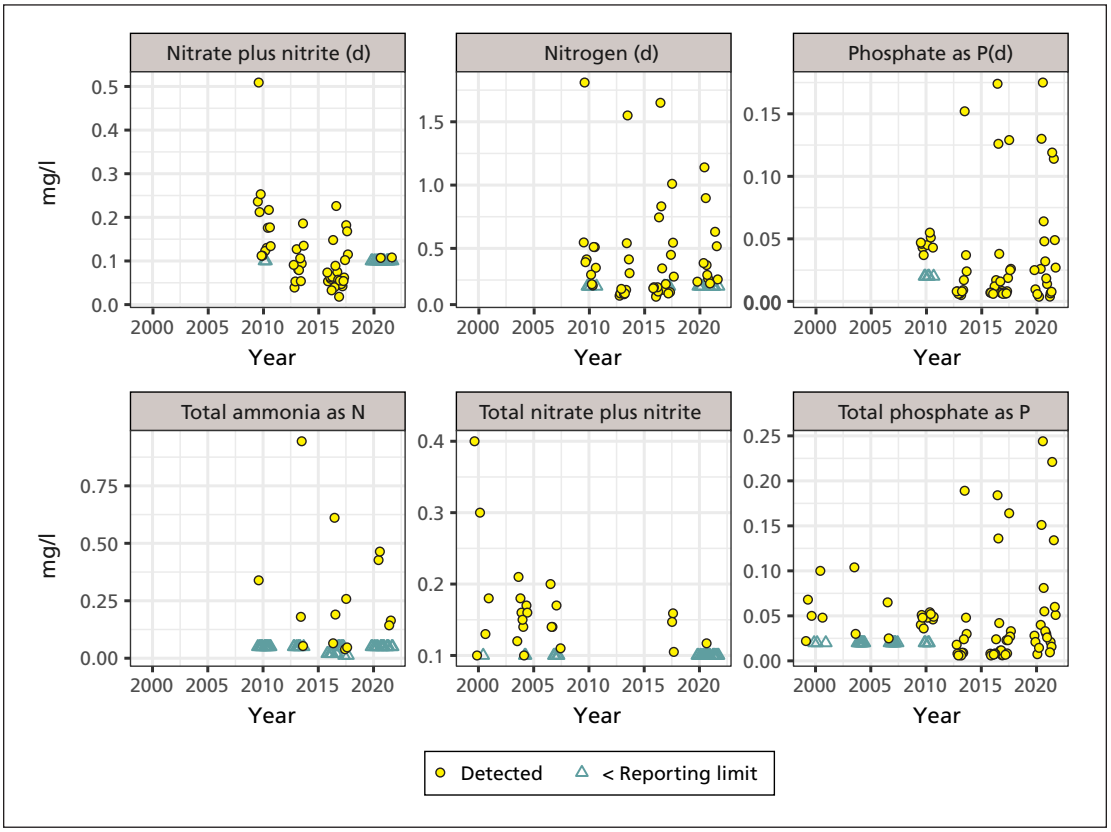


Figure 3-13. Concentrations of nutrients at Square Tower Spring, 1999–2021. Dissolved nitrate plus nitrite decreased over time, while total nitrogen, dissolved phosphorus, and total phosphorus had no trend. Total ammonia and total nitrate plus nitrite had >50% censored data. Values below the reporting limit were at levels too low to be precisely measured, and are plotted at the reporting limit.

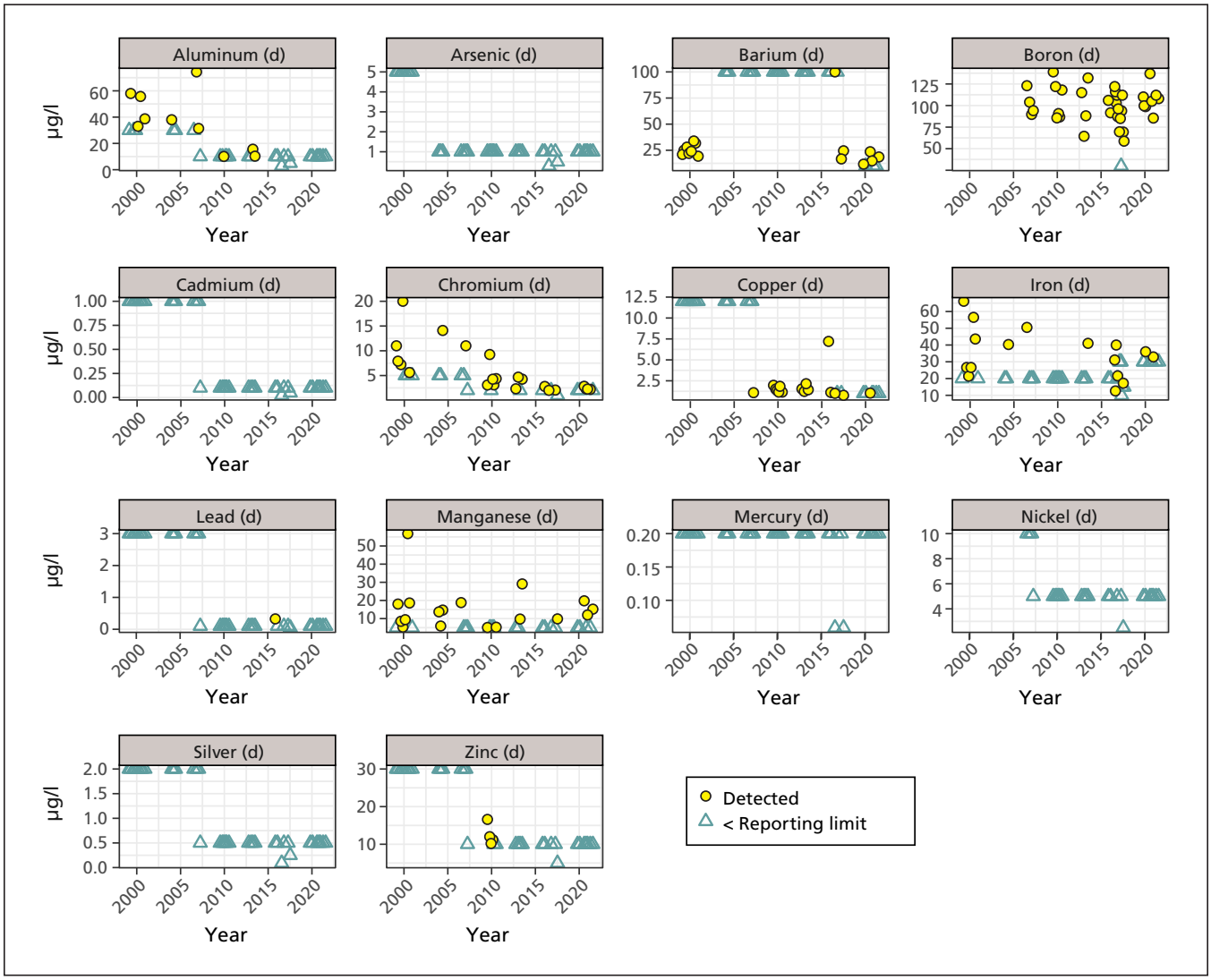


Figure 3-14. Trace element concentrations at Square Tower Spring, 1999–2021. Most trace elements had >50% censored data and therefore were not tested for trends. The exceptions are chromium, which had a decreasing trend, and boron, which had no trend over time. Values below the reporting limit were at levels too low to be precisely measured, and are plotted at the reporting limit.

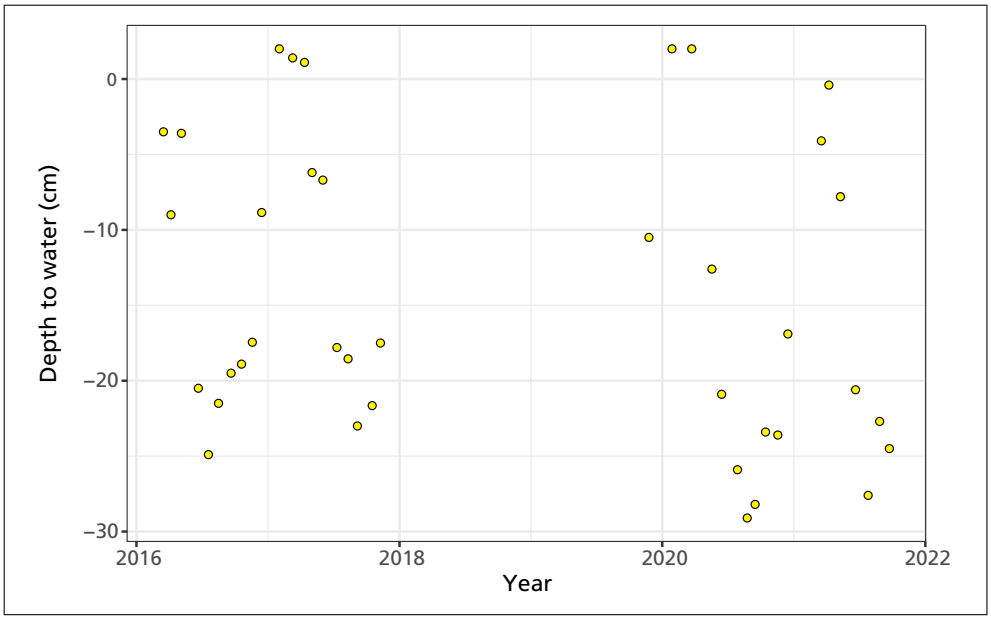


Figure 3-15. Depth to water from the ground surface in the runoff channel downstream of Square Tower Spring, 2016–2021.

3.2.2 Hackberry Pool

Hackberry Pool is located in a large alcove at the head of Hackberry Canyon. Hackberry House and other ancestral Puebloan structures are located above the alcove on the canyon rim and in the alcove. Numerous large hackberry trees grow in the area, mostly on the canyon floor downslope of the alcove. Hackberry Pool is a small perennial spring-fed pool, roughly 2 × 1 meters in surface area, on the west side of the alcove and canyonhead. It was a water-chemistry sampling location from 1999 to 2010. The pool is fed by perched subsurface groundwater from a buried contact zone and was dug out and developed by the ancestral Puebloans. The floor of the alcove slopes inward toward the pool, and runoff and snowmelt have been observed entering the pool. Water-chemistry sampling was suspended after 2010, due to a reprioritization and decrease in sampling sites (Hackbarth and Weissinger 2013), but the site continues to be sampled for pool level, water temperature, pH, and specific conductance as part of NCPN's springs monitoring protocol.

The spring-associated area for monitoring includes a deep, dry alcove (Figure 3-16). A grove of large hackberry trees begins just past the alcove dripline (Figure 3-17). A second alcove at the head of the canyon has some moss and a few drips, and was previously monitored as Upper Hackberry Spring (Spring #4).

3.2.2.1 Site characterization

The spring-associated area for monitoring is approximately 308 m^2. The spring orifice is heavily shaded by the deep alcove, receiving about 18% of the annual potential solar radiation at the site and 10% of the potential growing-season solar radiation. In September 2020, eight vegetation species were identified at the site, none considered wetland species. Total vegetation cover was estimated at approximately 38%. Exotic species detected included cheatgrass (*Bromus tectorum*), lamb's quarters (*Chenopodium album*), and horehound (*Marrubium vulgare*). A full species list for the site is available in Appendix A.



Figure 3-16. Water-quality and pool-level monitoring location at Hackberry Pool, April 2017.

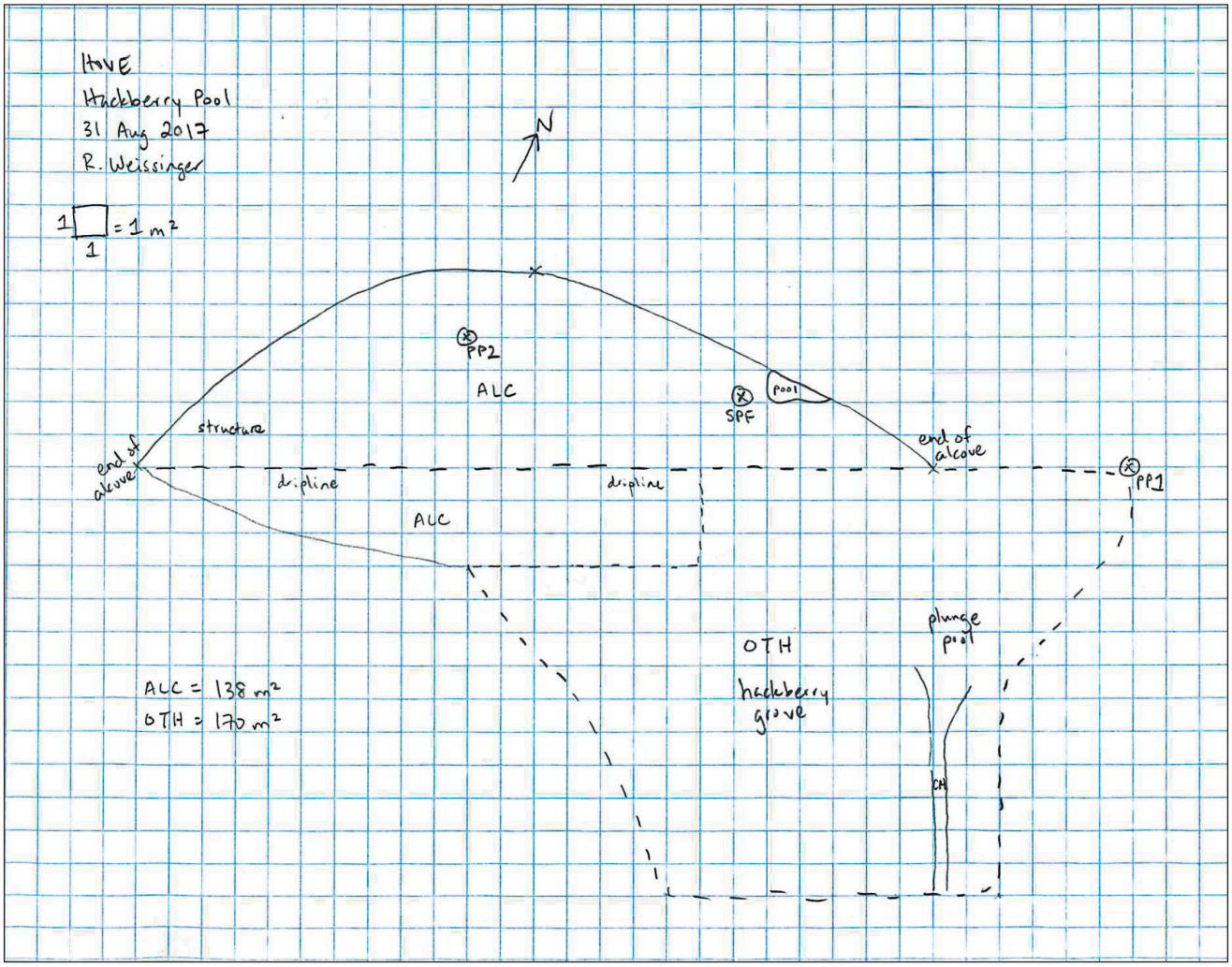


Figure 3-17. Sketch map of spring-associated area at Hackberry Pool.

3.2.2.2 Hydrologic summary and trends

Hackberry Pool's water level increased by an estimated 0.05 meters from 2004 to 2021, with a notable step increase in 2016 (Figure 3-18, Table 3-6). Specific conductance decreased over time. After adjusting for pool levels, all core parameters had trends, with additional decreases in pool level-adjusted dissolved oxygen and pH and an increase in water temperature (Table 3-6). Summary statistics and timeseries graphs for core parameters are presented in Table 3-7 and Figure 3-19. Discontinued water-chemistry parameters are presented in Section 3.2.2.3.

3.2.2.3 Discontinued parameters

Water-chemistry samples were collected from 1999 to 2010. All major ions except for alkalinity showed decreases in ambient concentrations over time (Table 3-8), as did total nitrate plus nitrite. Many of these trends disappeared after adjusting for pool levels, suggesting that changes in pool level may be the primary driver in these trends. Samplers observed increasing runoff into the pool over time, so an increasing proportion of rainwater and snowmelt may contribute to some of these changes in water chemistry. Summary statistics and timeseries graphs for discontinued parameters are presented in Tables 3-9 to 3-10 and Figures 3-20 to 3-21.

3.2.3 Goodman Point Spring

Located near Cortez, Colorado, the Goodman Point Unit is the furthest outlier of the units of Hovenweep NM. It has a different setting than the other units, consisting primarily of deep loamy alluvial soils with a shallow bedrock drainage but no canyons. It is the site of a large expanse of mostly unexcavated ancestral Puebloan structures. The spring is on the east side of the unit, located approximately centrally in a north-south direction. The habitat abruptly changes from upland to thick riparian at a ledge in a shallow drainage that drops down to the spring-associated area. Surface water is sometimes present immediately below the ledge and gains from alluvial slopes on the sides of the shallow channel over the course of about 100 meters. The drainage also flows during snowmelt and runoff events. Flowing water is difficult to locate in the thicket of riparian vegetation downstream of Goodman Point Spring. An accessible site approximately 100 meters downstream of the ledge has been established as the hydrologic measurement site (Figure 3-22, 3-23).

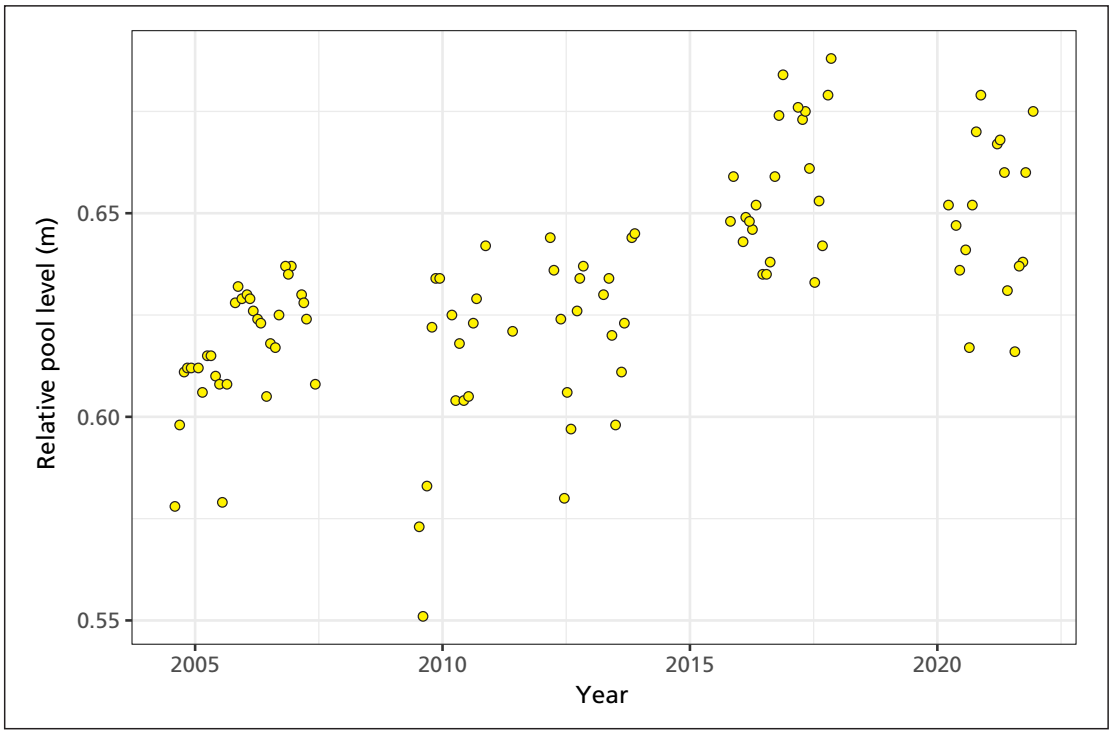


Figure 3-18. Relative pool level increased at Hackberry Pool from 2004 to 2021.

Table 3-6. Trends in currently monitored parameters at Hackberry Pool, 1999–2021.

Parameter	Analysis type	Period of record (yrs)	p-value	Ambient trend	Median concentration	Ambient change	Percent change	Pool level-adjusted measure	
								p-value	Trend
Dissolved oxygen (mg/l)	Qr	23	0.583	none	7.12	–	–	<0.001	down
pH	Qr	23	0.731	none	7.69	–	–	0.006	down
Relative pool level (m)	Qr	18	<0.001	up	0.63	0.05	8	–	–
Specific conductance (µs/cm)	Qr	23	<0.001	down	594	–347	–58	<0.001	down
Water temperature (°C)	Qr	23	0.386	none	11.6	–	–	<0.001	up

Table 3-7. Summary statistics for core parameters at Hackberry Pool, 1999–2021.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Dissolved oxygen (mg/l)	2/19/1999	12/8/2021	16	104	0	3.49	7.12	13.19
pH	2/19/1999	12/8/2021	16	107	0	7.47	7.69	8.21
Relative pool level (m)	8/5/2004	12/8/2021	14	103	0	0.60	0.63	0.67
Specific conductance (µs/cm)	2/19/1999	12/8/2021	16	108	0	497	594	797
Water temperature (°C)	2/19/1999	12/8/2021	16	109	0	6.4	11.6	17.3

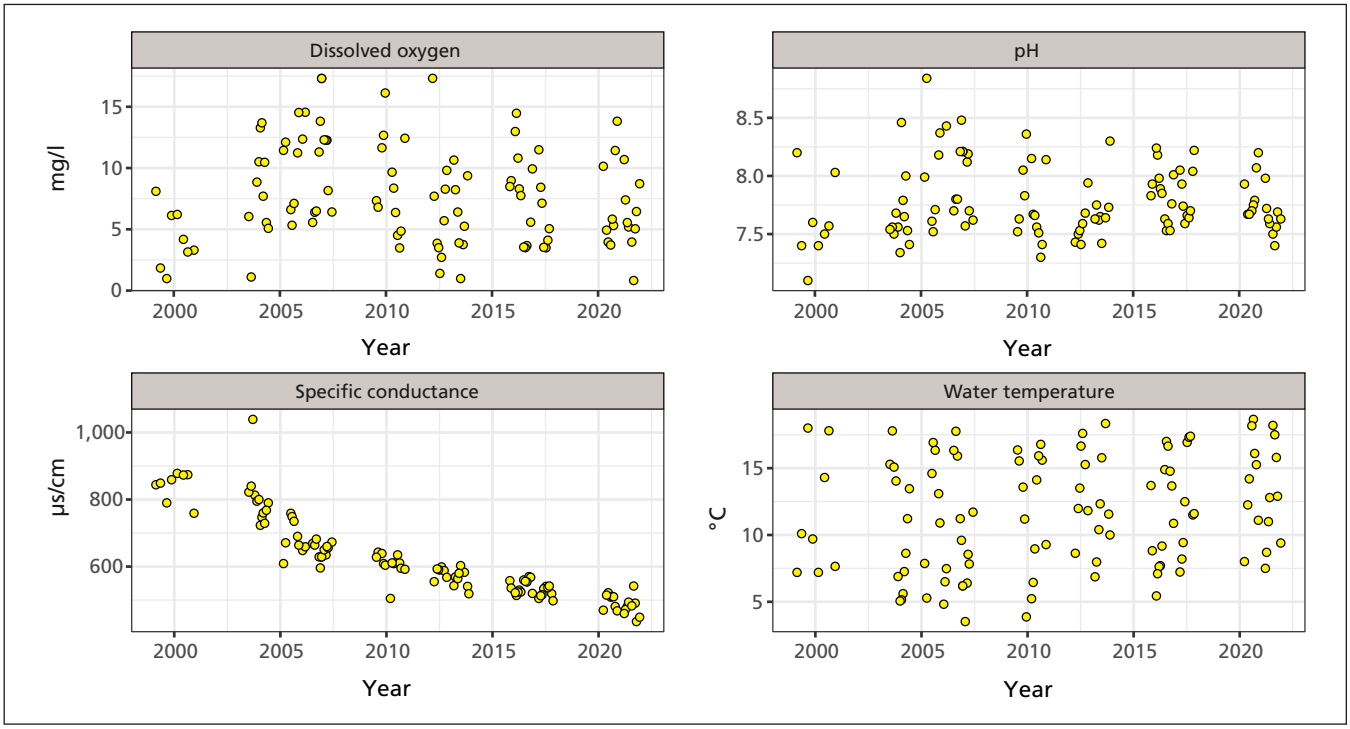


Figure 3-19. Trends in core parameters at Hackberry Pool, 1999–2021. Dissolved oxygen, pH, and temperature showed no trend, while ambient specific conductance decreased over time.

Table 3-8. Trends in discontinued water-chemistry parameters with <50% censored data at Hackberry Pool, 1999–2010.

Parameter	Analysis type	Period of record (yrs)	p-value	Ambient trend	Median concentration	Ambient change	Percent change	Pool level-adjusted measure	
								p-value	Trend
Alkalinity (mg/l)	Qr	12	0.732	none	169	–	–	0.075	none
Calcium (d) (mg/l)	Qr	12	<0.001	down	83.3	–30.8	–37	0.609	none
Chloride (mg/l)	Qr	12	<0.001	down	34	–41.4	–122	0.003	down
Magnesium (d) (mg/l)	Qr	12	<0.001	down	14.9	–6.8	–46	0.068	none
Potassium (d) (mg/l)	Qr	12	<0.001	down	2.3	–1.0	–43	0.298	none
Sodium (d) (mg/l)	Qr	12	<0.001	down	38.3	–29.6	–77	0.013	down
Sulfate as SO_4 (mg/l)	Qr	12	<0.001	down	88.4	–67.1	–76	0.056	none
Total dissolved solids (mg/l)	Qr	12	<0.001	down	394	–203	–52	0.127	none
Total nitrate plus nitrite (mg/l)	Qr	9	0.005	down	12.6	–11.0	–88	0.884	none

Table 3-9. Summary statistics for major ions at Hackberry Pool, 1999–2010.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10^{th}	50^{th}	90^{th}
Alkalinity (mg/l)	2/19/1999	9/9/2010	8	39	0	158	169	180
Calcium (d) (mg/l)	2/19/1999	9/9/2010	8	39	0	71.3	83.3	104
Chloride (mg/l)	2/19/1999	9/9/2010	8	39	0	28.2	34	63
Magnesium (d) (mg/l)	2/19/1999	9/9/2010	8	39	0	13.1	14.9	18.7
Potassium (d) (mg/l)	2/19/1999	9/9/2010	8	39	0	1.9	2.3	3.2
Sodium (d) (mg/l)	2/19/1999	9/9/2010	8	39	0	30.7	38.3	55.9
Sulfate as SO_4 (mg/l)	2/19/1999	9/9/2010	8	38	0	68.4	88.4	121
Total dissolved solids (mg/l)	2/19/1999	9/9/2010	8	39	0	356	394	535

Table 3-10. Summary statistics for nutrients in Hackberry Pool, 1999–2010.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10^{th}	50^{th}	90^{th}
Total nitrate plus nitrite (mg/l)	5/9/1999	6/7/2007	6	28	1	7.9	12.6	16.5
Total phosphate as P (mg/l)	2/19/1999	9/9/2010	8	39	27	<0.02	<0.02	0.05

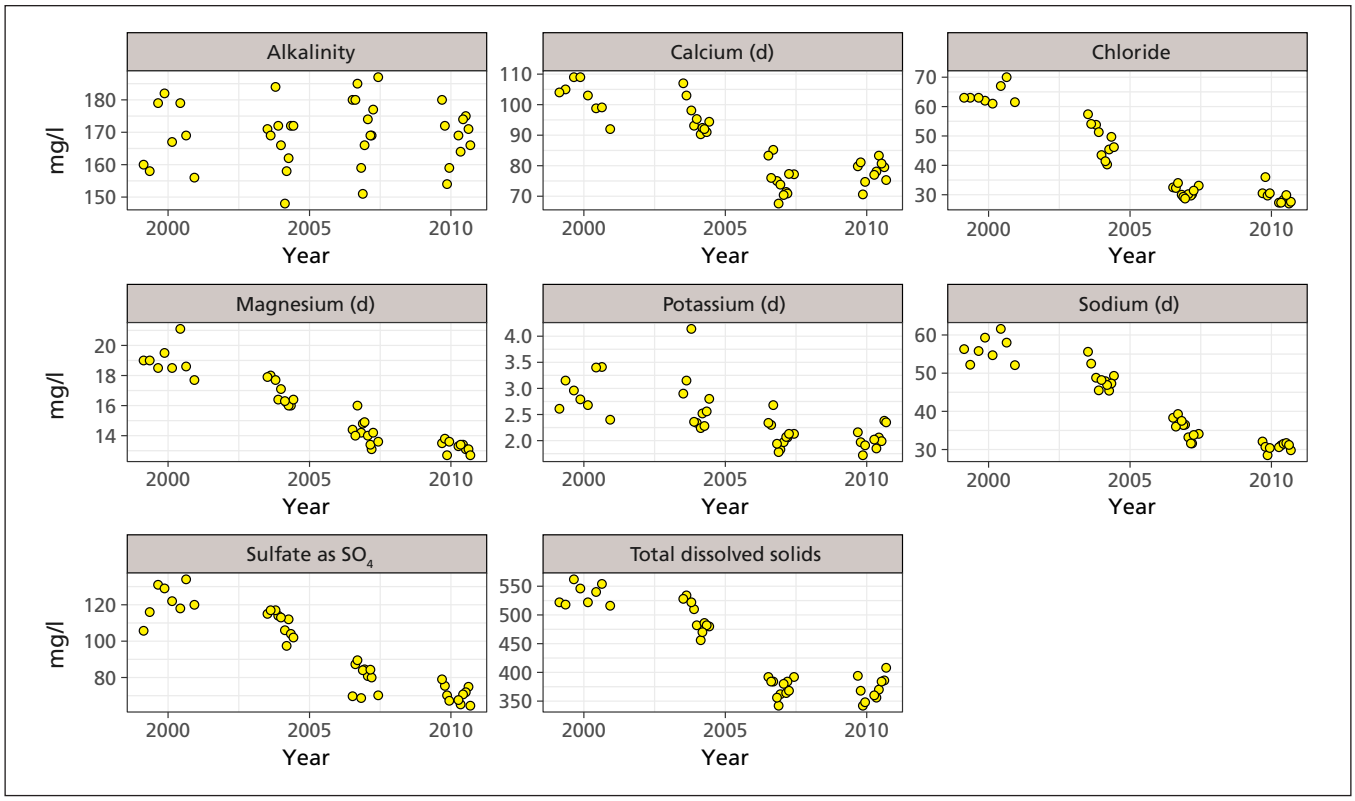


Figure 3-20. Concentrations of major ions in Hackberry Pool, 1999–2010. All major ions except alkalinity decreased over time.

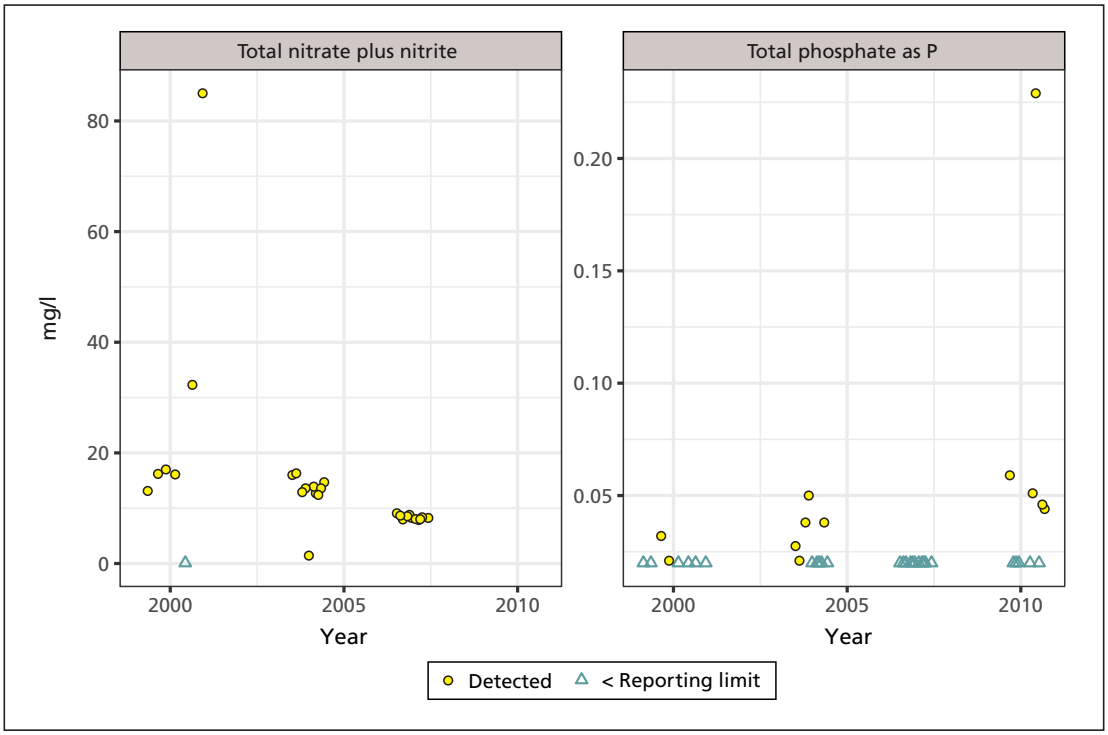


Figure 3-21. Concentrations of nutrients in Hackberry Pool, 1999–2010. Total nitrate plus nitrite decreased over time. Total phosphorus had >50% censored data and was not tested for trend. Values below the reporting limit were at levels too low to be precisely measured, and are plotted at the reporting limit.



Figure 3-22. Springflow monitoring location at Goodman Point, April 2017. The core parameter measurement location is also visible at the upstream reach of the stream in the photo.

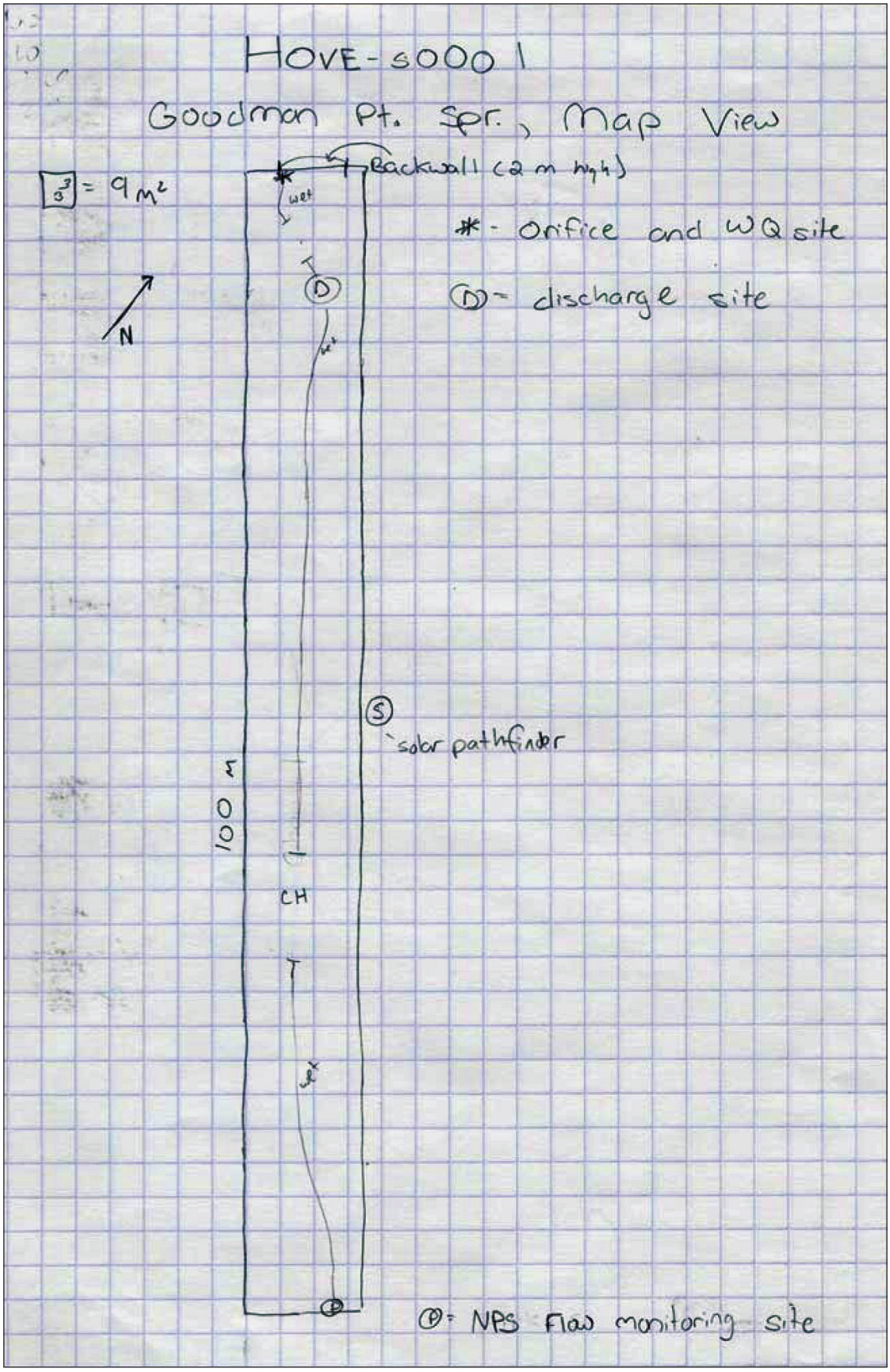


Figure 3-23. Sketch map of spring-associated area at Goodman Point Spring. The hydrologic monitoring location used in this report is the NPS site at the downstream end of the sketch map.

3.2.3.1 Site characterization

The spring-associated area for monitoring is approximately 1,000 m^2, with a spring channel that flows for more than 50 meters, extending beyond the monitored area. The spring receives about 95% of the annual potential solar radiation at the site and 97% of the potential growing-season solar radiation. In September 2020, 29 vegetation species were identified at the site, seven of which are considered wetland species. Wetland vegetation cover was estimated at approximately 28%, and non-wetland cover at about 21%. There were 10 exotic species: burdock (*Arctium minus*), smooth brome (*Bromus inermis*), Japanese chess (*Bromus japonicus*), musk thistle (*Carduus nutans*), Canada thistle (*Cirsium arvense*), prickly lettuce (*Lactuca serriola*), sweet clover (*Melilotus officinalis*), catnip (*Nepeta cataria*), broadleaf plantain (*Plantago major*), and mullein (*Verbascum thapsus*). A full species list for the site is available in Appendix A.

3.2.3.2 Hydrologic summary and trends

Goodman Point Spring's flow decreased by an estimated 4.19 l/min (about 70%) from 2004 to 2021 (Figure 3-24, Table 3-11). There were no ambient or flow-adjusted trends in water-quality parameters. Summary statistics and timeseries graphs for core parameters are presented in Table 3-12 and Figure 3-25.

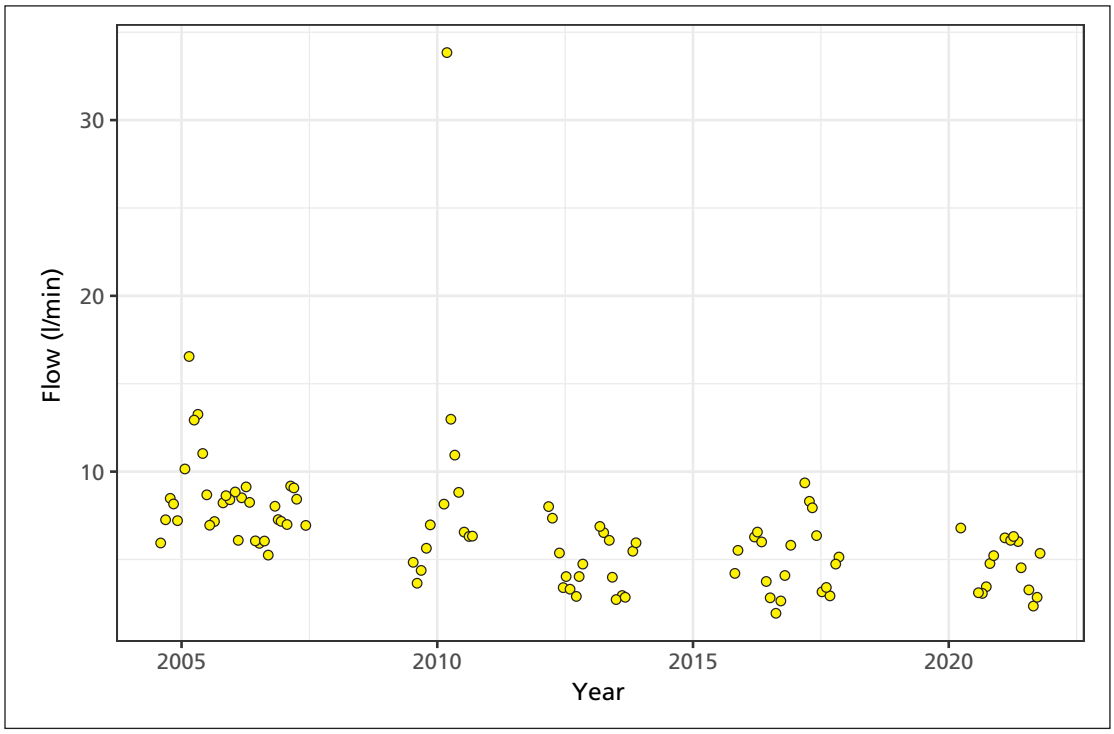


Figure 3-24. Measured springflow decreased at Goodman Point Spring from 2004 to 2021.

Table 3-11. Trends in core parameters at Goodman Point Spring, 2004–2021.

Parameter	Analysis type	Period of record (yrs)	p-value	Ambient trend	Median concentration	Ambient change	Percent change	Flow-adjusted measure	
								p-value	Trend
Dissolved oxygen (mg/l)	qr	17	0.278	none	8.27	–	–	0.507	none
Flow (l/min)	qr	18	<0.001	down	6.11	–4.19	–69	<0.001	–
pH	qr	17	0.404	none	8.06	–	–	0.151	none
Specific conductance (µs/cm)	qr	17	0.949	none	1,321	–	–	0.320	none
Water temperature (°C)	qr	18	0.124	none	9.4	–	–	0.164	none

Table 3-12. Summary statistics for core parameters at Goodman Point Spring Spring, 2004–2021.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Dissolved oxygen (mg/l)	2/24/2005	12/8/2021	8	54	0	7.15	8.27	9.11
Flow (l/min)	8/5/2004	12/8/2021	13	101	0	3.07	6.11	9.13
pH	2/24/2005	12/8/2021	9	65	0	7.86	8.06	8.22
Specific conductance (µs/cm)	4/1/2005	12/8/2021	9	66	0	1,253	1,321	1,395
Water temperature (°C)	12/3/2004	12/8/2021	10	69	0	4.0	9.4	15.8

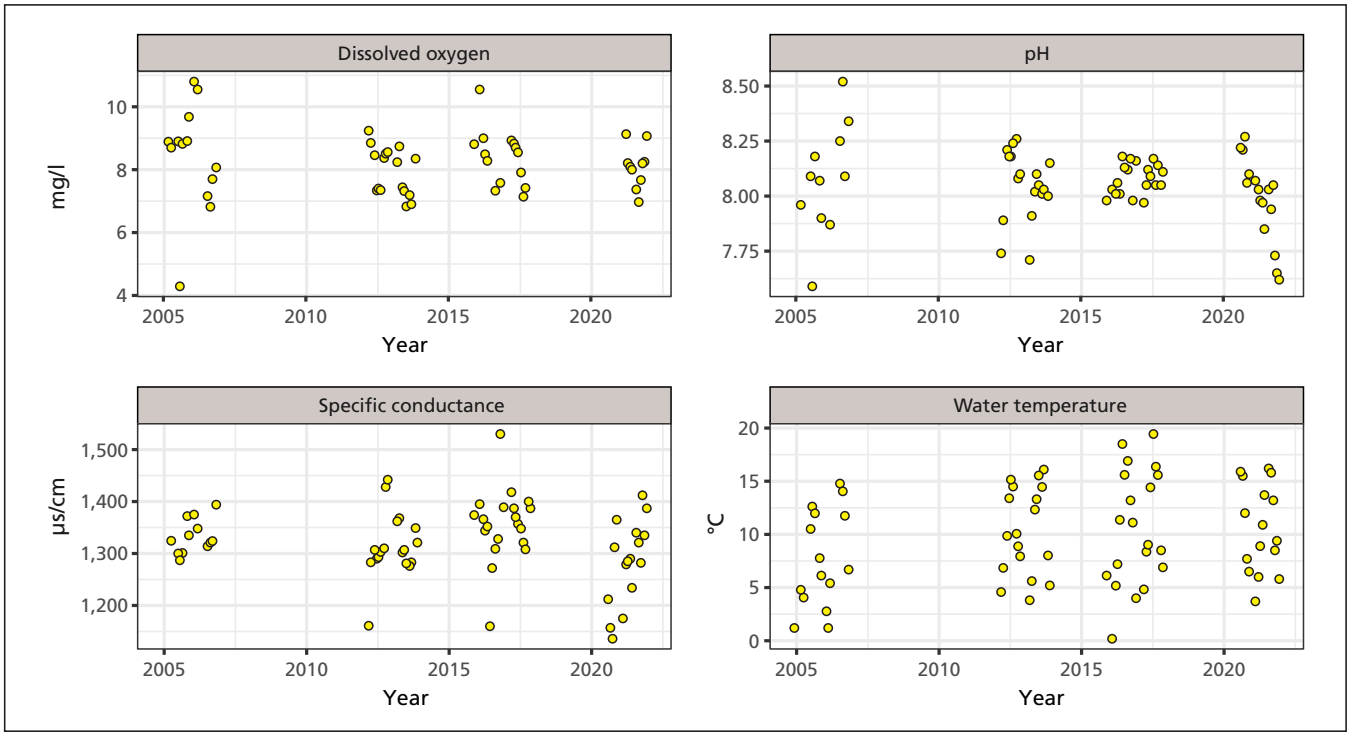


Figure 3-25. Core parameters in Goodman Point Spring, 2004–2021. There were no trends over time.

3.3 Discontinued locations

3.3.1 Cajon Pool

A pool in the Cajon Unit of Hovenweep was sampled from 1999 to 2013. It is at the head of a small canyon located near ancestral Puebloan structures along the canyon rim. A slickrock pouroff less than 10 meters upstream of the pool funnels precipitation into the drainage. At the pouroff, wet seep areas are sometimes visible under the overhang. The sample pool is relatively deep, holding water for extended periods after runoff events. An old steel pipe in the pool remains, probably from a past effort to funnel the water downstream for livestock use (Figure 3-26). The pool dries up during dry seasons or dry years; recorded pool levels of zero indicate the pool was dry (Figure 3-27). Sampling in the pool was discontinued after 2013, due to the frequency of dry visits, high variability in sampling results because of the dynamics of the pool's serving as a rainwater catchment, and logistical constraints on the monitoring program (Hackbarth and Weissinger 2013).



Figure 3-26. Cajon Pool location during a dry site visit in April 2013.

From 1999 to 2013, there were increasing trends in potassium and total phosphate as P (Table 3-13). Most core parameters and major ions remained stable over time, while most nutrients and trace elements had insufficient data for trend analysis. Summary statistics and timeseries for discontinued parameters are presented in Tables 3-14 to 3-15 and Figures 3-28 to 3-30.

3.3.2 Upper Hackberry Spring (Spring #4)

At the beginning of the monitoring period, a spring also emerged from a small alcove just west and upgradient of Hackberry Pool, called Upper Hackberry Spring or Spring #4 in previous reports (Figure 3-31; Schelz and Moran 2006). Volumetric flow measurements were recorded at this site during visits to Hackberry Pool through 2013, but by 2010 the outflow channel was mostly dry (Figure 3-32). Flow monitoring was suspended after 2013 (Table 3-16). Seepage still persists under the low, sloping alcove wall at this location, but there has been no outflow from this area in recent years (M. Moran, pers. comm. 2/6/2020).

3.3.3 Horseshoe Spring

The Horseshoe Spring site is an alcove seep located directly below Horseshoe House in the Horseshoe/Hackberry Unit of Hovenweep NM. Water consistently drips from the walls at the back of the alcove, and tiny shallow pools were sometimes present (Figure 3-33), but measurable surface flow was rare since observations began in June 2004 (Table 3-17, Figure 3-34). Visits were suspended after 2013. No trend analysis was completed because more than 50% of visits were dry.

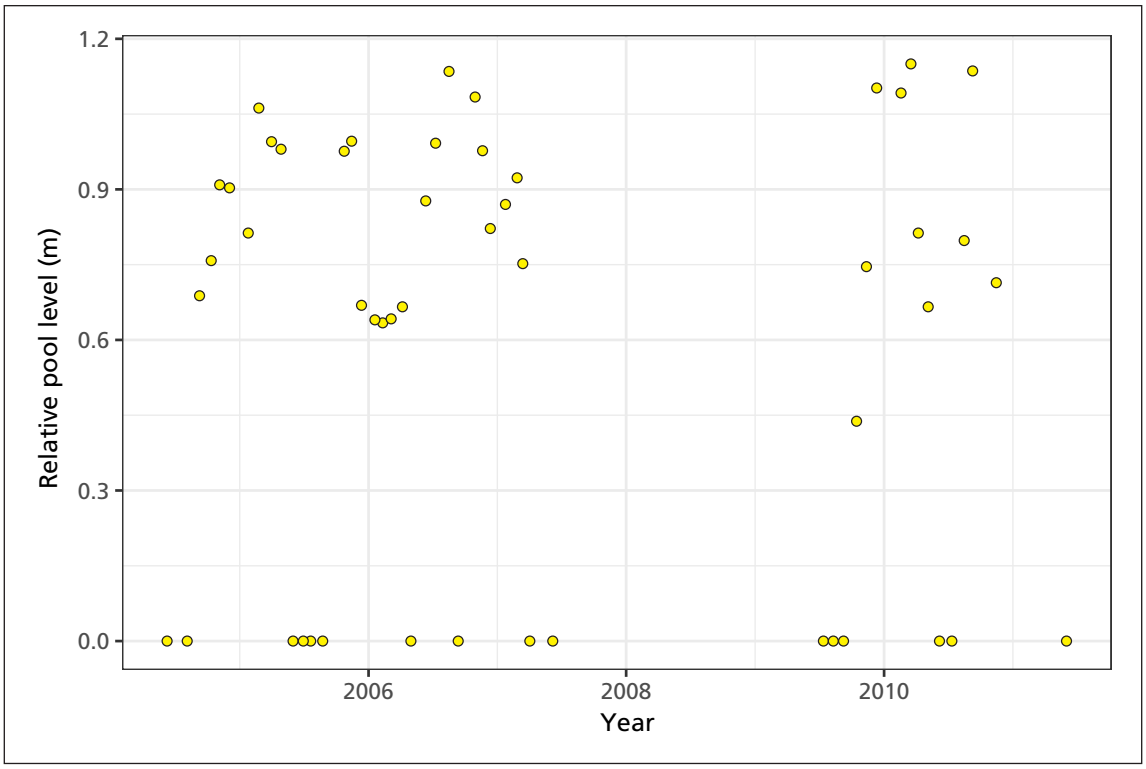


Figure 3-27. Relative pool level at Cajon Pool, 2004–2013. Dry visits are represented by zeros.

Table 3-13. Trends in discontinued water-chemistry parameters in Cajon Pool, 1999–2013.

Parameter	Analysis type	Period of record (yrs)	p-value	Ambient trend	Median concentration	Ambient change	Percent change
Dissolved oxygen (mg/l)	Qr	15	0.167	none	3.83	–	–
pH	Qr	15	0.595	none	7.43	–	–
Relative pool level (m)	Qr	8	0.923	none	0.730	–	–
Specific conductance (µs/cm)	Qr	15	0.987	none	426	–	–
Water temperature (°C)	Qr	15	0.746	none	8.4	–	–
Alkalinity (mg/l)	Qr	15	0.178	none	162	–	–
Calcium (d) (mg/l)	Qr	15	0.209	none	61.9	–	–
Magnesium (d) (mg/l)	Qr	15	0.584	none	5.1	–	–
Potassium (d) (mg/l)	Qr	15	0.025	up	2.7	2.1	77
Sodium (d) (mg/l)	Qr	15	0.923	none	18.4	–	–
Sulfate as SO_4 (mg/l)	cqr	15	0.389	none	34.1	–	–
Total dissolved solids (mg/l)	Qr	14	0.938	none	256	–	–
Total phosphate as P (mg/l)	Qr	15	0.008	up	0.08	0.18	235

Table 3-14. Summary statistics for core parameters at Cajon Pool, 1999–2013.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Dissolved oxygen (mg/l)	2/19/1999	3/7/2013	11	37	0	1.39	3.83	8.55
pH	2/19/1999	3/7/2013	11	36	0	7.06	7.43	8.09
Relative pool level (m)	6/9/2004	6/2/2011	7	50	0	dry	0.730	1.085
Specific conductance (µs/cm)	2/19/1999	3/7/2013	11	39	0	148	426	740
Water temperature (°C)	2/19/1999	3/7/2013	11	39	0	1.8	8.4	20.3

Table 3-15. Summary statistics for major ions and nutrients at Cajon Pool from 1999 to 2013.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile		
						10th	50th	90th
Alkalinity (mg/l)	2/19/1999	3/7/2013	10	31	0	75	162	277
Calcium (d) (mg/l)	2/19/1999	3/7/2013	10	31	0	30.7	61.9	119
Chloride (mg/l)	2/19/1999	3/7/2013	10	31	16	<10	<10	22.3
Magnesium (d) (mg/l)	2/19/1999	3/7/2013	10	31	0	2.4	5.1	9.7
Potassium (d) (mg/l)	2/19/1999	3/7/2013	10	31	0	1.8	2.7	7.0
Sodium (d) (mg/l)	2/19/1999	3/7/2013	10	31	0	4.3	18.4	39.4
Sulfate as SO_4 (mg/l)	2/19/1999	3/7/2013	10	31	9	<20	34.1	68.7
Total dissolved solids (mg/l)	2/19/1999	12/5/2012	9	29	0	130	256	420
Total phosphate as P (mg/l)	2/19/1999	3/7/2013	10	31	1	0.02	0.08	0.36

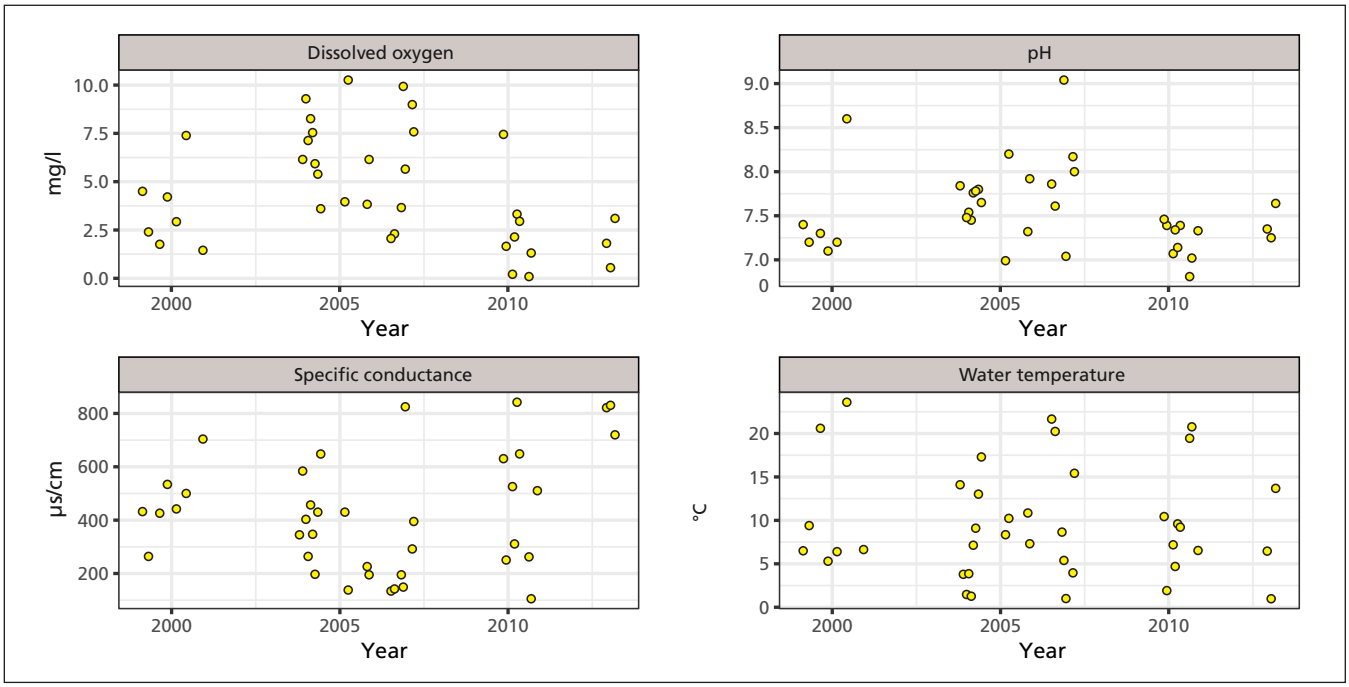


Figure 3-28. Core parameters at Cajon Pool, 1999–2013. There were no trends over time.

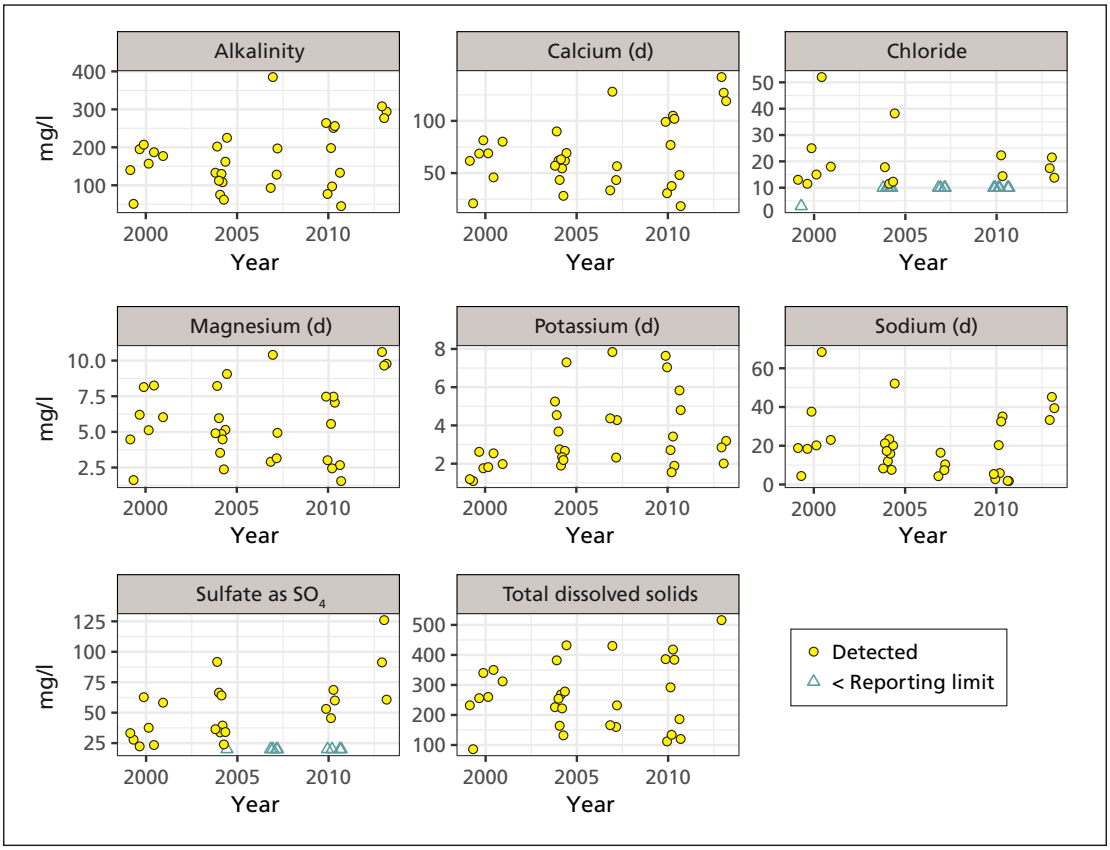


Figure 3-29. Major ions at Cajon Pool, 1999–2013. Potassium increased over time, while all other major ions remained stable. Values below the reporting limit were at levels too low to be precisely measured, and are plotted at the reporting limit.

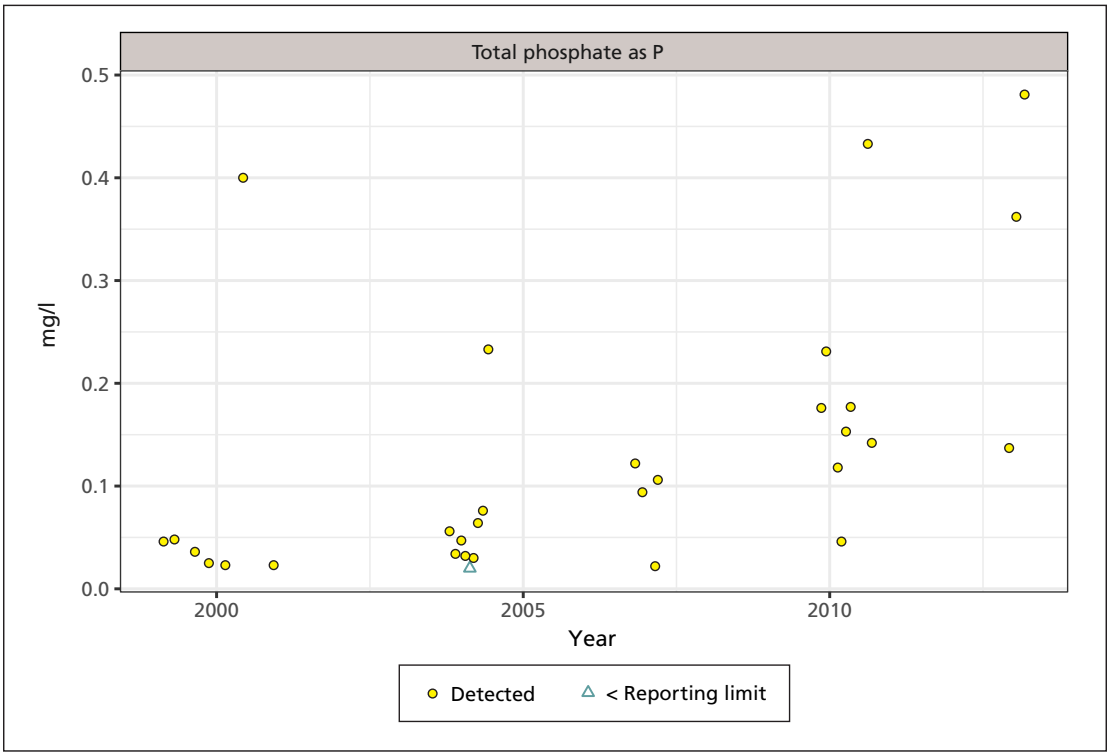


Figure 3-30. Total phosphate was the only nutrient with sufficient data for analysis at Cajon Pool. It increased over time. Values below the reporting limit were at levels too low to be precisely measured, and are plotted at the reporting limit.



Figure 3-31. Representative photo of flow monitoring site at Upper Hackberry Spring, taken sometime in 2004–2005, from Schelz and Moran 2006.

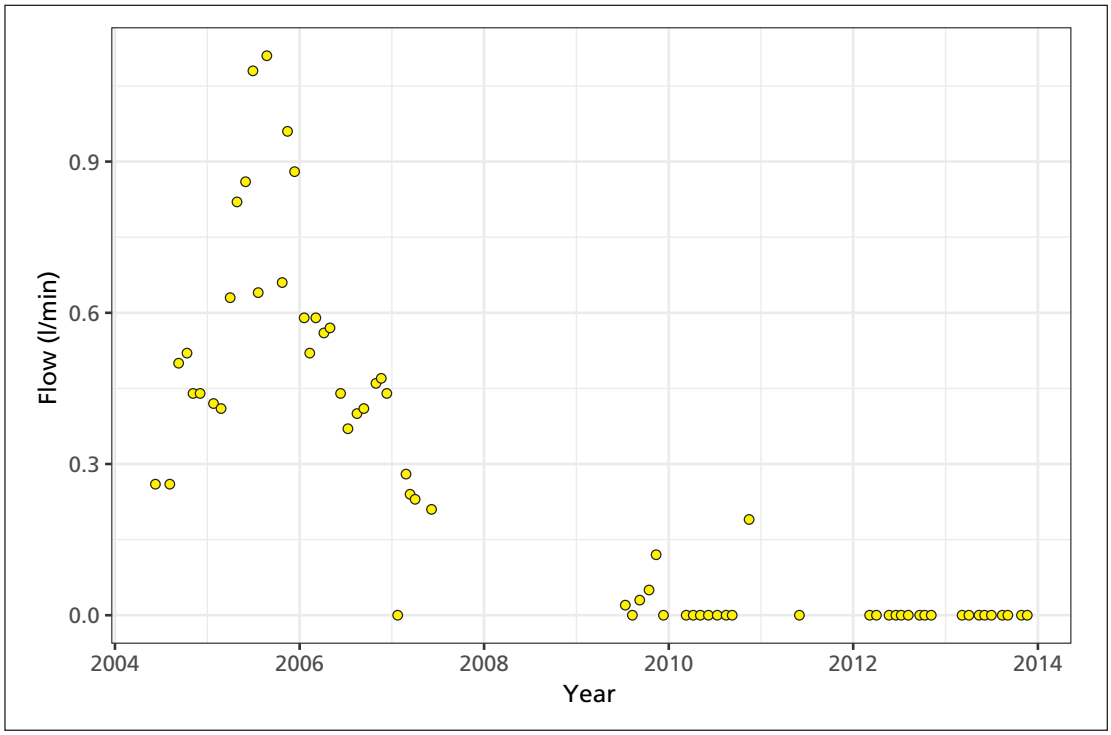


Figure 3-32. Decrease in flow at Upper Hackberry Spring (Spring #4), 2004–2013. Flow measurements ended in 2013 after several years of zero flow.

Table 3-16. Summary statistics and trend in flow at Upper Hackberry Spring (Spring #4), 2004–2013.

Parameter	Start	End	Sample yrs	N	Censored N	Percentile			Trend
						10th	50th	90th	
Flow (l/min)	8/5/2004	11/15/2010	6	37	0	0.162	0.44	0.868	down



Figure 3-33. Springflow monitoring location at Horseshoe Spring, December 2009.

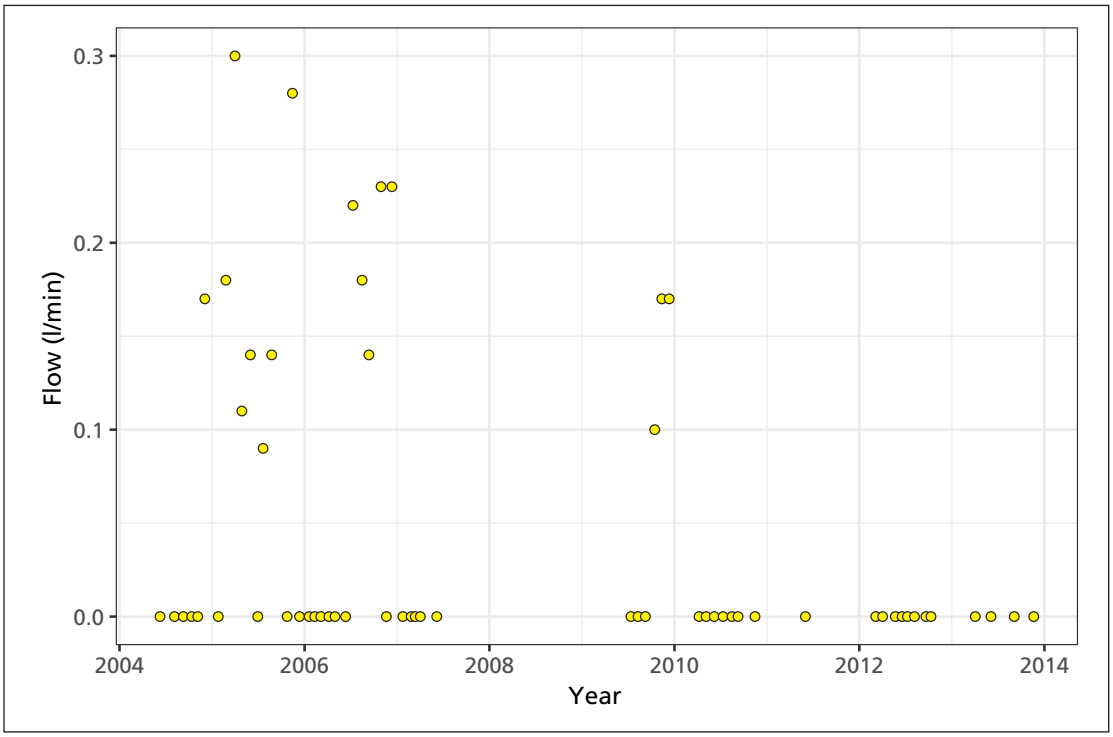


Figure 3-34. Measured flow at Horseshoe Spring from 2009 to 2013. Many visits were dry or had flow too low to be measured.

Table 3-17. Summary statistics for flow in Horseshoe Spring, 2004–2013.

Parameter	Test	Start	End	Samples	Censored	Percentile		
						10th	50th	90th
Flow (l/min)	N	6/9/2004	11/20/2013	60	44	0.00	0.00	0.18

4 Discussion

The water resources at Hovenweep NM have exhibited many trends over the previous 20 years. Flow has decreased by more than half at Goodman Point Spring and ceased at Upper Hackberry Spring (Spring #4). Flow at Horseshoe Spring was also increasingly absent or too low to be measured, although the period of record at this site was very short. In contrast, pool levels at both Square Tower Spring and Hackberry Pool went up, with a step increase shown in 2016 (after no sampling in 2014–2015).

The water chemistry in both Square Tower Spring and Hackberry Pool changed significantly, but in oppositional ways. Square Tower Spring had increasing total dissolved solids (TDS) and specific conductance, with all major ions showing increases over time. Hackberry Pool had decreases in TDS and most major ions through 2010, when water-chemistry lab analyses were suspended. Specific conductance continued to decrease at Hackberry Pool through 2021. Decreases at Hackberry Pool may be because of an observed increase in runoff and snowmelt making its way into the pool due to geomorphic changes at the site. In contrast, Square Tower Spring is isolated from runoff. Potential causes of trends are discussed below.

Groundwater is naturally low in dissolved oxygen, but the dissolved-oxygen concentrations in the two pools are persistently below state water-quality criteria for aquatic life. Dissolved oxygen was below the Utah warmwater aquatic-life standard of 5.5 mg/l on more than 50% of visits to Square Tower Spring and more than 30% of visits to Hackberry Pool. During the summer, dissolved oxygen can drop close to zero at these sites. Water temperatures also warm in conjunction with air temperatures, with temperatures as warm as 18°C in the pools and 19°C in Goodman Point Spring. Persistent low- to no-flow conditions and dissolved-oxygen concentrations do not support most aquatic life.

Springs are culturally important locations for many indigenous communities in the southwestern US. Water resources at Hovenweep NM were actively managed during ancestral occupancy. Ancestral people of the Southwest built infrastructure, such as check dams, walled springs, basins, and reservoirs, to manage and improve access to surface water (Crown 1987) and potentially augment groundwater recharge (Rohn 1972). Both Square Tower Spring and Hackberry Pool were excavated and reinforced by ancestral Puebloans, and check dams dot the landscape around Hovenweep NM. Goodman Point Spring is located downstream from an ancestral retention basin. Spring water quality was managed through techniques including clearing debris from springs and cleaning sediment from ponded areas (Rohn 1972; Wilshusen et al. 1997). If reinstated, these traditional cultural-management techniques could be useful in improving infiltration into aquifers and aquatic-habitat conditions. The effects of such techniques have not been scientifically studied, and potential increases in water quantity and dissolved-oxygen concentrations are plausible but not guaranteed. The potential risks of such techniques are also unknown.

4.1 Water quantity, drought stress, and climate resilience

The period of record for our monitoring data (1999–2021) corresponds almost exactly to the severest drought recorded in the US Southwest for more than 1,200 years (Wahl et al. 2022; Williams et al. 2022). Studies suggest that such prolonged droughts will increase in frequency and duration over the next century or more, due to anthropogenic climate change (Cook et al. 2021). Despite fluctuations in annual precipitation, water deficit is increasing and drought conditions were common at Hovenweep NM from 2000 to 2019 (US Drought Monitor https://droughtmonitor.unl.edu accessed 6/27/2023). Our data suggest that flowing springs and spring-associated vegetation are vulnerable to drought because of increased evapotranspiration associated with higher air temperatures.

Vegetation in the spring-associated area showed signs of increased water stress at most sites. During site visits in 2020

and 2021, the namesake hackberry trees (*Celtis reticulata*) at Hackberry Pool showed canopy browning (Figure 4-1) and dieback, with some trees losing large limbs (Figure 4-2). Canopy browning and dieback were also visible at the nearby locations of Horseshoe Spring and Holly House (Figure 4-3). It should also be noted that no true wetland species grow in the spring-associated area at Hackberry Pool. Similar signs of water stress have not yet been noted at Square Tower Spring, which also has a small grove of mature hackberry trees. After a robust monsoon season in 2021, hackberry-tree seedlings were noted at both Hackberry Pool and Square Tower Spring.

There is also evidence of long-term drying at Goodman Point Spring, in addition to the reductions in flow. A spring inventory project in 2005 documented the presence of cattails (*Typha latifolia*), a wetland obligate species, just below the ledge at the head of the spring area (Springer et al. 2006, Figure 4-4). In 2021, cattails were no longer present in the spring-associated area (Figure 4-5). Hackberry trees were noted in 2005 but not in 2020 or 2021, although thick vegetation at this site means species can easily be overlooked. Foliar browning was also noted on chokecherry (*Prunus virginiana*), a large shrub species, in 2021.



Figure 4-1. Poor leaf health on a hackberry tree at Hackberry Pool, September 2021.



Figure 4-2. Limb shedding on a mature hackberry tree, Hackberry Pool, September 2020.



Figure 4-3. Poor canopy health of a mature hackberry tree at Holly House, September 2020.



Figure 4-4. Wetland vegetation, including cattails, just below the ledge at Goodman Point Spring, July 2005. Standing water was also present in this area during the July 2005 visit.



Figure 4-5. Vegetation just below the ledge at Goodman Point Spring, September 2021. Note the lack of cattails and standing water.

The aquifers feeding Square Tower Spring and Hackberry Pool do not yet seem to have been affected by changes in precipitation or recharge. Both monitored sites showed increases in pool levels over time, although lower pool levels were associated with air temperatures above about 20°C. Regionally, a USGS groundwater well in the Dakota aquifer that is part of the national climate response network showed annual fluctuations in groundwater depth but no long-term change from 2008 to 2017 (Figure 4-6). However, from 2018 to 2021, groundwater levels declined at the USGS well. This well is located approximately 51 kilometers (32 mi) north of the Square Tower unit of Hovenweep NM. It is not directly connected to the local aquifers that feed the springs in Hovenweep NM but should be representative of the status of the Dakota aquifer regionally, given no withdrawals for human development (Cunningham et al. 2007). Decreases at this well have concerning implications for the aquifers emerging at Hovenweep NM, although it is unknown whether the aquifer is responding to recent climate conditions or has a time lag reflective of more ancient climate changes.

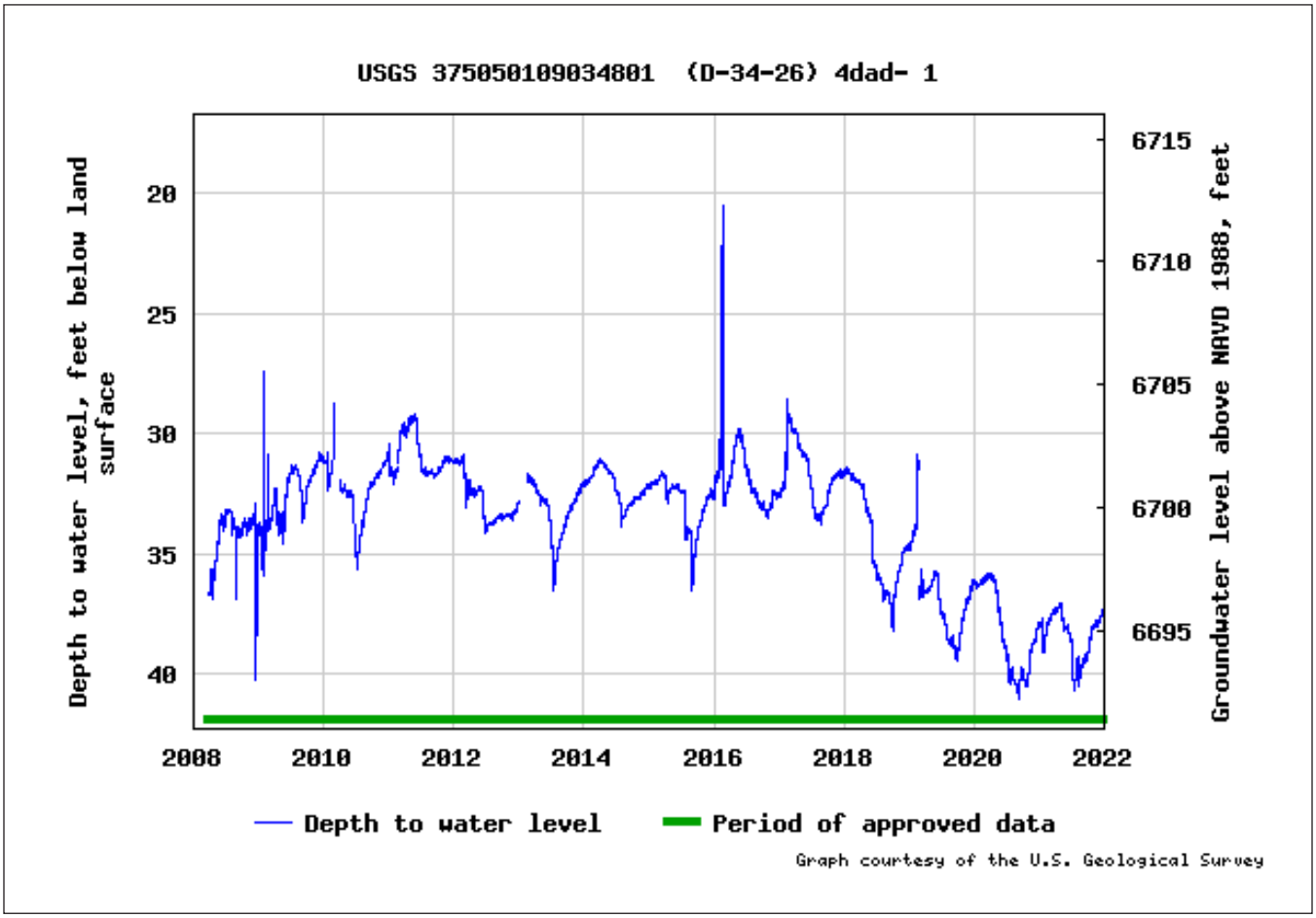


Figure 4-6. Depth-to-water in feet below ground surface from 2008 to 2021 at USGS groundwater well 375050109034801, completed in San Juan County, Utah, in the Dakota aquifer as part of the USGS climate response network. Figure accessed at USGS Current Conditions for USGS 375050109034801 (D-34-26) 4dad- 1 on 2/3/2023.

There are few existing diversions or anthropogenic withdrawals that could potentially affect Hovenweep NM (Figure 4-7). One small earthen dam intersects a drainage upgradient from Square Tower Spring, but it is unknown whether this structure is still functioning or how it might affect local recharge to the spring. A well near Goodman Point Spring has a 0.5-cfs (cubic feet per second) water right for stock watering and irrigation of 40 acres with an appropriation date of 1912, predating the Goodman Point Spring federal reserved right dating to 1951. The domestic well for consumptive use at Square Tower is completed in aquifers over a thousand feet below the Dakota aquifer and should not affect groundwater levels at Square Tower Spring (Martin 2000). Surface water at the Square Tower and Hackberry pools has shown great resilience through historic drought. This suggests that if the local Dakota aquifer remains protected from increased withdrawals, these springs may be able to persist through a warming future.

4.2 Water chemistry and quality

Although all three currently monitored springs emerge from the Dakota aquifer, their flow paths are likely quite different. Square Tower Spring, in particular, has elevated TDS and sulfate in comparison to the other springs. Goodman Point Spring has intermediate specific conductance, between that of Hackberry Pool and Square Tower Spring. A grab sample of water chemistry at Goodman Point Spring in 2005 (Springer et al. 2006) was also intermediate (between the water chemistry of the two pools). Square Tower Spring is characterized as a calcium sulfate water, which is typical of gypsum groundwater. Hackberry Pool and Goodman Point Spring are characterized as calcium bicarbonate waters, which are typical of shallow fresh groundwater (Figure 4-8).

Decreases in specific conductance and major ions in Hackberry Pool may be related to changes in geomorphology at the spring that have allowed additional runoff and melting snow to drain into the spring alcove and pool. After adjusting for pool levels, most of the decreasing trends stabilized, suggesting that pool level was a likely factor. However, Square Tower Spring had a similar increase in pool level, but rather than decreases, there were increases in specific conductance and major ions over time.

4.3 Potential effects of oil and gas development

One of the primary concerns when establishing the monitoring program at Hovenweep NM was a rapid increase in oil and gas drilling in the region (Schelz and Moran

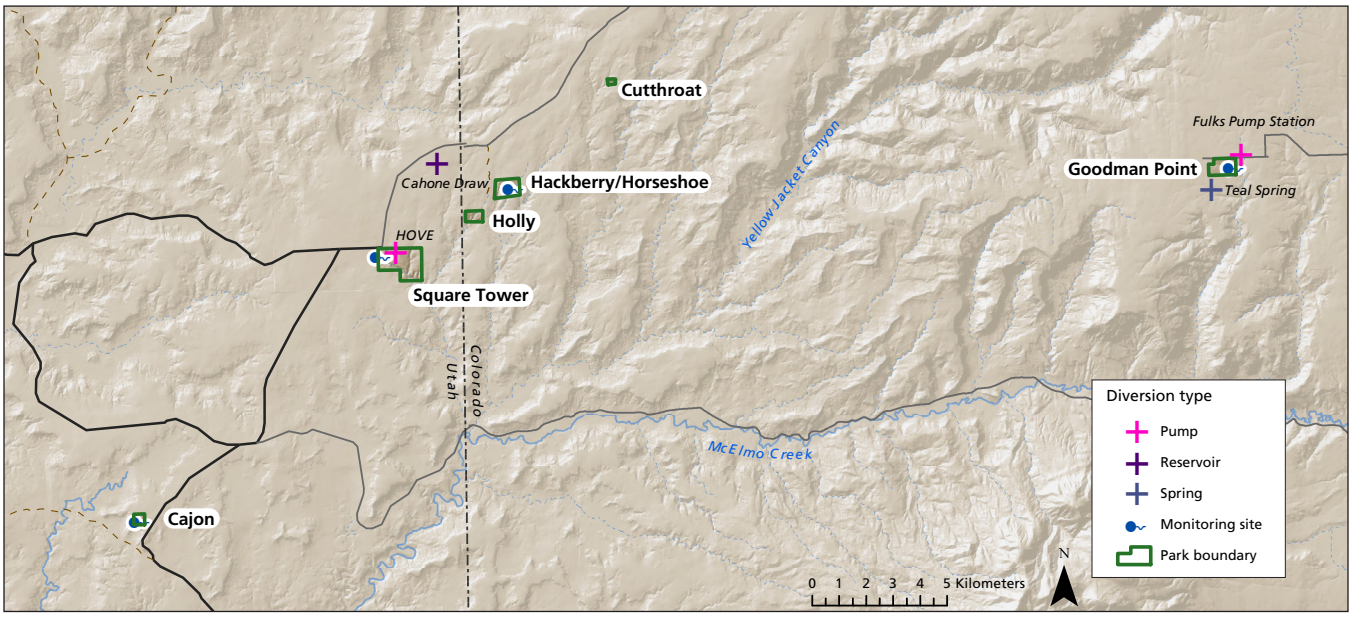


Figure 4-7. State-permitted consumptive water rights in proximity to Square Tower and Goodman Point springs, including the domestic well at the Square Tower unit. There are no state-permitted water rights near other Hovenweep NM units.

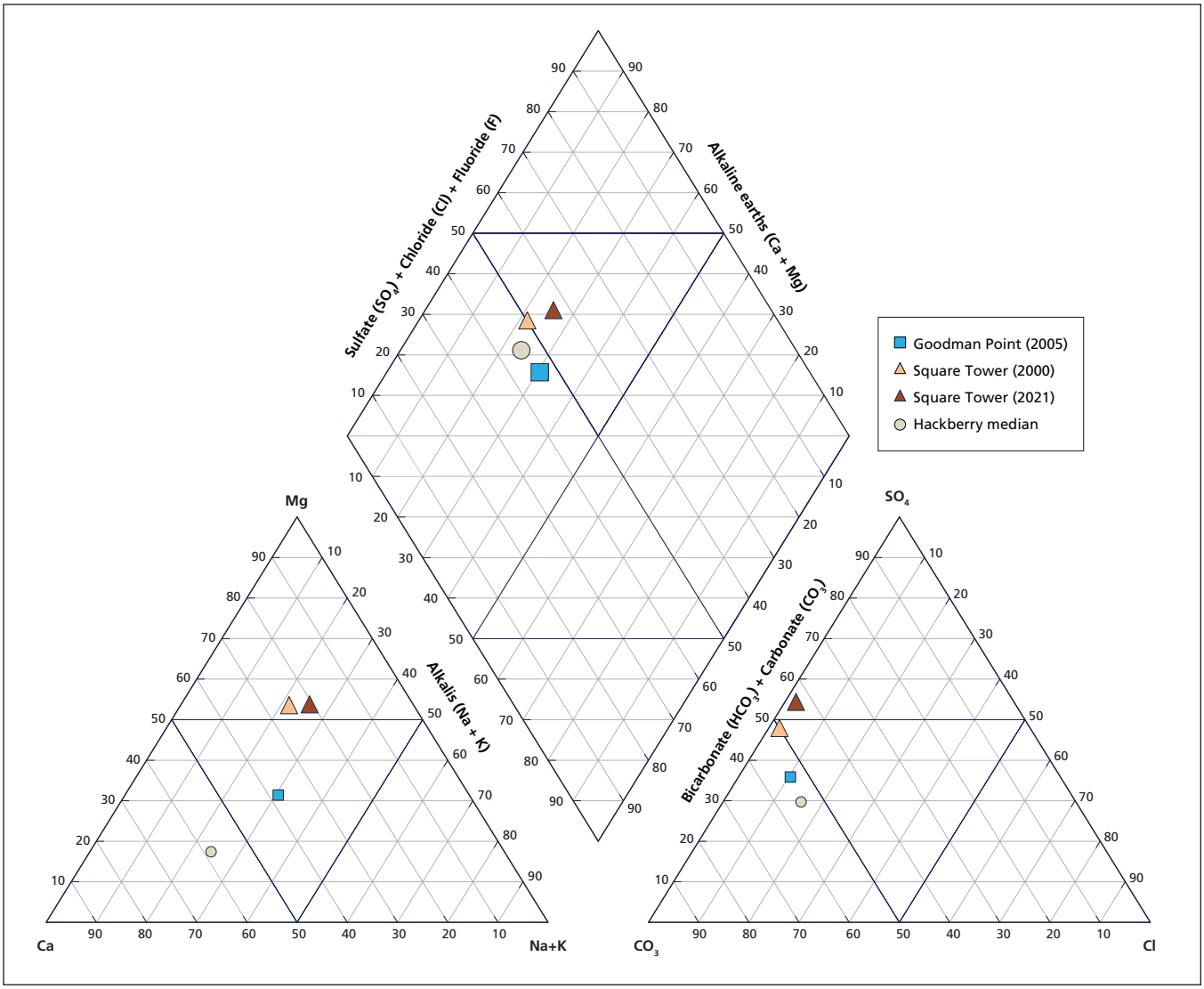


Figure 4-8. Piper plot showing water chemistry based on one sample from Goodman Point Spring in 2005, estimated median concentrations at the beginning and end of the period of record at Square Tower Spring, and median concentrations at Hackberry Pool. Piper plots show the relative contributions of different ions as a percentage of the total dissolved ions, with cations on the lower left triangle and anions on the lower right triangle. The upper diamond combines cations and anions to characterize the dominant water chemistry of the sample.

2006). Highly saline groundwater is found in the underlying Hermosa Group, which is also the target of oil and gas drilling in the region. Water chemistry of this type would be found in the middle-right quadrant of the diamond in the piper plot (Figure 4-8), indicating sodium-chloride waters. This saline groundwater is naturally confined from the Dakota aquifer by intervening impervious layers (Whitfield et al. 1983). Oil and gas wells penetrate through the Dakota aquifer to access underlying plays. While well construction is regulated to prohibit mixing of saline groundwater with overlying aquifers, contamination can occur via surface or subsurface processes (Goode 1958; Miller 2019). Groundwater contamination in proximity to oil and gas wells has been noted nearby on the Navajo (Avery 1986) and Ute Mountain Ute (Bauch and Arnold 2020) reservations.

Surface contamination can occur when oil wastes mixed with highly saline brine are deposited on the land surface after drilling. One such soil remediation site is located about 2.5 kilometers northwest of the Square Tower unit (Martin 2000). According to Martin: “Soil contaminated with crude oil from oilfields and crude oil storage sites

are brought to the site and allowed to undergo natural bioremediation. Berms have been constructed to prevent runoff from soil undergoing bioremediation. The site is underlain by about 150 feet of clayey soil." Surface drainage at the site moves away from Square Tower, and prevailing winds in the region are from the east-northeast (https://wrcc.dri.edu/Climate/comp_table_show.php?stype=wind_dir_avg, accessed 2/26/2020), which would also tend to blow dust from the site away from Square Tower Spring.

Subsurface contamination can be the result of unplugged or poorly plugged test holes or leaking water-injection wells (Goode 1958). There are several active and inactive wells within a three-kilometer radius of Square Tower Spring that penetrate the underlying brine layer (Martin 2000). Brines in the region typically have TDS of >35,000 mg/l and are dominated by sodium and chloride (Masbruch and Shope 2014). Brines in the nearby Aneth oilfield have chloride concentrations approaching 100,000 mg/l (Miller 2019).

Where the Paradox Formation surfaces in Paradox Valley, Colorado, natural inflow into the Dolores River caused TDS to increase from 370 mg/l to 1,570 mg/l (76%), sodium to increase from 66 mg/l to 480 mg/l (86%), and chloride to increase from 78 mg/l to 760 mg/l (90%; Watts 2000). Groundwater contamination by brines in the Williston Basin in eastern Montana shifted the composition of a sulfate/bicarbonate water to a chloride-dominated water and greatly exceed acute chloride concentrations of 860 mg/l (Preston et al. 2019). Increases at Square Tower Spring are relatively modest in comparison, and chloride concentrations remain quite low, with larger increases in sulfate. While chemistry shifted slightly toward an increased proportion of sodium from 2000 to 2021, chloride remained a negligible proportion of the water at Square Tower Spring (Figure 4-8).

The current water chemistry does not suggest a high likelihood that increases in TDS and major ions at Square Tower Spring are caused by contamination from oil and gas production. However, the cause of these trends is unknown. Regional studies indicate that the Burro Canyon Formation can have relatively high concentrations of uranium, while deepwater brines have signature levels of strontium and bromide (Kim et al. 2022). Bromide-to-chloride ratios and hydrogen and oxygen isotope ratios have also been used to distinguish between water sources (Miller 2019). Most of these analytes have not been part of the water-chemistry suite at Hovenweep NM. Follow-up sampling with targeted analytes could provide additional information about sources of water and potential mixing in Square Tower Spring.

4.4 Conclusions

Overall, the primary threat to springs at Hovenweep NM at this time is likely the effects of climate change. Increasing air temperature threatens springflow and spring-associated vegetation. While spring pool levels have increased, recent decreases in the regional Dakota aquifer raise concerns about the stability of pools in the future. Managers could consider:

- Prioritizing protections and actions at Square Tower Spring, which has been the most resilient site at Hovenweep NM in persistence of surface water and spring vegetation health during extreme drought.
- Implementing potential climate-adaptation actions that could improve groundwater infiltration upgradient of spring sites. This could include rehabilitating traditional structures to slow the flow of surface water.
- Implementing traditional management techniques that could improve dissolved-oxygen concentrations in the spring pools.
- Increasing invasive-plant removal efforts at Goodman Point Spring, which had the greatest number and cover of invasive-plant species of the three currently monitored locations.
- Developing interpretive stories about water-management techniques and the role of climate change in creating drought stress on hackberry trees.

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Appendix A. Supplemental Information

Table A-1. Analytical methods and reporting limits for water-quality parameters analyzed at the Utah Public Health Laboratory.

Category	Parameter	Analytical method[1]	Start date	End date	Highest reporting limit	Samples analyzed
Major ions	Alkalinity (mg/l)	SM 2320-B	2/19/1999	9/23/2021	NR	175
Major ions	Calcium (d) (mg/l)	EPA 200.7(W)	2/19/1999	9/23/2021	NR	163
Major ions	Calcium (d) (mg/l)	EPA 200.8(W)	10/19/2016	1/28/2020	NR	12
Major ions	Chloride (mg/l)	EPA 325.2	7/8/2003	9/23/2021	10	151
Major ions	Chloride (mg/l)	EPA 325.3	2/19/1999	12/6/2000	3	23
Major ions	Magnesium (d) (mg/l)	EPA 200.7(W)	2/19/1999	9/23/2021	NR	163
Major ions	Magnesium (d) (mg/l)	EPA 200.8(W)	10/19/2016	1/28/2020	NR	12
Major ions	Potassium (d) (mg/l)	EPA 200.7(W)	2/19/1999	9/23/2021	NR	163
Major ions	Potassium (d) (mg/l)	EPA 200.8(W)	10/19/2016	1/28/2020	NR	12
Major ions	Sodium (d) (mg/l)	EPA 200.7(W)	2/19/1999	9/23/2021	NR	163
Major ions	Sodium (d) (mg/l)	EPA 200.8(W)	10/19/2016	1/28/2020	NR	12
Major ions	Sulfate as SO_4 (mg/l)	EPA 375.2	2/19/1999	9/23/2021	20	174
Major ions	Total dissolved solids (mg/l)	EPA 160.1	7/19/2016	8/27/2021	NR	32
Major ions	Total dissolved solids (mg/l)	SM 2540-C	2/19/1999	9/23/2021	NR	138
Nutrients	Nitrate plus nitrite (d) (mg/l)	EPA353.2	7/13/2009	9/23/2021	0.1	90
Nutrients	Nitrogen (d) (mg/l)	SM 4500-N-C	7/13/2009	9/15/2020	0.2	80
Nutrients	Nitrogen (d) (mg/l)	ASTM D8083-16	10/14/2020	9/23/2021	0.2	10
Nutrients	Phosphate as P(d) (mg/l)	EPA 365.1	7/13/2009	9/23/2021	0.02	90
Nutrients	Total ammonia as N (mg/l)	EPA 350.1	7/13/2009	9/23/2021	0.05	89
Nutrients	Total nitrate plus nitrite (mg/l)	EPA 353.2	5/9/1999	9/23/2021	0.1	103
Nutrients	Total phosphate as P (mg/l)	EPA 365.1	2/19/1999	9/23/2021	0.02	176
Trace elements	Aluminum (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	30	77
Trace elements	Arsenic (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	5	77
Trace elements	Barium (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	100	77
Trace elements	Boron (d) (µg/l)	EPA 200.7(W)	7/10/2006	7/26/2021	30	41
Trace elements	Boron (d) (µg/l)	EPA 200.8(W)	10/19/2016	1/28/2020	30	11
Trace elements	Cadmium (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	1	77
Trace elements	Chromium (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	5	77

Table A-2, cont. Cover class data for plant species observed at currently monitored springs in September 2020.

Category	Parameter	Analytical method[1]	Start date	End date	Highest reporting limit	Samples analyzed
Trace elements	Copper (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	12	77
Trace elements	Iron (d) (µg/l)	EPA 200.7(W)	1/27/2016	7/26/2021	30	64
Trace elements	Iron (d) (µg/l)	EPA 200.8(W)	2/19/1999	1/28/2020	30	23
Trace elements	Lead (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	3	76
Trace elements	Manganese (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	5	76
Trace elements	Mercury (d) (µg/l)	EPA 200.8(W)	6/4/2004	6/7/2004	0.2	3
Trace elements	Mercury (d) (µg/l)	EPA 245.1	2/19/1999	7/26/2021	0.2	74
Trace elements	Nickel (d) (µg/l)	EPA 200.8(W)	7/10/2006	7/26/2021	10	41
Trace elements	Silver (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	2	77
Trace elements	Zinc (d) (µg/l)	EPA 200.8(W)	2/19/1999	7/26/2021	30	76

[1]SM = Standard Methods for the Examination of Water and Wastewater, EPA = US Environmental Protection Agency methods, ASTM = American Society for Testing and Materials (ASTM International). NR = Not Reported (all results detected and quantified).

Table A-2. Cover class data for plant species observed at currently monitored springs in September 2020.

Family	Species	Lifeform	Duration	Nativity	Wetland code[1]	Cover class[2]		
						Goodman Point	Hackberry	Square Tower
Anacardiaceae	*Rhus aromatica*	Shrub	Perennial	Native	FACW	2	NA	2
Asteraceae	*Achillea millefolium*	Forb	Perennial	Native	FACU	1	NA	NA
Asteraceae	*Arctium minus*	Forb	Biennial	NonNative	UPL	1	NA	NA
Asteraceae	*Artemisia ludoviciana*	Forb	Perennial	Native	FACU	NA	1	2
Asteraceae	*Artemisia tridentata*	Shrub	Perennial	Native	UPL	1	NA	1
Asteraceae	*Brickellia californica*	Shrub	Perennial	Native	UPL	NA	1	NA
Asteraceae	*Carduus nutans*	Forb	Perennial	NonNative	UPL	1	NA	NA
Asteraceae	*Chrysothamnus nauseosus*	Shrub	Perennial	Native	FAC	1	NA	1
Asteraceae	*Cirsium arvense*	Forb	Perennial	NonNative	FACU	1	NA	NA
Asteraceae	*Lactuca serriola*	Forb	Annual	NonNative	FACU	1	NA	NA
Chenopodiaceae	*Chenopodium album*	Forb	Annual	NonNative	FACU	NA	1	NA
Cupressaceae	*Juniperus osteosperma*	Tree	Perennial	Native	UPL	1	NA	NA
Cyperaceae	*Carex praegracilis*	Graminoid	Perennial	Native	FACW	1	NA	NA
Fabaceae	*Melilotus officinalis*	Forb	Biennial	NonNative	FACU	1	NA	NA
Fagaceae	*Quercus gambelii*	Shrub	Perennial	Native	UPL	2	NA	NA
Grossulariaceae	*Ribes aureum*	Shrub	Perennial	Native	FACW	2	NA	2
Lamiaceae	*Marrubium vulgare*	Forb	Perennial	NonNative	FACU	NA	1	1
Lamiaceae	*Nepeta cataria*	Forb	Perennial	NonNative	FACU	1	NA	NA
Onagraceae	*Epilobium ciliatum*	Forb	Perennial	Native	FAC	1	NA	NA
Pinaceae	*Pinus edulis*	Tree	Perennial	Native	UPL	2	NA	NA
Plantaginaceae	*Plantago major*	Forb	Perennial	NonNative	FAC	1	NA	NA
Poaceae	*Bromus inermis*	Graminoid	Perennial	NonNative	UPL	1	NA	NA
Poaceae	*Bromus japonicus*	Graminoid	Annual	NonNative	UPL	1	NA	NA
Poaceae	*Bromus tectorum*	Graminoid	Annual	NonNative	UPL	NA	2	1
Poaceae	*Elymus elymoides*	Graminoid	Perennial	Native	UPL	1	NA	NA
Poaceae	*Elymus smithii*	Graminoid	Perennial	Native	FACU	1	NA	NA
Poaceae	*Glyceria striata*	Graminoid	Perennial	Native	OBL	1	NA	NA
Poaceae	*Poa fendleriana*	Graminoid	Perennial	Native	UPL	NA	2	NA
Poaceae	*Poa* sp.	Graminoid	NA	NA	NA	NA	NA	1
Poaceae	*Stipa speciosa*	Graminoid	Perennial	Native	UPL	NA	1	NA

Table A-2, cont. Cover class data for plant species observed at currently monitored springs in September 2020

Family	Species	Lifeform	Duration	Nativity	Wetland code[1]	Cover class[2]		
						Goodman Point	Hackberry	Square Tower
Ranunculaceae	*Clematis ligusticifolia*	Vine	Perennial	Native	FACU	1	NA	NA
Rosaceae	*Prunus virginiana*	Shrub	Perennial	Native	FACU	2	NA	NA
Rosaceae	*Rosa woodsii*	Shrub	Perennial	Native	FAC	2	NA	NA
Salicaceae	*Populus fremontii*	Tree	Perennial	Native	FACW	2	NA	NA
Salicaceae	*Salix exigua*	Shrub	Perennial	Native	OBL	3	NA	3
Scrophulariaceae	*Verbascum thapsus*	Forb	Perennial	NonNative	UPL	1	NA	NA
Scrophulariaceae	*Veronica anagallis-aquatica*	Forb	Perennial	Native	OBL	1	NA	NA
Ulmaceae	*Celtis reticulata*	Tree	Perennial	Native	FAC	NA	3	2

[1]Wetland codes UPL = upland, FACU = facultative upland, FAC = facultative, FACW = facultative wetland, OBL = obligate wetland.
[2]Cover classes 1 = <1%, 2 = 1–10%, 3 = 10–25%, NA = not observed at the site.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 320/190090, August 2023

National Park Service
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