SPRING HEALTH MONITORING FOR THE FOUR FOREST RESTORATION INITIATIVE FINAL 2022 ANNUAL PROGRESS REPORT

USFS Cost Share Agreement #19-CS-11030400-015

Mud Springs, Kaibab National Forest.

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Summary of Key Points

- This report provides the results from the fourth year of pre-treatment springs monitoring at 56 sites, plus Hoxworth Spring.
- Results provided within this report indicate the baseline condition of the springs sites and will be helpful for understanding change created by forest thinning and prescribed fire.
- Springs flow and inundation timing were grouped by springs type, geology, and landscape. Baseline trends will be compared to trends post-treatment once treatment is completed.
- A small sub-set of springs sites (14) have received either mechanical treatments (4) or are fire impacted (10). This small sample size has not provided enough flow or Tidbit inundation information to provide a conclusive comparison to non-treatment springs.
- Water quality results indicate that most springs are locally sourced (low specific conductance, pH similar to rainwater), this would indicate rapid response to disturbance including forest treatment.
- Springs flow declined significantly at most sites between 2020 and 2021, this indicates very responsive springs ecosystems to short term climatic drivers (in this case drought). Springs flow data for 2022 shows some improvement at some sites.
- Very responsive springs sites should be ideal for monitoring short-term impacts of forest treatments.
- Hoxworth Spring is included in the hydrologic data collection as a long-term spring monitored by Northern Arizona University. Future analysis will be completed in coordination with NAU.
- The springs monitored exhibit a wide array of ecological integrity, ranging from pristine to highly impaired by livestock and wildlife impacts, flow manipulation, and proximity to development.
- Channel geometry, soil integrity, and vegetation cover reflect the intensity of grazing and browsing at individual springs, which influences habitat quality.
- Potential aquatic and riparian invertebrate indicator species vary among sedimentary- and igneous aquifer-sourced springs, and among ephemeral and perennial sources.

- Several Ephemeroptera, Odonata, Plecoptera, and Trichoptera, elmid beetles, *Enochrus* hydrophilid beetles, as well as turbellarian flat worms are characteristic of ecologically intact, perennial springs, while sepsid, tipulid, and other Diptera, some caddisflies, Annelida, and non-native isopods and amphipods characterize ephemeral and ecologically impaired springs.
- Identification of aquatic invertebrate taxa is on-going.

INTRODUCTION

Four National Forests—Kaibab, Coconino, Apache-Sitgreaves and Tonto National Forests, are engaged in the Four Forest Restoration Initiative (4FRI), a collaborative, landscape-scale initiative designed to restore 2.4 million acres of fire-adapted ponderosa pine ecosystems in northern Arizona. The greater part of the 4FRI restoration effort consists of thinning forests through felling trees or using prescribed burning. In addition, 4FRI also encompasses a diversity of other restoration actions, which include monitoring to detect changes in watershed health as the program is implemented. Springs ecosystems, while frequently undervalued, are vital components of watersheds; indeed, the hydrologic and ecological condition of the springs within a watershed serve as indicators of overall watershed health. Due to the ecological importance of springs habitats and the often high levels of biodiversity that they support, the Museum of Northern Arizona's Spring Stewardship Institute (SSI) is collaborating with the US Forest Service and the Multi-Party Monitoring Board (MPMB), a stakeholder group associated with 4FRI, to develop and implement the 4FRI Springs Health Monitoring Program.

SSI is an initiative of the 501c3 private, non-profit Museum of Northern Arizona (MNA), which was founded in 1928. SSI's mission is to improve understanding and stewardship of springs ecosystems. SSI's objectives are to create and disseminate information, tools, protocols, and advisement to enhance natural and cultural resource management of springs ecosystems. SSI's work throughout the 4FRI region is advancing the knowledge and understanding of springs ecological integrity as a component of ecosystem management in this landscape-scale restoration effort.

The purpose of the 4FRI Spring Health Monitoring Program is to document hydrologic and ecological changes that occur at springs as a result of 4FRI restoration actions. This five-year monitoring program documents and compares ecological and hydrologic conditions at 56 springs, half of which are located within the 4FRI treatment boundary and half of which are located outside the treatment boundary and serve as a control group. As forest restoration treatments are completed and trees are removed from large swaths of the northern Arizona landscape, we expect that springs discharge and flow duration may increase. With increases in springs discharge, we predict that the spatial extent of springs-dependent ecosystems will expand and floral and faunal diversity at these ecosystems will increase. Furthermore, because 4FRI is implementing major landscape-scale changes to northern Arizona forests, we also anticipate that unexpected ecological changes may follow. This springs monitoring program will help land managers quickly understand the broad and potentially unanticipated impacts of 4FRI influences on watershed condition.

This report presents data from the fourth year (2022) of this five-year monitoring program. The data presented here build on the 2019, 2020, and 2021 baseline data for assessing hydrologic and ecological changes to springs ecosystems, and which can be used to test the effects of implementation of the 4FRI program and in relation to climate variation during this initial five-year study period.

METHODS

Overview of the Monitoring Study Design

SSI designed this springs monitoring plan in collaboration with the US Forest Service and the 4FRI Stakeholder Group's Comprehensive Implementation Work Group (CIWG). The full monitoring plan (Schenk *et al.* 2019) was submitted and accepted by the US Forest Service in June 2019 and is attached as Appendix F. Here we present a summary of the monitoring plan, with emphasis on the tasks completed and data collected during years one through four.

In year one of the study (2019) SSI staff completed study site selection according to a stratified design (see Fig. 1, Table 1, and Appendix A) and conducted initial visits at 56 springs. The stratified design incorporates 56 springs located across the Kaibab and Coconino National Forests, which are equally sampled from within and outside the 4FRI treatment boundary and furthermore equally sampled from igneous and sedimentary sources. The springs are also subdivided by springs type (Stevens et al. 2021) into helocrenic (wet meadow) and hillslope springs. One additional spring, Hoxworth Springs, was added for hydrologic data collection only due to a long history of data collection at this spring within a mechanical treatment area (Donovan et al. 2023).

At each of the 56 core springs sites, the field crews produced a baseline dataset for this monitoring study by completing (or reviewing) a Level 2 spring inventory and installing a Onset HOBO Tidbit data logger device for yearly water presence/ absence assessment. At Hoxworth Springs, crews installed a Tidbit datalogger but did not complete a Level 2 spring inventory. SSI staff updated the Springs Online Database (https://springsdata.org/) with the new data from the above inventories and conducted quality control checks on all data entered. Results of this 2019 work were submitted to the US Forest Service in an annual report in April of 2020.

In 2020, 2021, and 2022, SSI staff continued the monitoring study by completing the following sets of tasks both years, as outlined in the scope of work, at all 56 study springs. In

Because of the Coronavirus Pandemic it was not feasible to engage volunteers as planned in 2020 and 2021, so SSI staff and contractor Ed Schenk completed all field work those years.

1. Download hydrologic data from HOBO Tidbit dataloggers.

2. Measure springs discharge and document habitat area change and springs invertebrate assemblages.

3. Conduct quality control checks on data from springs and thermistors, and upload data to Springs Online or other agreed upon databases.

During year five of this monitoring program, SSI field crews will conduct a comparative Level 2 springs inventory at each of the 56 springs. SSI staff will analyze the ecological and hydrologic data from all five years of the monitoring program. They will produce a report that describes changes recorded over the study period, and compares the treatment group to the control group—to the extent possible based on actual forest treatments that have been completed at that time—in order to determine whether 4FRI treatments have resulted in detectible changes in springs ecohydrology.

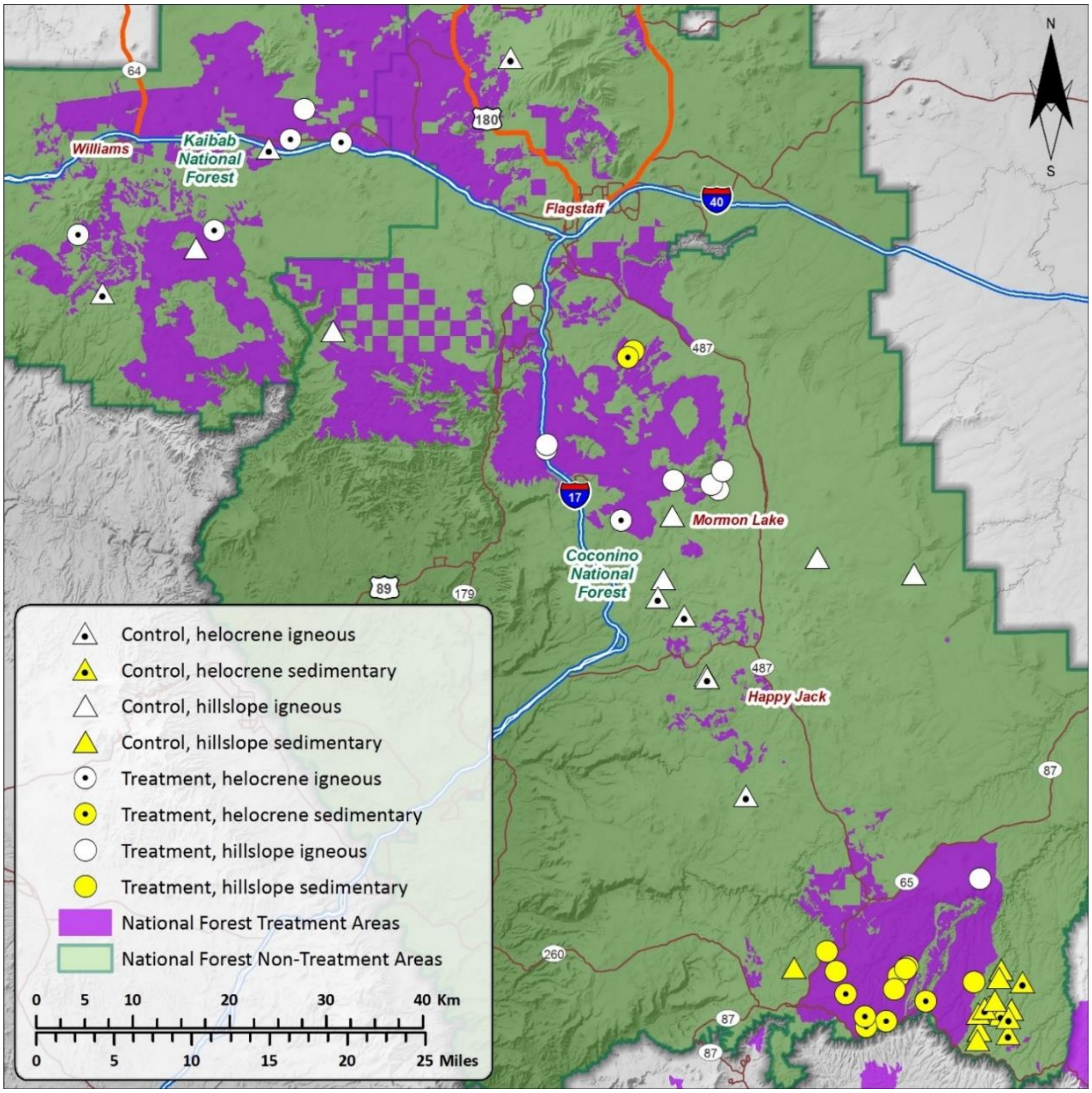

Figure 1. Map showing the 56 study sites in the 4FRI Spring Health Monitoring Study. The list of monitoring sites, with geographic coordinates and elevations, is included as Appendix A.

Table 1. The stratified design used for monitoring site selection. All study sites are located in the Kaibab National Forest (Williams RD) or Coconino National Forest (Mogollon Rim or Flagstaff RD) between 1,829 and 2,591 m (6,000 and 8,500 ft) elevation. See the 2019 annual report for more details about site selection.

Spring Type	Primary Lithology	Total
Treatment		
Helocrene	Igneous	7
Helocrene	Sedimentary	7
Hillslope	Igneous	7
Hillslope	Sedimentary	7
Control Group		
Helocrene	Igneous	7
Helocrene	Sedimentary	7
Hillslope	Igneous	7
Hillslope	Sedimentary	7
Total		**56**

Year 4 (2022) Tasks

Task 1: Download hydrologic data from HOBO Tidbit dataloggers

SSI field crews visited each of the 56 study springs, searched for the HOBO Tidbit Datalogger, and if found, downloaded the data. Field staff made detailed notes about where the device was located when found in 2022 and whether it appeared to have been disturbed during the year. They also noted whether it was necessary to disturb the device to download the data (the devices cannot transmit data when submerged under water) and documented the precise configuration of the device after reinstallation. Crews recorded the absolute water depth where the device was installed, and whether it was installed in standing or flowing water.

In some cases, the survey crew was not able to find the dataloggers. In these cases, they installed a new datalogger and properly documented the installation location.

Task 2: Measure springs discharge and document habitat area change and springs invertebrate assemblages

Springs Discharge Rate: Survey crews measured the springs discharge rate at all sites where there was flowing water. Flow measurement techniques were selected according to the amount of flow and site geomorphology. The timed flow capture (volumetric) technique was used at most springs where flow was measured. At one spring, surveyors used a portable cutthroat flume to measure flow. Crews documented the flow measurement location by describing it on the data sheet and marking it on the sketchmap.

Habitat Change: Crews documented changes in habitat areas by using a green pencil to draw edits on the site sketchmap from the original baseline dataset. Site sketchmaps are drawn to scale and include the configuration and area of microhabitats at the springs ecosystem, such as pools, channels, stream banks, wet backwalls, and cienegas (wet meadows). The sketchmap edits were used to estimate any changes in the areas of microhabitats. Surveyors also documented the water depth, percent inundation, and soil moisture status of each microhabitat, to allow comparison in moisture levels from year to year.

Invertebrate Assemblages: Opportunistic sampling of benthic macroinvertebrates (BMI) was conducted at the study springs using dip- and kick-net sampling, aerial net sweeping of shoreline vegetation, and examination of firm strata in subaqueous and shoreline habitats. Specimens, when collected, were placed in 80% EtOH and transferred to the MNA Merkel Laboratory for sorting, preparation, and identification.

Task 3: Conduct quality control checks on data and upload to Springs Online or other agreed upon database

SSI staff updated the Springs Online database with the new data from all 2022 field inventories and conducted quality control checks on all data entered. The paper field sheets are archived in the SSI lab, and electronic scans of the field sheets are archived on the SSI server. Hydrologist Ed Schenk conducted quality control checks on the data downloaded from the Hobo dataloggers and completed preliminary analyses. SSI staff archived the downloaded Hobo data on the SSI server. Eventually all Hobo data will be uploaded onto Springs Online or other agreed-upon database.

RESULTS

Treatment Springs- as of 2022

While 23 of the 56 study springs are located within the 4FRI treatment boundary, forest treatments have not been completed at all springs in this group. We used the 2021 Treatment Area geodatabase provided by the 4FRI project (4FRI_RapidAssessment_2022_06_29.gdb, downloaded August 2022) to determine that 14 of the 56 study springs have been treated to date. Four of these sites underwent mechanical thinning in the catchment area for the spring source, and another ten sites were impacted by either prescribed fire or wildfire during the study period (Table 2, Appendix B). The number of treatment sites is below the anticipated level when this study was designed and implemented, making a comparison of treatment to control sites difficult. Recent Federal funding should increase the treatment implementation schedule but unfortunately may be too late in this current study timetable to provide the study design's intended analysis of treatment beneficial impacts.

*Table 2. List of treatment springs by type of treatment and year of impact. *East Twin Spring received only minor mechanical treatment that will likely not impact spring flow.*

Springs ID	Springs Name	Type of Treatment	Year of Treatment
739	Big Spring	Wildfire	2019
426	Bone Dry Spring	Prescribed fire	2019
182083	Clark Spring	Mechanical treatment	2022
776	East Twin Spring	Mechanical treatment	2019
989	Homestead Spring	Prescribed fire	2019
997	Hoxworth Spring	Mechanical treatment	2019
545	Hunter Spring	Prescribed fire	2020
546	Keller Spring	Prescribed fire	2019
1011	Lauren Spring	Prescribed fire	2019
1036	Middle Kehl Spring	Wildfire	2019
425	Moonshine Spring	Wildfire	2019
226446	Overhang Spring	Wildfire	2019
1096	Strahan Spring	Wildfire	2021
250584	Trotting Turkey Spring	Mechanical treatment	2022

It should be noted this designation is based on GIS polygons, a dataset that lacks information one fire or thinning intensity. Some springs sites (Moonshine, Middle Kehl, Hunter, Big, and East Twin) do not appear to have widespread landscape disturbance or treatment despite reporting in the 4FRI geodatabase (Appendix B).

Task 1: Download hydrologic data from HOBO Onset Tidbit dataloggers

Completeness of the dataset

In 2022, survey crews obtained successful downloads from all but two of the Hobo Tidbit dataloggers (Table 3). There was one missing datalogger, at Clover Spring West. The surveyor was unable to find the device at that spring and installed a new one in its place. However, the water level was high at the time of the visit, and it is possible that a survey crew might find the device during a future survey in drier conditions.

At Lauren Spring, the survey crew successfully downloaded data from the Hobo Tidbit in 2022, but quality control checks in the office revealed that the device had malfunctioned and failed to log any data after September 2021. A survey crew will need to return to Lauren Spring as soon as possible to install a functional datalogger, and to remove the malfunctioning unit to be sent to Onset for data recovery.

At Griffiths Spring, the survey crew was unable to download data from the Onset Hobo in the field and installed a new datalogger in its place. SSI staff mailed the malfunctioning device to Onset and fortunately the manufacturer’s technicians were able to recover the data. Therefore there is no missing data at Griffiths Spring in 2022.

Table 3. Springs monitoring sites where it was not possible to locate the Hobo Tidbit or download a full set of data, in 2020 (monitoring year 2) 2021 (monitoring year 3), and 2022 (monitoring year 4).

Spring Name	Status of Hobo Tidbit dataloggers
Missing/ Malfunctioning in 2020	
East Twin Spring	Installed in a dry pond (2019). Pond was full of water in 5/2020 and surveyors could not find the datalogger. Surveyors planned to return in late summer when water level might be lower, but USFS closed the access road.
George Spring	Destroyed by rodents. New device installed 5/5/20.
Griffiths Spring	Successful download 6/5/20. Missing when surveyors returned for botany survey 8/25/20; new device installed 9/12/20.
McFarland Spring	Not found. New device installed 5/16/20.
Mineral Spring	Not found, though it was possibly to download the data via Bluetooth on 5/5/20. Could not access via Bluetooth connection on 6/25/20, so surveyors installed a new datalogger.
Spikerush Spring	Not found, though the PVC pipe it had been attached to was found. New datalogger installed 5/15/20.
Willard Spring	Not found. New device installed 4/19/20.
Wilson Spring	Hobo installed at channel headcut (2019). In 2020, rebar was in place but Hobo missing; data successfully downloaded via Bluetooth. Second Hobo installed in 2020, attached to original rebar but moved to creek-left edge of channel.
Missing/ Malfunctioning in 2021	
Big Spring	Installed at the south source (2019). Reinstalled at same location using rebar (2020). Not found in 2021, but data downloaded via Bluetooth. Second Hobo installed using rebar at same location.
Bootlegger Spring	Installed at source, hidden by aspen round (2019). Successfully located and downloaded in 2020. Not found in 2021, not detected via Bluetooth; replacement installed.
East Twin Spring	Installed in a dry pond (2019). Not found in 2020. Surveyors not able to return to install replacement Hobo in 2020 due to fire closures. Replacement installed 2021.
Homestead Spring	Installed at source in 2019. Reinstalled using rebar in 2020. Not physically located in 2021, but data were downloaded using Bluetooth.
Hunter Spring	Installed at source in 2019. Successfully located and downloaded in 2020. Not physically located in 2021, but data were downloaded using Bluetooth.
Rosilda Spring	Installed along exclosure fenceline in 2019. Successfully located and downloaded in 2020. Located in 2021 but malfunctioned and data were not

Spring Name	Status of Hobo Tidbit dataloggers
	recoverable via Bluetooth. Replacement installed 2021. Malfunctioning device sent to Onset and data were recovered in 2022.
Wilson Spring	Both Tidbit units successfully downloaded, but original Hobo still not physically located.
Missing/ Malfunctioning in 2022	
Clover Spring West	Installed at culvert exit in 2019. Successfully located and data downloaded in 2020, 2021. Not found in 2022, not detected via Bluetooth; replacement installed.
Griffiths Spring	Device installed in Sept 2020; successful download in 2021. Located in 2022 but malfunctioned and data were not recoverable via Bluetooth. Replacement installed 2022. Malfunctioning device sent to Onset and data were recovered in 2022.
Lauren Spring	Device installed in 2019; successful downloads in 2020 and 2021. Data were downloaded in 2022, but subsequent quality checks showed that the device stopped logging data in September 2021. A survey crew will need to return to the spring ASAP to install a new datalogger.

Hydrology Results

Because data for only three monitoring periods (2019-2020, 2020-2021, and 2021-2022) are available at this time, we present a preliminary analysis that focuses on establishing baseline condition of the springs sites, and comparing the hydrologic conditions at different springs types and geologic and landscape settings. The summary table of hydrologic data used for the following analyses and figures is attached as Appendix C.

Climate results: The 2021-2022 monitoring period was in severe drought for the majority of the time period. This drought was a continuation of the short-term extreme drought experienced for the last four years and part of the decadal long-term drought situation in the Southwest USA region. Annual total precipitation and snowfall are provided in Figures 2 and 3. Note the consistently low snowfall over the last decade while total precipitation is not as severely under the long term average.

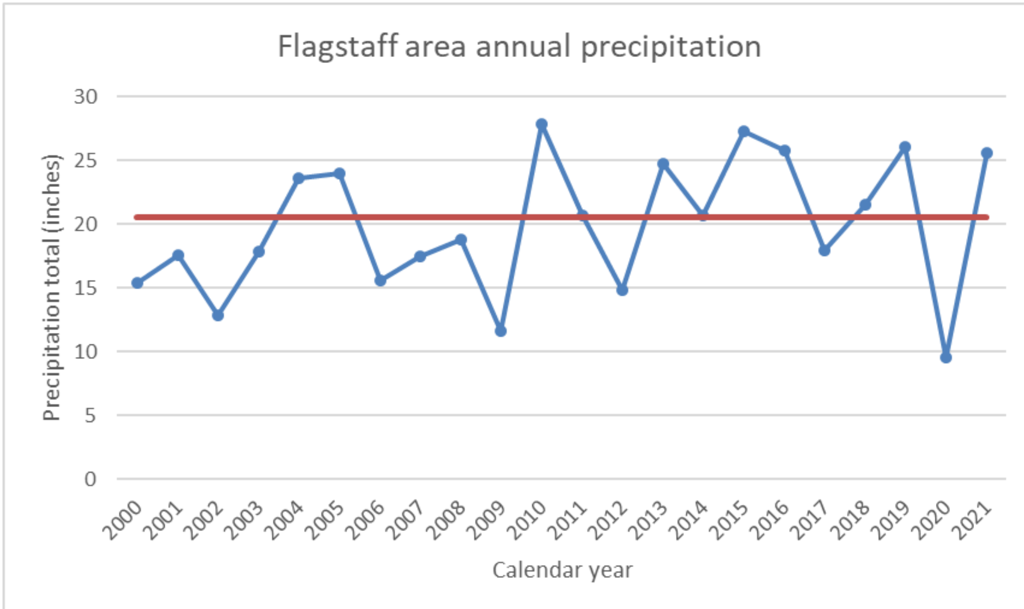

Figure 2. Total annual precipitation for Flagstaff, AZ with 100-year long term average marked with the orange line. Data is from the NOAA long term climate website, Flagstaff Area (FLG) weather station, accessed August 2022.

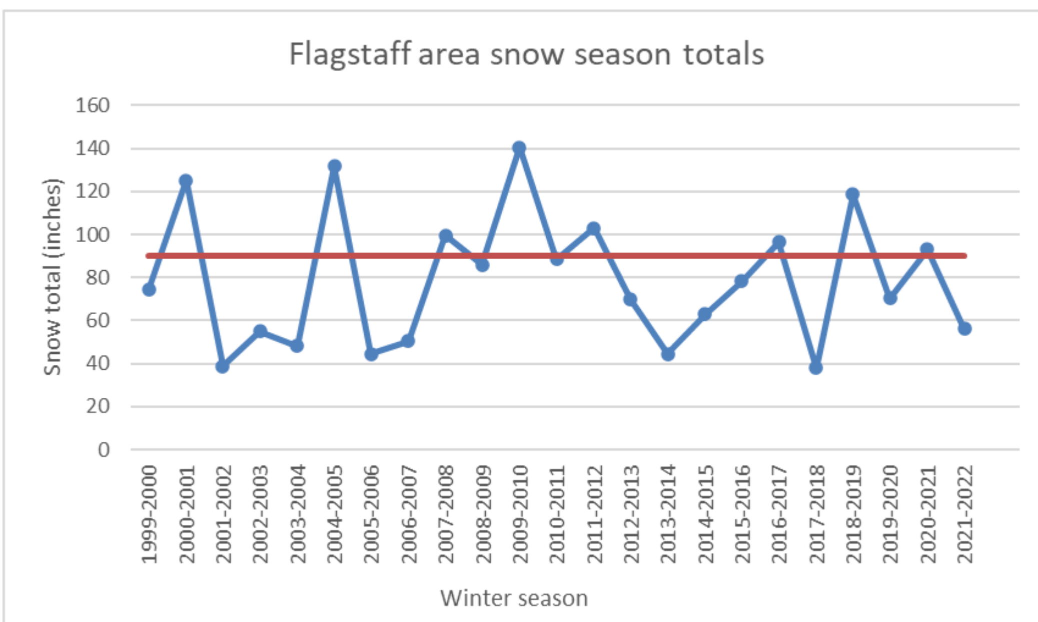

Figure 3. Snowfall season totals for Flagstaff, AZ with long term 100 year average marked by the orange line. Data is from the NOAA long term climate website, Flagstaff Area (FLG) weather station, accessed August 2022.

Springs water depth: Absolute water depth was measured at the location of the Hobo Onset Tidbit installation and before and after each data download. The depth was approximately the same between helocrenic and hillslope spring types in 2020 (ANOVA $p = 0.88$). The water depth was higher at hillslope sites compared to helocrenic sites in 2021 but again this difference was not statistically significant. Mean water depth at both springs types decreased between 2020 and 2021 and then rose slightly in 2022, with hillslope mean depths of 12.8 cm, 5.3 cm, 6.8 cm in 2020, 2021, and 2022 respectively and helocrene spring pool depths of 12.8 cm, 5.1 cm, and 6.2 cm in 2020, 2021, and 2022 respectively.

Onset Tidbit Inundation Time: The percent time that an Onset Tidbit was submerged was evaluated for the period of record (Tables 4 and 5). In general this spanned from summer 2019, the initial installation, to summer 2022, the fourth year of monitoring. There were some exceptions for Tidbits that were lost, re-programmed, and/or replaced (Tables 6 and 7).

The percent time inundated will be used to determine climate and 4FRI treatment impacts on springs flow (Table 4 and 5). The inundation period for these first few years pre-treatment should be interpreted with caution for any trends or correlation since the location of the Onset Tidbit water sensor was chosen to be at the fringe of springs flow. The location is arbitrary and does not record absolute springs perenniality, though it does provide relative trends through time as the data logger position is not intended to change at each individual site.

Table 4. Percent of time a Tidbit sensor was inundated by year at 28 hillslope springs. Orange shading indicates a site impacted by prescribed fire or wildfire, and grey shading indicates mechanical treatment.

Hillslope Springs	**Percent Time Inundated**			
Site	**2019-2020**	**2020-2021**	**2021-2022**	**Period of Record 2019-2022**
Bear Seep	36	46	100	63
Big	59	---	100	85
Bone Dry	67	5	7	19
Bootlegger	68	---	100	88
Carla	78	100	97	94
Clover W	77	55	---	63
Dairy	100	100	100	100
Derrick	88	100	95	95
Double	100	51	30	55
Dove	93	69	98	87
George	---	100	99	99
Goshawk	66	100	96	90
Grapevine	100	100	100	100
Griffiths	79	35	48	53

Homestead	45	14	25	28
Hunter	39	0	8	12
Jones	100	100	100	100
Keller	100	60	49	66
Lauren	79	98	---	92
Leopard Frog	84	100	95	94
McFarland	---	100	96	98
N Willard	68	32	67	53
One Hundred One	100	100	100	100
Pivot Rock	100	65	25	62
Rock Top	21	61	90	63
Sawmill	73	15	0	22
Spikerush		96	97	97
Strahan	76	8	91	48

Table 5. Percent of time a Tidbit sensor was inundated by year at 28 helocrene springs. Orange shading indicates a site impacted by prescribed fire or wildfire, and grey shading indicates mechanical treatment.

Helocrene Springs	**Percent Time Inundated**			
Site	**2019-2020**	**2020-2021**	**2021-2022**	**Period of Record 2019-2022**
Banfield	32	---	0	0
Clark	52	---	0	17
Coyote	82	100	98	95
Driftfence	100	100	98	99
East Twin	---		63	63
Fain	95	84	75	83
Foster Canyon	---	19	64	69
General	77	24	71	49
Immigrant	22	0	0	5
Kehl	59	0	16	25
Lee	100	100	100	100
Lower McDermit	18	4	9	8
Meadow	51	4	100	58
Merritt	21	100	97	81
Middle Kehl	20	82	100	72
Mineral	17	100	100	81
Monkshood	48	---	12	24
Moonshine	14		0	5
Mud	72	52	90	73
Overhang	64	16	0	21
Rosilda	71	0	82	78
Smith	100	---	100	100
Spitz	36	100	99	80

Trotting Turkey	22	1	1	6
Tsix	74	28	21	35
Whistling	55	83	91	86
Willard	100	36	97	85
Wilson	---	0	1	9

Table 6. Dates of visits for Hobo Onset Tidbit install, maintenance, and data download for hillslope springs.

Hillslope Springs

Site	Start	Year 1	Year 1, update	Year 2 install	Year 2	Year 3
Bear Seep	9/18//19	9/4//20			6/9//21	7/19/22
Big	10/12//19	5/6//20		5/22//21		5/5/22
Bone Dry	9/27//19	5/7//20			9/6//21	7/16/22
Bootlegger	10/14//19	5/8//20		6/9//21		5/9/22
Carla	9/8//19	5/5//20			6/6//21	7/18/22
Clover W	9/25//19	6/10//20			8/5//21	*Datalogger missing
Dairy	9/18//19	4/26//20			6/8//21	5/9/22
Derrick	9/8//19	5/5//20			6/6//21	7/17/22
Double	9/8//19	4/23//20			6/8//21	5/9/22
Dove	10/2//19	6/9//20	8/27//20		8/5//21	7/19/22
George	5/5//20				6/6//21	7/17/22
Goshawk	9/7//19	5/15//20			6/8//21	7/14/22
Grapevine	10/2//19	6/14//20			8/8//21	7/19/22
Griffiths	9/25//19	6/5//20	lost	9/12//20	5/14//21	5/10/22
Homestead	10/14//19	5/16//20	9/13//20		9/25//21	7/15/22
Hunter	9/26//19	5/8//20			6/8//21	9/5/22
Jones	9/20//19	6/9//20			6/17//21	6/28/22
Keller	9/19//19	5/7//20			9/6//21	7/16/22
Lauren	10/14//19	5/7//20	6/6//20		9/6//21	*Datalogger damaged
Leopard Frog	9/7//19	5/17//20			6/5//21	9/6/22
McFarland	5/16//20				6/8//21	7/18/22
N Willard	9/28//19	4/29//20			5/24//21	5/10/22
One Hundred One	9/20//19	5/23//20			8/6//21	7/15/22
Pivot Rock	9/20//19	5/23//20			8/6//21	5/11/22
Rock Top	9/19//19	5/7//20			6/17//21	7/8/22
Sawmill	9/25//19	5/5//20			8/4//21	5/12/22
Spikerush	5/15//20				6/6//21	7/14/22
Strahan	10/3//19	5/17//20			10/7//21	9/5/22

Table 7. Dates of visits for Hobo Onset Tidbit install, maintenance, and data download for helocrenic (wet meadow) springs.

Helocrene Springs						
Site	**Start**	**Year 2**	**Year 2, update**	**Year 2 install**	**Year 3**	**Year 4**
Banfield	9/27/19	6/10/20			8/5/21	9/8/22
Clark	10/8/19	6/5/20			6/9/21	7/20/22
Coyote	9/7/19	5/17/20			6/5/21	9/6/22
Driftfence	9/8/19	5/17/20			6/7/21	7/15/22
East Twin	no data					5/5/22
Fain	9/19/19	5/7/20			6/17/21	6/28/22
Foster Canyon	9/20/19	6/9/20			6/17/21	6/28/22
General	9/8/19	5/4/20			9/25/21	7/14/22
Immigrant	10/13/19	5/4/20			9/6/21	5/10/22
Kehl	10/14/19	5/4/20	9/14/20		9/25/21	5/10/22
Lee	10/1/19	5/7/20			6/17/21	7/8/22
Lower McDermit	9/19/19	5/5/20			8/4/21	7/12/22
Meadow	9/7/19	5/15/20	9/13/20		6/5/21	7/18/22
Merritt	9/8/19	5/6/20			6/7/21	7/15/22
Middle Kehl	10/13/19	5/24/20			9/5/21	5/10/22
Mineral	9/22/19	5/5/20		6/26/20	5/22/21	7/12/22
Monkshood	9/7/19	5/25/20			6/5/21	9/6/22
Moonshine	10/13/19	5/8/20			6/7/21	7/18/22
Mud	10/3/19	5/6/20			5/22/21	5/5/22
Overhang	10/14/19	5/4/20			8/6/21	5/10/22
Rosilda	9/22/19	5/6/20		5/22/21		5/5/22
Smith	9/8/19	4/23/20			6/8/21	5/9/22
Spitz	9/22/19	5/5/20			8/4/21	5/5/22
Trotting Turkey	10/9/19	6/5/20			6/9/21	7/20/22
Tsix	9/28/19	5/8/20			8/4/21	5/10/22
Whistling	10/14/19	5/6/20	6/6/20		6/7/21	7/17/22
Willard	4/19/20	8/25/20			5/24/21	5/10/22
Wilson	5/31/20				5/13/21	7/21/22

The percent of time the Tidbit was inundated will be used to determine climate and 4FRI treatment impacts on springs discharge. The inundation period for these first few years pre-treatment should be interpreted with caution for any trends or correlation since the location of the Hobo Onset Tidbit water sensor was chosen to be at the fringe of springs flow. The location is arbitrary and does not necessarily record absolute spring perenniality, although it does provide relative trends through time as the data logger position is not intended to change at each individual site.

Springs response (hydrogeologic response time to precipitation events): Continuous water temperature can provide a measure of springs responsiveness to surface activities. Similar studies at the Grand Canyon using water temperature were able to determine the response time of Roaring Springs to rain and snow events (e.g., Schindel 2015; Jones et al. 2017). Monitoring the springs response rate will help interpret future results from this study. This annual report provides continuous data from mid-2019 to mid-2022, enough of a time period to provide preliminary interpretations of springs responsiveness to external events (in this case precipitation and temperature).

Individual springs have their own character. For example, some springs that had continuously inundated Tidbit thermistors (temperature gauges) had either similar temperature responses (e.g., Grapevine versus Lee Springs) despite different stressors or different temperature regimes (e.g., Grapevine versus Driftfence). Grapevine Spring shows a true fast groundwater response time (Fig. 4). Lee Spring appears to have a fast groundwater response time, but is likely more impacted by seasonal air temperatures at the data logger rather than groundwater response time (Fig. 5). Driftfence Spring shows a "complacent" response or a slow groundwater response (Fig 6). Understanding the individual springs landscape position and flow regime is critical for understanding how responsive a spring is to groundwater response times.

A preliminary analysis of precipitation events versus continuous temperature was attempted but will require a larger computer coding (e.g. MatLab or Python) approach to provide relevant results. Preliminary comparisons of precipitation events to individual continuous temperature data did not show a strong correlation between the two variables.

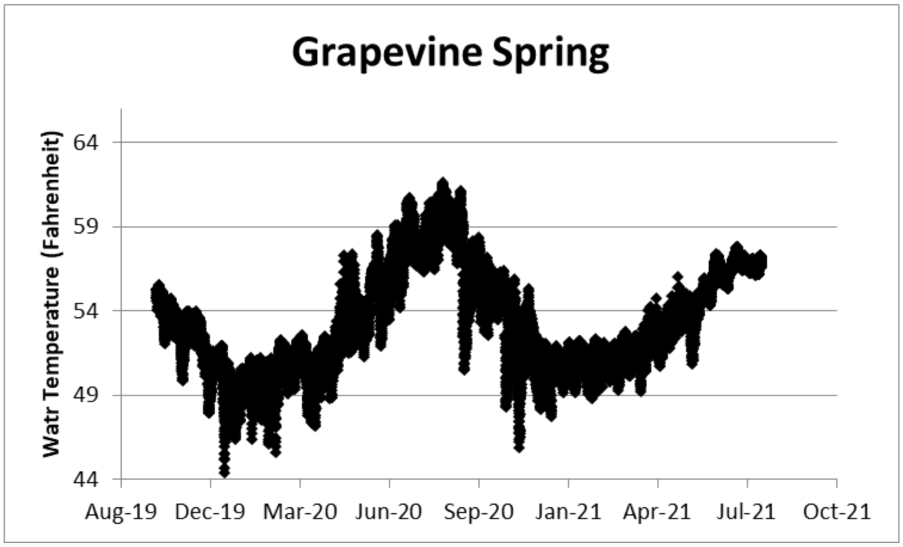

Figure 4. Springs water temperature for a hillslope spring with a high groundwater response time. The water temperature changes are rapidly driven likely both by groundwater recharge (high groundwater response) and air temperature (surface response). Further data, including modeled precipitation data, will elucidate a better response interpretation. The Hobo Onset Tidbit logger was submerged for the entirety of the monitoring period.

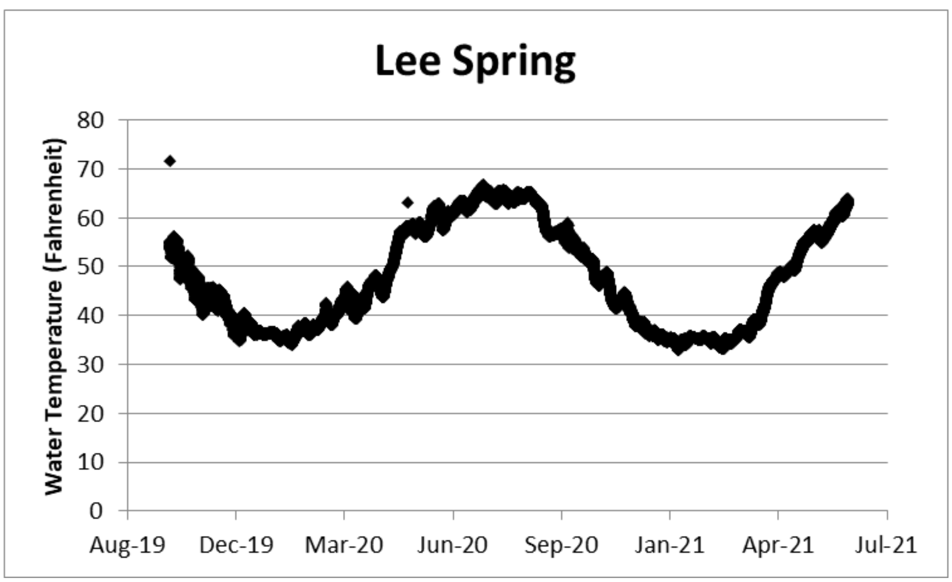

Figure 5. Spring water temperature graph of a helocrene spring with low flow. The groundwater response time cannot be determined due to the water temperature being driven by air temperature. The Hobo Onset Tidbit logger was submerged for the entirety of the monitoring period.

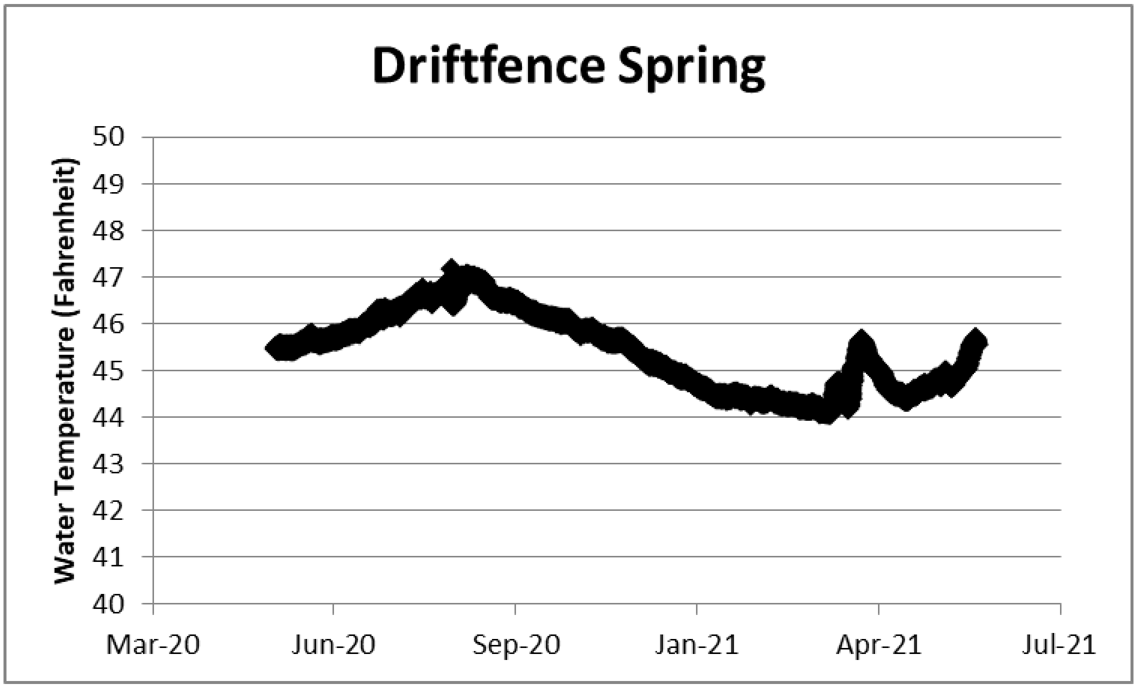

Figure 6. An example of a less responsive spring (note y-axis scale). This spring is complacent with regard to both groundwater response time and air temperature, indicating that discharge emerges from a relatively old groundwater source. The Hobo Onset Tidbit logger was submerged for the entirety of the monitoring period.

Inundation timing (Hobo Onset Tidbit data): Baseline data on inundation timing at specific spring sites are now available and have been grouped by springs type (wet meadow/helocrene and hillslope). There is no trend to date, which is not surprising due to the lack of broad landscape forest treatments near, or within, the study sites. The baseline data will be important for measuring change when forest treatments are initiated. Figures 7 and 8 show the inundation period of each springs site up to 2021. Results through 2022 were analyzed but not presented in this report (there was a similar lack of trend as previous years). Onset Tidbits were set near the springs source in a location that is sensitive to changing water levels. The inundation time is relative to each springs site and shows trends in perenniality at each spring site.

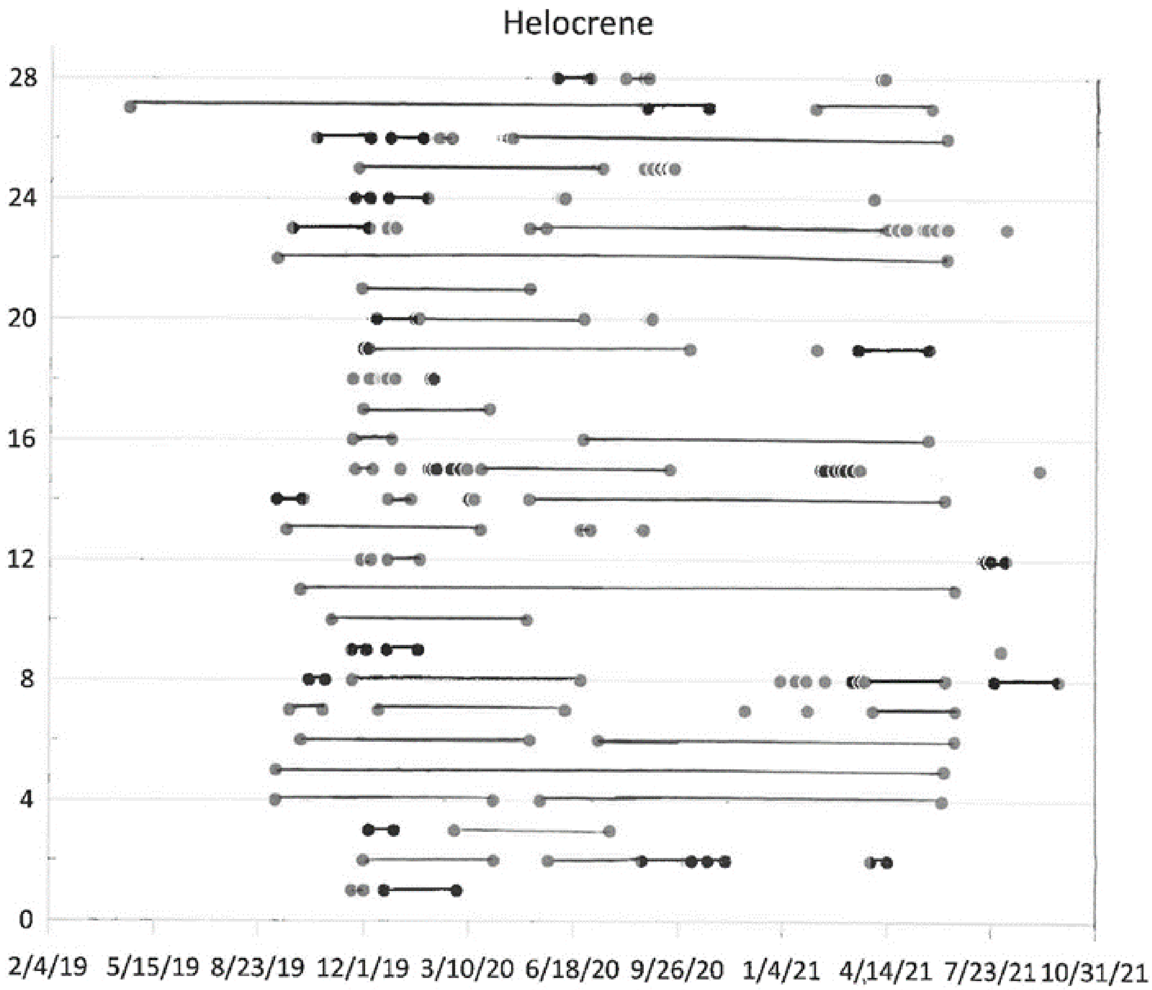

Figure 7. Helocrenic springs Hobo Onset Tidbit inundation at or near springs source, from 2019 through 2021. Solid lines indicate that the data logger was underwater. Y-axis indicates individual spring sites (alphabetical). Dates in M/D/YY are on the x-axis. The 2022 dataset was analyzed for this report, but results are not presented graphically.

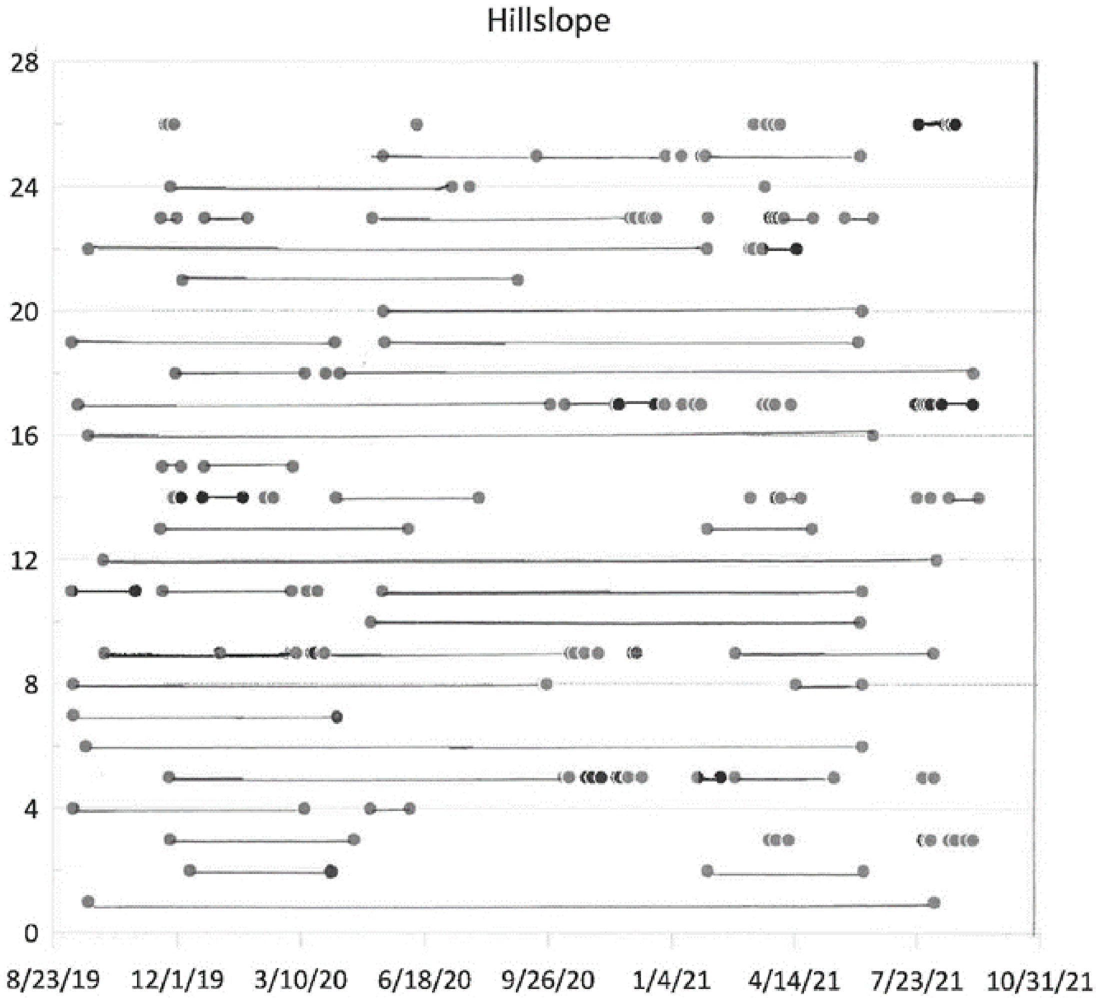

Figure 8. Hillslope springs Hobo Onset Tidbit inundation at or near springs source, for 2019-2021. Solid lines indicate that the data logger was underwater. Y-axis indicates individual spring sites (alphabetical), dates in M/D/YY are on the x-axis. The 2022 dataset was analyzed for this report but results are not presented graphically.

Springs Type Inundation Results: Percent inundation for individual springs was compared based on the springs type (helocrene or hillslope). The median time inundated for helocrene springs was 66% of the study period. The median time inundated for hillslope springs was 86% of the study period. Hillslope springs tended to have more consistent springs flow than helocrene springs (Appendix C).

Igneous springs were inundated 60% of the time between the start of the study and mid-2021 compared to 63% of the time for sedimentary springs (median values), there was no statistical significance between the two springs geologic province (ANOVA single factor, p=0.7). A comparison of treatment springs to non-treated springs as of 2021 found no significant difference, though the sample size is low (8 springs treated in 2019) and the study period short, caution should be taken in making inferences. Springs treated in 2019 were inundated 37.1% of the time in 2021 based on the median of the eight treatment sites. This was lower than in 2019-2020 immediately after treatment (median inundation = 61.6%).).

Water quality results: During the initial year of the study, water quality was measured in the field for basic parameters including water temperature, pH, alkalinity, dissolved oxygen, and specific conductance. These measurements provide baseline conditions for groundwater outputs to the surface environment. Data are provided in Appendix D, and further interpretations will be provided after forest treatments are completed. Initial baseline data indicates fairly neutral acidity (pH) consistent with shallow igneous and sedimentary spring sources. Specific conductance is also low, which is to be expected for short groundwater pathway springs (Schenk et al. 2018).

Task 2: Measure springs discharge and document habitat area change and springs invertebrate assemblages

Springs Discharge Rate

Discharge was measured at all study springs where there was flowing water. In 2020 sampling period, hillslope springs had greater flow than helocrenic springs (mean flow of 2.22 L/s at hillslope springs versus 0.42 L/s at helocrenic springs; ANOVA single factor p = 0.04; Table 8). In 2021, hillslope springs continued to have a higher discharge, with a mean flow rate of 0.15 L/s compared to helocrenic springs (0.04 L/s). The difference continued to be statistically significant (ANOVA single factor p=0.01). In 2022, hillslope springs continued to have higher discharge rates than helocrenic springs (0.32 L/s for hillslope springs and 0.13 L/s for helocrene springs). Median flow values show the same trend and are more representative of the differences between springs groups as averages (means) are influenced by a handful of relatively high flow springs (Table 8, 9). Spring discharge mirrored the absolute water depth results with an overall decrease in discharge and water depth at both springs types between 2020 and 2021, followed by a slight increase in 2022.

Table 8. Mean (average) flow values in liters/second for springs type (helocrene v. hillslope), geology (igneous v. sedimentary), and landscape position.

	2020	**2021**	**2022**	**n**
Helocrene	0.42	0.04	0.13	28
Hillslope	2.22	0.15	0.32	28
Igneous	1.36	0.08	0.24	27
Sedimentary	1.16	0.11	0.20	28
Mogollon Rim	1.47	0.13	0.27	21
Non-Rim	1.29	0.06	0.19	35

Table 9. Median flow values in liters/second for springs type (helocrene v. hillslope), geology (igneous v. sedimentary), and landscape position.

	2020	2021	2022	n
Helocrene	0.04	0.00	0.00	28
Hillslope	0.32	0.06	0.03	28
Igneous	0.04	0.00	0.00	27
Sedimentary	0.36	0.07	0.03	28
Mogollon Rim	0.51	0.08	0.06	21
Non-Rim	0.04	0.01	0.00	35

Flow rate was compared between the eight springs that had seen some type of treatment in 2019 and the un-treated springs. An ANOVA test of the 2021 springs flow showed no statistical significance in flow rate between the two populations ($p = 0.60$). Flow rates were higher at the treatment sites in all three years but lacked a clear statistical signal above untreated springs. Historical flow rates are provided in Appendix E.

Habitat Change

SSI survey crews documented changes in microhabitat areas at 15 (27%) of the 56 springs in 2020, at five (9%) of the 56 springs in 2021, and at one of the springs in 2022 (Table 10). Changes in 2020 were in almost all cases related to wetter conditions during the 2020 survey, compared to baseline conditions. Most of the 2020 surveys were completed in late spring, when flow rates were elevated following the winter season. In contrast, the 2019 baseline surveys were conducted in late summer and early autumn, and at that time conditions were exceptionally dry because the region received almost no monsoon activity in 2019.

In some cases, it was not possible to reliably report microhabitat area changes between 2019 and 2020. This is because some of the baseline surveys were conducted prior to the start of this monitoring study in 2019. In many of these cases, when SSI surveyors conducted site visits in 2020, they judged the original (pre-2019) sketchmaps to be inadequate to support project purposes, and re-drew the maps. In such cases, the new 2020 maps are being used as the baseline, and microhabitat changes between 2019 and 2020 are not reported.

Of the five springs where microhabitat changes were recorded in 2021, two were influenced by wetter conditions (one sampled during the active monsoon season and the other sampled in late spring and likely influenced by snowmelt). Microhabitat changes at one spring were related to drier conditions, changes at one spring were due to trampling by ungulates, and changes at one spring were due to a combination of drier conditions and trampling.

Microhabitat changes were recorded at only one spring in 2022. Strahan Spring is in a canyon that experienced a major flood between monitoring visits in 2021 and 2022. This resulted in geomorphic change altering the area and configuration of channels, pools, and terraces.

Table 10. Description and explanation of changes in microhabitat areas between the baseline survey map and 2020, and between 2020 and 2021. Of the 56 springs, changes were documented at 15 springs in 2020, at 5 springs in 2021, and at 1 spring in 2022.

Site ID	Site Name	Microhabitat Area Changes
2020 Changes		
739	Big	Source channel expanded by 11 m^2 due to wetter conditions. This area was subtracted from the colluvial slope that surrounds the source.
162	Clover West	Channel increased by 9 m^2 due to higher flow rate. Channel margin decreased by 3 m^2 due to being subsumed into channel.
956	Dove	Pool increased by 9 m^2 due to wetter conditions. Pool margin decreased by 9 m^2 due to pool expansion.
226460	Driftfence	4 m^2 shifted from source to channel. It's possible the channel has become more incised through the source area, or flow is greater, making that 4 m^2 appear more channel-like. 210 m^2 shifted from terrace to low gradient cienega due to wetter conditions.
776	East Twin	Pool decreased by 26 m^2. It was dry when originally mapped in 2019. In 2020 surveyors reduced pool size to only the area that containing water during the survey. The pool perimeter increased by 12 m^2 due to pool size decrease. Uphill low gradient cienega increased by 28 m^2 and downhill low gradient cienega increased by 161 m^2 due to wetter conditions.
963	Fain	17 m^2 shifted from low gradient cienega to pool due to wetter conditions.
972	Foster Canyon	Low gradient cienega increased by 17 m^2 due to wetter conditions.
181912	North of Willard	A new map was drawn in April 2020. In August 2020, the surveyor decreased the low gradient cienega by 23 m^2 due to dryer conditions in late summer compared to spring.
1075	Rock Top	The source cienega decreased by 7 m^2. This was related to the source shifting to is slightly different location.
588	Rosilda	Pool increased by 113 m^2 due to wetter conditions. Pool margin decreased by 55 m^2 due to expansion of pool.
782	Sawmill	The lower low gradient cienega shrank by 1 m^2.
770	Spitz lower	The channel decreased by 8 m^2, but surveyors added a 161 m^2 low gradient cienega to reflect dramatically wetter conditions.
1096	Strahan	Channel increased by 1 m^2 and terrace decreased by 1 m^2. Despite the small area of the changes, there was shifting of several microhabitat boundaries (see sketchmap).

Site ID	Site Name	Microhabitat Area Changes
1113	T-Six	Due to wetter conditions and likely also geomorphic recovery following restoration in 2018, the boundary of this site expanded, increasing the source channel by 80 m^2 and increasing the low gradient cienega by 3,334 m^2. The downstream channel was subsumed into the two previously mentioned microhabitats, as it could no longer be distinguished.
1052	Wilson	Due to much wetter conditions, the pool increased by 44 m^2 and the channel increased by 46 m^2. The channel margin decreased by 40 m^2 due to the expansion of the channel.
2021 Changes		
899	Bear Seep	Pond contained water (was previously dry). Surveyor sketched the wetted pond boundary; this reduced the pond by 150 m^2 compared to its estimated size when dry. Pond margin increased by 150 m^2 due to reduction of pool.
426	Bone Dry	Spring was flowing for the first time during this study. Surveyors added a new 115 m^2 microhabitat to capture the wetted (standing water) and flowing reach of the springbrook, down to the road crossing.
951	Derrick	Reduction in area of wet channel by 7 m^2 and reduction in channel margin by 25 m^2 due to trampling by elk combined with reduction in springflow and riparian soil moisture.
972	Foster Canyon	Low gradient cienega was substantially drier; split into A: Wet low gradient cienega (25 m^2, reduced from 113 m^2) and B: Dry low gradient cienega (newly created, 59 m^2).
1075	Rock Top	Pool expanded into its margin slightly due to trampling. Pool area increased by 1 m^2 and pool margin decreased by 1 m^2.
2022 Changes		
1096	Strahan	The spring is in a canyon that experienced a major flood between monitoring visits in 2021 and 2022. This resulted in geomorphic change altering the area and configuration of channels, pools, and terraces.

Invertebrate Assemblages

Overview: Taxonomic identifications are on-going. However, several generalizations about assemblage composition among treatments and with regard to differences among springs can be made at this time.

Assemblage Composition: We have detected a total of 5804 BMI among at least 75 aquatic and riparian invertebrate taxa, including representatives among 54 families in 26 orders (Fig. 9). The overall composition of invertebrates detected in or on the riparian wetted edges of the springs is dominated by several groups with the following relationship (Fig. 9):

Diptera > Trichoptera = Coleoptera > Ephemeroptera > Plecoptera > Turbellaria > Microcrustaceans > Oligochaetae = Hemiptera > Bivalvia = Ixodes > Gastropoda > Amphipoda > Nematoda > Other

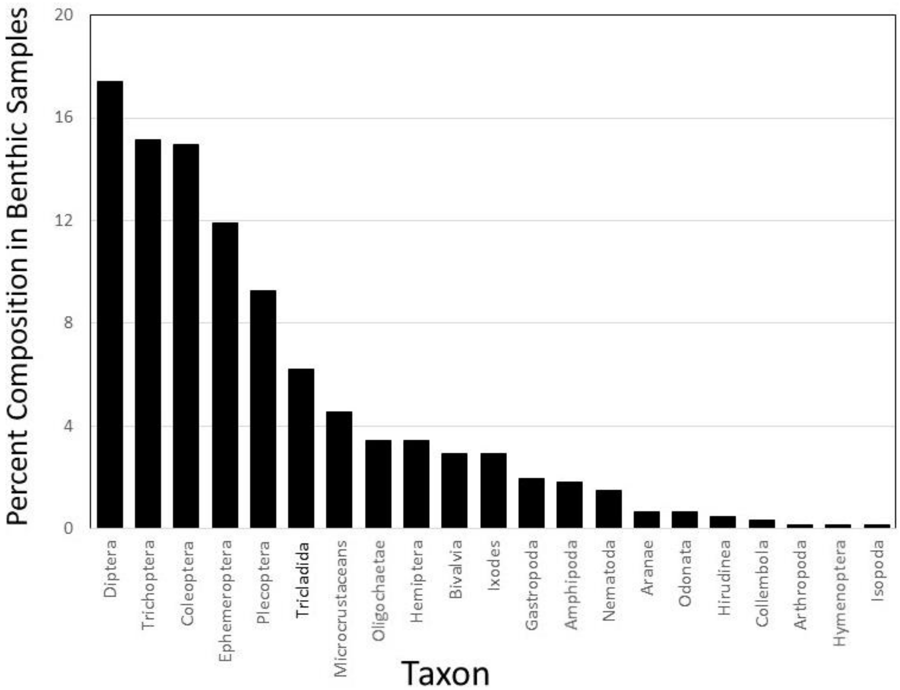

Figure 9. Percent composition of benthic macroinvertebrates in quantitative samples, ordered by abundance.

The overall spring invertebrate assemblage is dominated by Diptera, with Chironomidae the most abundant, followed by Sepsidae and many other true fly taxa. Within this diverse macroinvertebrate assemblage are several taxa often recognized as indicators of ecological integrity, including the native amphipod *Hyalella azteca*, dryopoid beetles (e.g., Elmidae), as well as Ephemeroptera mayflies, Plecoptera stoneflies, and Trichoptera caddisflies (Fig. 9). The latter three orders (abbreviated as "EPT") are widely used as indicators of high water quality. However, only some individual EPT taxa serve as water quality indicators, while others can be tolerant of lower water quality.

At present, differences among spring types, aquifer (bedrock) types, and forest treatments are complex to interpret (Fig. 10). Abundance varies substantially among taxa and spring, rock, and treatment types, necessitating log-transformation to reduce variance. Some taxa only have been detected in ecologically impaired lentic, helocrenic habitats (e.g., Ostracoda), while others are largely restricted to lotic hillslope springs (e.g., Plecoptera), and others are more catholic in their distribution (e.g., Ephemeroptera, Chironomidae). The array of species varied between the two springs types (wet meadow helocrene springs versus hillslope springs), between the two rock types (igneous and sedimentary), and the proposed treatments. The most stenotolerant taxa (those taxa confined to a relatively narrow range of environmental conditions, including several Plecoptera, Elmidae beetles, and perhaps *Enochrus* water scavenger beetles) are patchily distributed, but generally occur in the least impaired habitats.

However, it is not fair to assume that the absence of these taxa in various settings is attributable to population loss due to anthropogenic stewardship. Rather, such absence may simply reflect absence of colonization. Much variation exists among closely adjacent springs, in large part due to the vagaries of colonization and to the high level of ecosystem individuality that characterizes many springs, and which may have naturally excluded those species. More resolution on habitat affinity among taxa in spring, rock, and treatment types will emerge as additional sampling is conducted and taxonomy is refined.

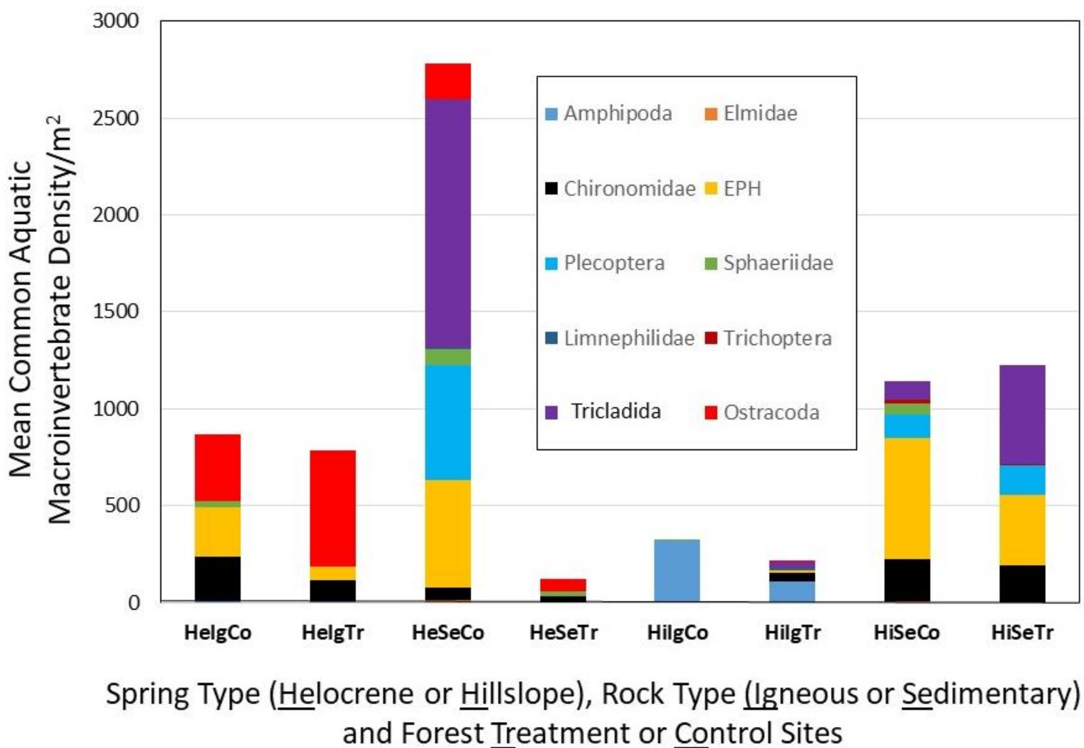

Figure 10. Mean density (no. indivs/ m2) of common aquatic macroinvertebrates among spring types, parent bedrock types, and forest treatments.

Substratum composition is a strong determinant of BMI composition and density (Stevens et al. 2020a; Fig. 11). Mixed gravels and cobbles channel floors tend to support more complex BMI assemblages, while fine sediment (embedded) benthos supports high densities of Ostracoda, some Diptera, and other BMI. Organic-dominated substrata support *Chironomus* bloodworms, Annelida, and other ooze-dwelling taxa.

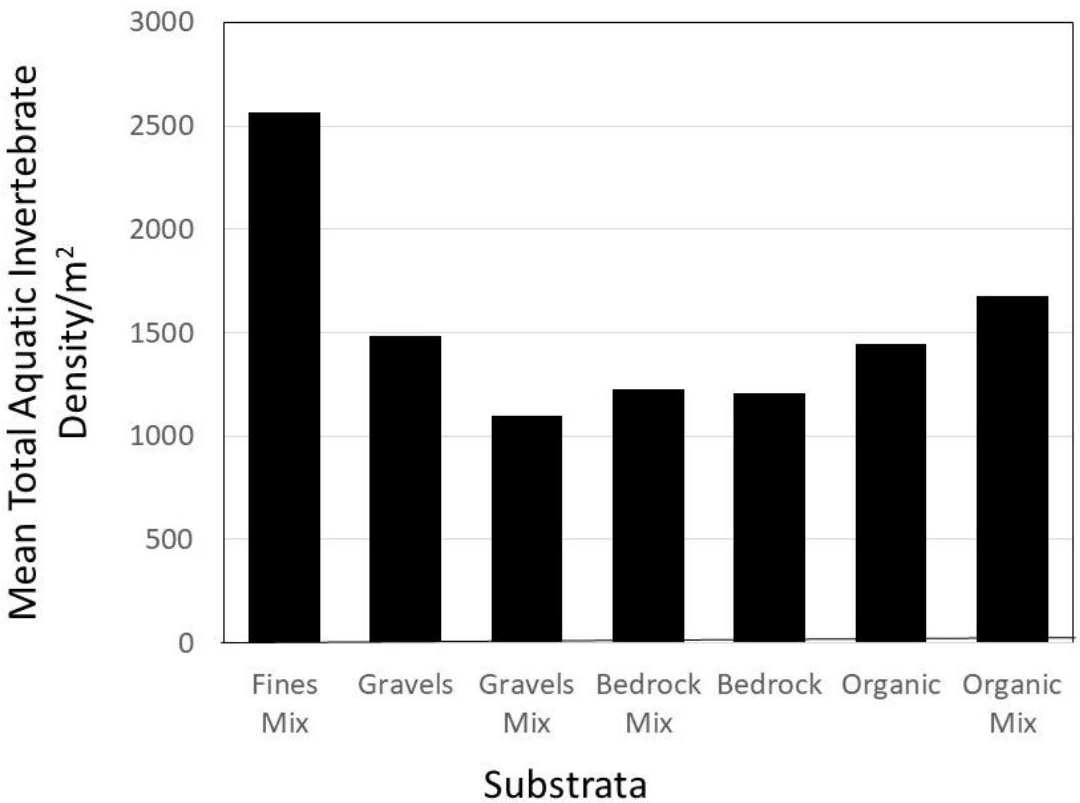

Figure 11. Mean total aquatic macroinvertebrate density(no. indivs/ m2) in relation to channel floor substrata.

Velocity is an important factor in BMI composition. Velocity varied from 0 to 1.2 m/s among the stations sampled at the springs visited that had sufficient flowing water for measurement and quantified BMI sampling (Fig. 12). Springbrook velocity strongly influences the composition and extent of embeddedness of channel floor materials, and consequently the habitat available for benthic macroinvertebrates. All taxa detected in this study except chironomid and related Nematocera midges were strongly asymptotically distributed in relation to velocity. Fig. 12 provides an example of the asymptotic distribution of Tricladida flatworm density/m^2, with highest values at lowest velocity and lowest density at highest velocities. However, this asymptotic velocity relationship is, in part, a function of the shallow depths of most springs in the study, with only a few cm of water depth at most sites. Velocity and overall discharge were not strongly related to total springs-influenced habitat area, due in many cases to the source(s) emerging onto steeply sloping bedrock or boulders, conditions that constrain the area of the wetted perimeter

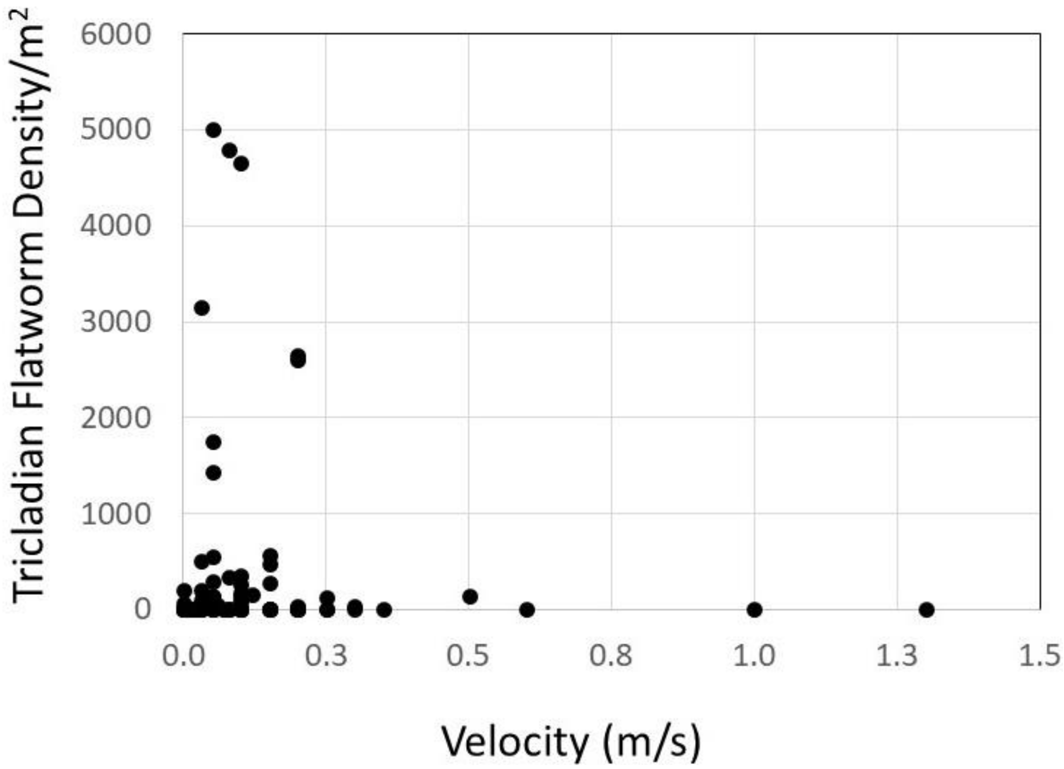

Figure 12. Asymptotic distribution of flatworm density (no. indivs/ m2) in relation to stream velocity (m/s).

Although still preliminary, Plecoptera stonefly density appears to be a promising invertebrate indicator of habitat quality among this suite of springs. Stoneflies are generally coolwater species that are highly intolerant of degraded water quality and habitat conditions. Several stonefly species are present in some of the springs, including the large, predatory *Hesperoperla pacifica*. Stonefly densities ranged from 0 to 2,767 individuals/m^2. Log10 transformation of Plecoptera density/m^2 was strongly related to the assessed condition of site geomorphology, which includes the ecological integrity of habitat configuration, springbrook channel geometry, soil integrity, geomorphic diversity (measured as the Shannon-Weiner H' value based on proportional contribution of associated microhabitats), and disturbance intensity. With SEAP assessment geomorphic condition scores categorized from 0 (obliterated) to 6 (pristine), Plecoptera density increased markedly with each increment of geomorphic integrity above a score of 2 (strongly degraded), reaching an average maximum of 107 individuals/m^2 under near pristine conditions (Fig. 13). We will present EPT scores for each sample in the final report; however, the affinity of many Ephemeroptera mayflies to occupy degraded, lentic waters is likely to result in reduced correlation between those taxa as indicators with habitat assessment scores (Fig. 14).

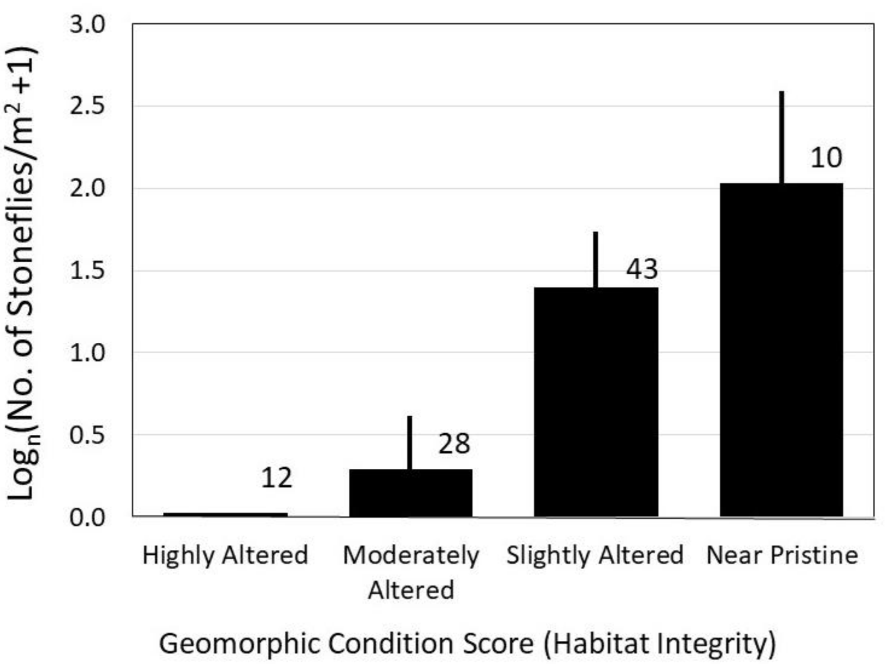

Figure 13. Log10-transformed stonefly density (no. indivs/m2) in relation to geomorphic habitat condition scores in the 4FRI study area, showing high affinity of Plecoptera for ecologically intact springs. Error bars are 95% confidence intervals.

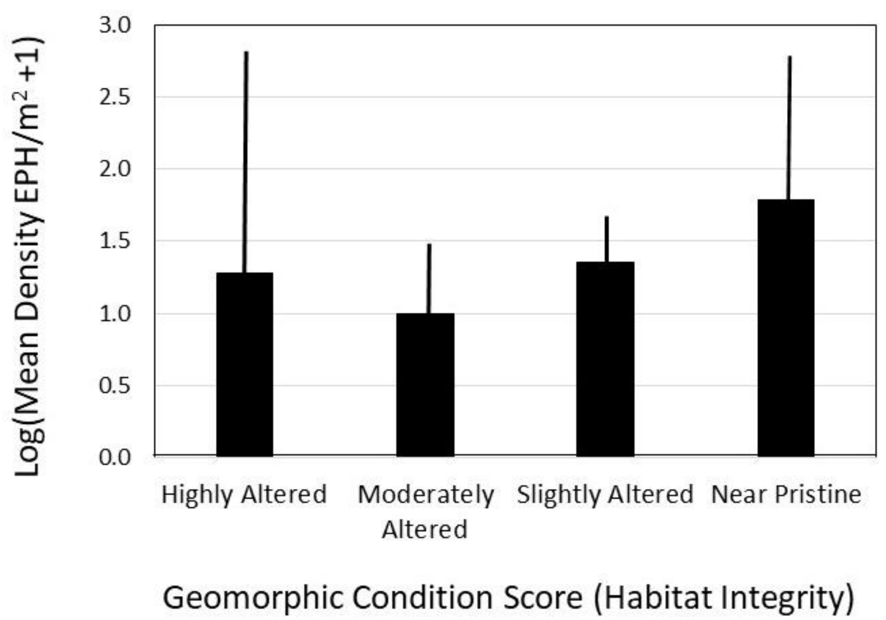

Figure 14. Log10-transformed mayfly density (no. indivs/m2) in relation to geomorphic habitat condition scores in the 4FRI study area, showing low affinity of Ephemeroptera for ecologically intact springs. Error bars are 95% confidence intervals.

Task 3: Conduct quality control checks on data and upload to Springs Online or other agreed upon database

All 2022 field data is in Springs Online and has been quality-checked. Project sponsors may access the data through their Springs Online accounts.

The data downloaded from the Hobo Tidbits are currently archived on the SSI server, and also are saved on at least one other computer. At the end of this five-year study, the complete dataset will be archived in a location to be determined through discussions with the US Forest Service.

DISCUSSION

Hydrology

Springs flow, depth, and inundation record are provided in this report for the fourth year of monitoring. The monitoring period includes limited forest treatments so the results to date provide mostly baseline information. This information is important as the state of the science is changing quickly with the increased interest in Western United States forest health and water availability (e.g., Meixner et al. 2016).

The state of the science on forest treatments and water availability has progressed since the 2019 4FRI springs monitoring report (Schenk et al. 2019 also Appendix F). Recent advances include an Arizona study indicating that snowpack and soil moisture is sustained longer in treated landscapes (O'Donnell et al. 2021); a review article highlighting the need for sustained forest treatments to increase groundwater yield (Schenk et al. 2020); and another review article that indicated that water yield impacts with forest disturbance are complex and driven by local variables (Goeking and Tarboton 2020). Empirical springs data from both the Mogollon Rim country and Kaibab Plateau indicate that most locally sourced springs systems are sensitive to snowpack (Donovan et al. 2023). Additionally, ecohydrologic models to predict water yield changes driven by forest treatments have also received greater interest than before (e.g., Schenk et al. 2020; Broxton et al. 2021; Giles-Hansen and Wei 2021; Wei et al. 2021). Studies on the importance of springs on surface water ecosystems (e.g., rivers) have also gained traction in recent years. The importance of springs as river baseflow is now widely documented (e.g., Fuchs et al. 2019; Reaver et al. 2019; Cantonati et al. 2020; Swanson et al. 2020; Donovan 2021) and acknowledged as crucial in semi-arid landscapes such as mid and high elevation Arizona and New Mexico.

Recent publications are likely to drive new study designs beyond this study and other 4FRI monitoring. Particularly relevant are studies on drought and forest thinning and detailed studies of forest thinning intensity versus water availability. The role of drought on the benefits of forest thinning and surface water was explored in the high elevation forests of Japan.

Drought-impacted watersheds showed a lower positive response to thinning than watersheds experiencing normal climate periods (Momiyama et al. 2021). Another paper identified that a 50% thinning intensity was needed for a quantitative water benefits and that a forest treatment return interval of 3 to 5 years is needed to maintain benefits in soil moisture and precipitation throughfall (del Campo et al. 2022). Continued research will help define study designs for improving the knowledge of forest treatments and water availability.

The increase in scientific interest in groundwater dependent ecosystems and forest management is partly driven by the record drought that the Southwest has been experiencing (as described in Williams et al. 2022). The drought conditions have impacted the springs flow, depth, and inundation by reducing flow and water depth at many of the 56 4FRI monitored springs. Impacts were especially noticeable at igneous springs and springs that were outside of the relatively wet Mogollon Rim landscape. The statistically significant drop in springs flow between years indicates that the springs monitoring network is responsive to rapid changes in climate and groundwater infiltration, this indicates that forest treatments will likely be noticeable in the springs monitoring network in a short (less than decadal) time period. Unfortunately, the lack of springs treatment sites (14 with several having marginal treatments) has led to inconclusive results to date in this study.

Despite the very recent international increase in interest in forest thinning benefits and the continued research of springs ecosystems in arid lands, the impact of forest thinning on groundwater dependent ecosystems (springs) is still relatively untouched. This study is timely and has the promise of being very useful not only for the 4FRI project and the US Forest Service but also for forest managers at an international scale. SSI looks forward to continued monitoring in future years and for the increase in frequency and scope of forest treatments to provide a measure of change on the landscape.

Habitat Change

The most striking differences noted in springs habitats between the baseline dataset and 2021 were related to the wetter conditions in 2020 compared to the other two years. Many ponds and cienegas that were recorded as dry in the baseline dataset had standing water or discernible springs flow in 2020. Differences between 2021 and 2022 conditions are less dramatic. Flow measurements and Onset Tidbit data suggest that conditions were slightly wetter, on average, compared to 2021. Geomorphic change was noted only at one spring, which had experienced a flood. The final analysis of habitat changes in Year 5 will incorporate the climate data into a model of springs responsiveness to short-term climate change, based on hydrologic data being collected by the Hobo Tidbits and annual flow measurements. The model developed from this first five- year's monitoring will provide a much-improved understanding of how climate and potential forest management affects groundwater and springs habitat conditions.

Invertebrate Assemblages

Preliminary examination of the BMI data reveals great variation among species and spring types, aquifer rock types, and forest treatment factors. Chironomidae are the most ubiquitous taxa, occurring at nearly every site; however, the many species in the chironomid assemblage likely play a wide number of ecological roles and have greatly varying tolerance levels. While Ephemeroptera (Fig. 14) and some Trichoptera are fairly widespread, these species exhibit a wider array of tolerance to anthropogenic disturbances than do Plecoptera, which appear to be the most sensitive indicators of high quality, unimpaired habitat. However, Plecoptera primarily occur in lotic habitats (Fig. 13), and therefore are not expected at all springs or springs types. Their habitat specificity may limit their utility in landscape treatment assessment. In contrast, the occurrence of undesirable species, such as sepsid flies, Ostracoda, and Annelida appear to serve as useful indicators of habitat degradation.

We are progressing with analysis of invertebrate assemblage differences between aquifer types, potential forest treatment types, and in relation to water quality variables. Quantitative aquatic macroinvertebrate samples have been collected, sorted, and preserved. Taxonomic analyses are still underway but will be sufficiently complete by the end of this first 5-year phase of the project to provide a suitable characterization of site variability and indicators of springs ecological integrity. Such modelling will be conducted using multivariate analyses, such as principal components analysis or non-metric multidimensional scaling. These statistical tests often are used to describe variation in distributional patterns among taxa that serve as indicators of quality habitat, and to reveal relationships between physical variables and BMI assemblage composition and structure.

Upcoming Work

In 2023, the final year of this five-year monitoring study, the SSI field inventory crew will re-visit all 56 study sites complete full Level 2 ecological inventories in addition to downloading data from the Hobo Tidbit dataloggers. We will submit a final report summarizing all ecological data from this long-term study.

CONCLUSIONS

In 2019 SSI completed data collection and entry on the 56 4FRI springs selected for this project. Those data serve as the baseline against which annual changes in discharge, springs area, springs invertebrates, and habitat conditions will be monitored through 2023. In 2020, 2021, and 2022, SSI completed hydrologic monitoring, recorded springs habitat changes, and revised sketchmaps. At the conclusion of the study in 2023, all sites will be fully re-inventoried, and changes in those and additional variables will be reported. SSI will continue monitoring springs throughout this large landscape restoration effort. We look forward to continuing to collaborate with the US Forest Service and the 4FRI planning group on this important, long-term experiment in sustainable natural resource management.

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List of Appendices

Appendix A. Springs selected as monitoring sites in the 4FRI Springs Health Monitoring Study and dates of monitoring visits.

Includes the date of the baseline inventory and year 2 and 3 monitoring visits, location, elevation, and lithology. Springs are organized according to treatment versus control designation and spring type latitude-longitude coordinates are in decimal degrees, WGS 84. Appendix A is included at the end of this document.

Appendix B. Map of Treatment Springs

As determined from 4FRI_RapidAssessment_2022_06_29.gdb, downloaded August 2022

Appendix C. Flow data by springs type, geology, and landscape position.

Includes measured spring flow rate from the baseline inventory and in 2020 and 2021. Appendix B is included at the end of this document.

Appendix D. Field water quality parameters at study springs.

Includes specific conductance, pH, and alkalinity. Appendix C is included at the end of this document.

Appendix E. Historical flow rates at 56 study springs.

Appendix F. 4FRI Monitoring Protocol.

Schenk et al. 2019. Groundwater Yield and Springs Monitoring Plan in Forest Thinning Treatments of the Four Forest Restoration Initiative (4FRI). Appendix F is attached as a separate document.

APPENDIX A: SPRINGS SELECTED AS MONITORING SITES IN THE 4FRI SPRINGS HEALTH MONITORING STUDY AND DATES OF MONITORING VISITS.

Springs selected as monitoring sites in the 4FRI Springs Monitoring Study, with date of baseline inventory and year 2 and 3 repeat monitoring visits, location, elevation, and lithology. Springs are organized according to treatment versus control designation and spring type. Latitude-longitude coordinates are in decimal degrees, WGS 84.

Site ID	Spring Name	Year 1 Survey	Year 2 Survey	Year 3 Survey	Latitude	Longitude	Elev. (m)	Primary Lithology
Treatment Sites								
Helocrene Springs								
182083	Clark Spring	10/8/2019	6/5/2020	6/9/2021	35.06545	-111.58367	2153	Sedimentary
776	East Twin Spring	7/29/2019	6/11/2020	5/2/2021	35.16906	-112.21548	2155	Igneous
430	General Springs	9/19/2019	5/4/2020	9/25/2021	34.45946	-111.24981	2192	Sedimentary
999	Immigrant Spring	10/13/2019	5/4/2020	9/6/2021	34.44087	-111.29438	2279	Sedimentary
1005	Kehl Spring	6/2/2017	5/4/2020, 9/14/20	9/25/2021	34.43563	-111.31711	2268	Sedimentary
582	Lower McDermit Spring	9/19/2019	5/5/2020	8/4/2021	35.25786	-111.91766	2165	Igneous
1036	Middle Kehl Meadow Spring	6/23/2017	5/24/2020, 9/14/2020	9/5/2021	34.44512	-111.31852	2311	Sedimentary
226446	Overhang Spring	6/22/2017	5/4/2020	8/6/2021	34.46616	-111.3401	2199	Sedimentary
588	Rosilda Spring	7/29/2019	5/6/2020	5/2/2021	35.17467	-112.06092	2051	Igneous
1089	Smith Spring	9/8/2019	4/23/2020	6/8/2021	34.93651	-111.48593	2199	Igneous
770	Spitz Spring Lower	6/11/2018	5/5/2020	8/4/2021	35.26033	-111.9751	2136	Igneous
250584	Trotting Turkey Spring	10/9/2019	6/5/2020	6/9/2021	35.05927	-111.5898	2122	Sedimentary
1113	T-Six Spring	6/12/2018	5/8/2020	8/4/2021	34.90741	-111.59618	2092	Igneous
1131	Willard Spring	9/11/2019	4/19/2020, 8/25/2020	5/24/2021	34.97329	-111.68184	2046	Igneous
Hillslope Springs								
899	Bear Seep Tank	9/18/2019	5/8/2020	6/9/2021	34.94475	-111.53757	2276	Igneous
426	Bone Dry Springs	9/27/2019	5/7/2020	6/9/2021	34.483	-111.28047	2195	Sedimentary

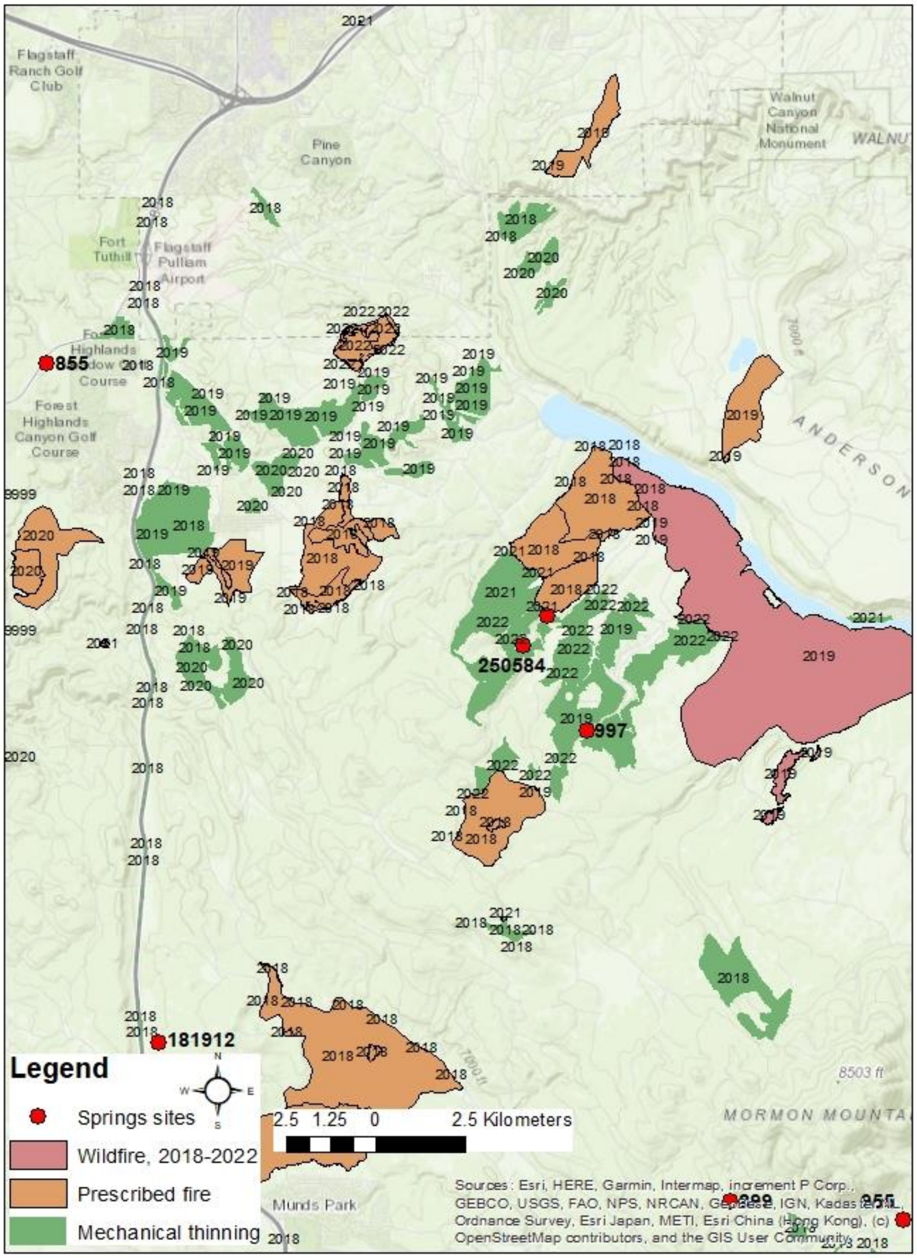
Site ID	Spring Name	Year 1 Survey	Year 2 Survey	Year 3 Survey	Latitude	Longitude	Elev. (m)	Primary Lithology
162	Clover Spring West	9/18/2019	6/10/2020	8/5/2021	34.50588	-111.36188	2089	Sedimentary
946	Dairy Spring	9/18/2019	4/26/2020	6/8/2021	34.95378	-111.48177	2166	Igneous
955	Double Springs (East)	9/8/2019	4/23/2020	6/8/2021	34.94106	-111.49433	2206	Igneous
855	Griffiths Spring	5/29/2019	6/5/2020	5/14/2021	35.11724	-111.70925	2092	Igneous
989	Homestead Spring	6/24/2017	5/16/2020, 9/13/2020	9/25/2021	34.47081	-111.28548	2212	Sedimentary
545	Hunter Springs	9/26/2019	5/8/2020	6/8/2021	34.57394	-111.18902	2189	Igneous
546	Keller Spring	9/19/2019	5/7/2020	6/9/2021	34.48976	-111.27278	2196	Sedimentary
1011	Lauren Spring	8/5/2017	5/7/2020	6/9/2021	34.49158	-111.27069	2112	Sedimentary
1032	McFarland Spring	7/19/2017	5/16/2020	6/8/2021	34.47773	-111.19592	2235	Sedimentary
181912	North of Willard Springs	9/11/2019	4/19/2020, 8/25/2020	5/24/2021	34.9776	-111.6814	2062	Igneous
578	One Hundred One Spring	9/20/2019	5/23/2020	8/6/2021	34.48732	-111.35115	2136	Sedimentary
782	Sawmill Spring	9/25/2019	5/5/2020	8/4/2021	35.28865	-111.95994	2219	Igneous

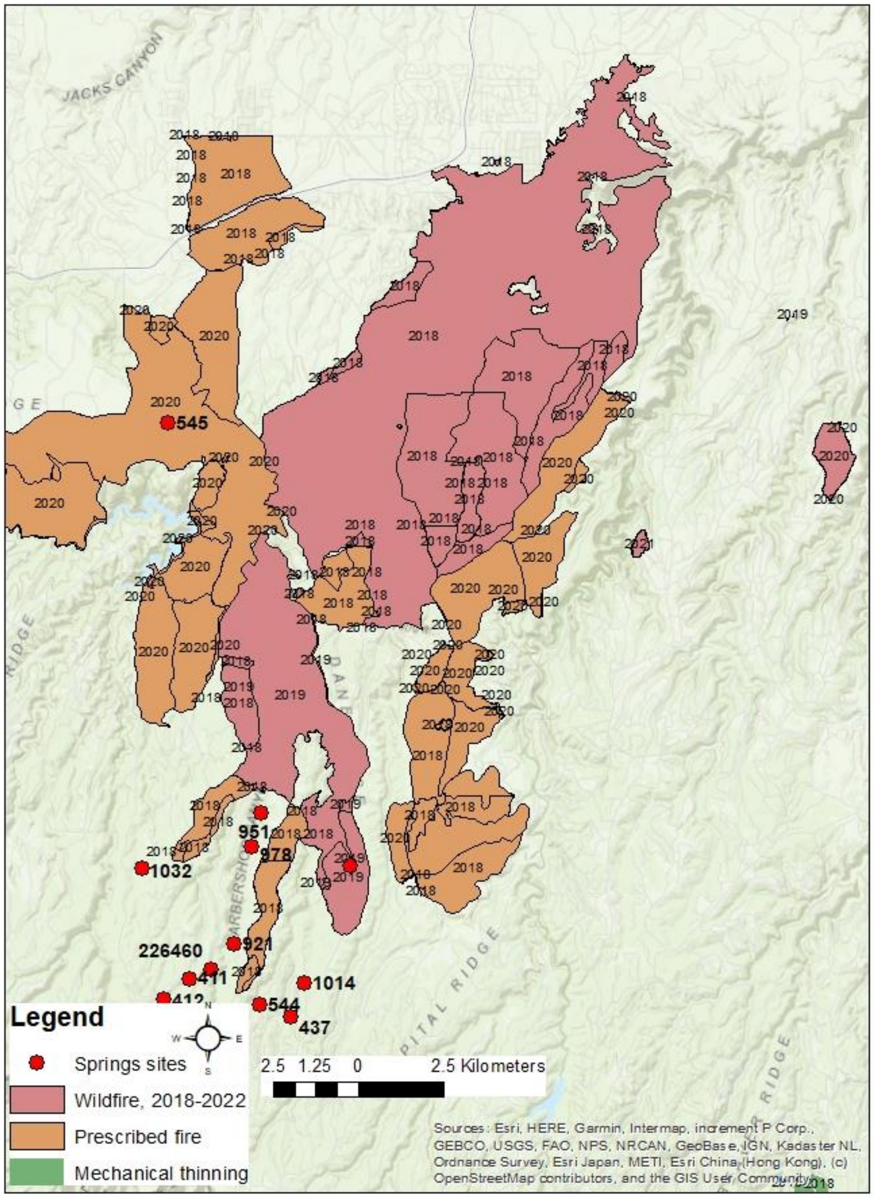
Site ID	Spring Name	Year 1 Survey	Year 2 Survey	Year 3 Survey	Latitude	Longitude	Elev. (m)	Primary Lithology
Control Sites								
Helocrene Springs								
896	Banfield Spring	9/27/2019	6/10/2020	8/5/2021	34.65101	-111.45337	2070	Igneous
437	Coyote Spring	9/26/2019	5/17/2020	6/5/2021	34.44445	-111.15651	2283	Sedimentary
226460	Driftfence Spring	7/19/2017	5/17/2020	6/7/2021	34.45502	-111.1777	2279	Sedimentary
963	Fain Spring	9/19/2019	5/8/2020	6/17/2021	34.81879	-111.52392	2000	Igneous
972	Foster Canyon Spring	9/20/2019	6/9/2020	6/17/2021	34.76072	-111.49747	1973	Igneous
1013	Lee Spring	10/1/2019	5/8/2020	6/17/2021	34.83571	-111.55419	2076	Igneous
1033	Meadow Spring	8/7/2017	5/15/2020, 9/13/2020	6/5/2021	34.42899	-111.15686	2247	Sedimentary
411	Merritt Springs	6/26/2019	5/6/2020	6/7/2021	34.4529	-111.18319	2274	Sedimentary

768	Mineral Spring	5/27/2014	8/27/2020	5/22/2021	35.25186	-111.99942	2124	Igneous
544	Monkshood Spring	9/26/2019	5/25/2020, 09/12/2020	6/5/2021	34.44723	-111.16472	2280	Sedimentary
425	Moonshine Spring	6/25/2019	5/8/2020	6/7/2021	34.47768	-111.14066	2206	Sedimentary
729	Mud Springs	7/29/2019	5/6/2020	5/22/2021	35.11495	-112.1868	2115	Igneous
412	Whistling Springs	6/26/2019	5/6/2020	6/7/2021	34.44828	-111.19014	2286	Sedimentary
1052	Wilson Spring	10/5/2019	5/31/2020	5/13/2021	35.33831	-111.72519	2491	Igneous
Hillslope Springs								
739	Big Spring	7/30/2019	5/6/2020	5/22/2021	35.15812	-112.08072	2088	Igneous
909	Bootlegger Spring	10/12/2016	5/8/2020	6/9/2021	34.91185	-111.53809	2257	Igneous
921	Carla Spring	7/19/2017	5/5/2020	6/6/2021	34.46048	-111.17152	2130	Sedimentary
951	Derrick Spring	6/26/2019	5/5/2020	6/6/2021	34.48902	-111.16452	2199	Sedimentary
956	Dove Spring	9/7/2016	6/9/2020	8/5/2021	34.8733	-111.37337	2229	Igneous
978	George Spring	6/26/2019	5/5/2020	6/6/2021	34.48148	-111.16695	2095	Sedimentary
982	Goshawk Spring	7/8/2017	5/15/2020	6/8/2021	34.43227	-111.18868	2302	Sedimentary
983	Grapevine Spring	10/2/2019	6/14/2020	8/8/2021	34.85841	-111.26418	2125	Igneous
1004	Jones Springs	9/20/2019	6/9/2020	6/17/2021	34.76321	-111.49854	1993	Igneous
1014	Leopard Frog Spring	7/7/2017	5/17/2020	6/5/2021	34.45205	-111.15308	2273	Sedimentary
144	Pivot Rock Spring	9/20/2019	5/23/2020	8/6/2021	34.49054	-111.3984	2130	Sedimentary
1075	Rock Top Spring	9/19/2019	5/8/2020	6/17/2021	34.85246	-111.548	1995	Igneous
226652	Spikerush Spring	7/8/2017	5/15/2020	6/6/2021	34.4236	-111.19143	2321	Sedimentary
1096	Strahan Spring	10/3/2019	5/17/2020	10/7/2021	35.08205	-111.92416	1947	Igneous

APPENDIX B: MAP OF TREATMENT SPRINGS

As determined from 4FRI_RapidAssessment_2022_06_29.gdb, downloaded August 2022.





JACKS CANYON
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Springs sites
Wildfire, 2018-2022
Prescribed fire
Mechanical thinning
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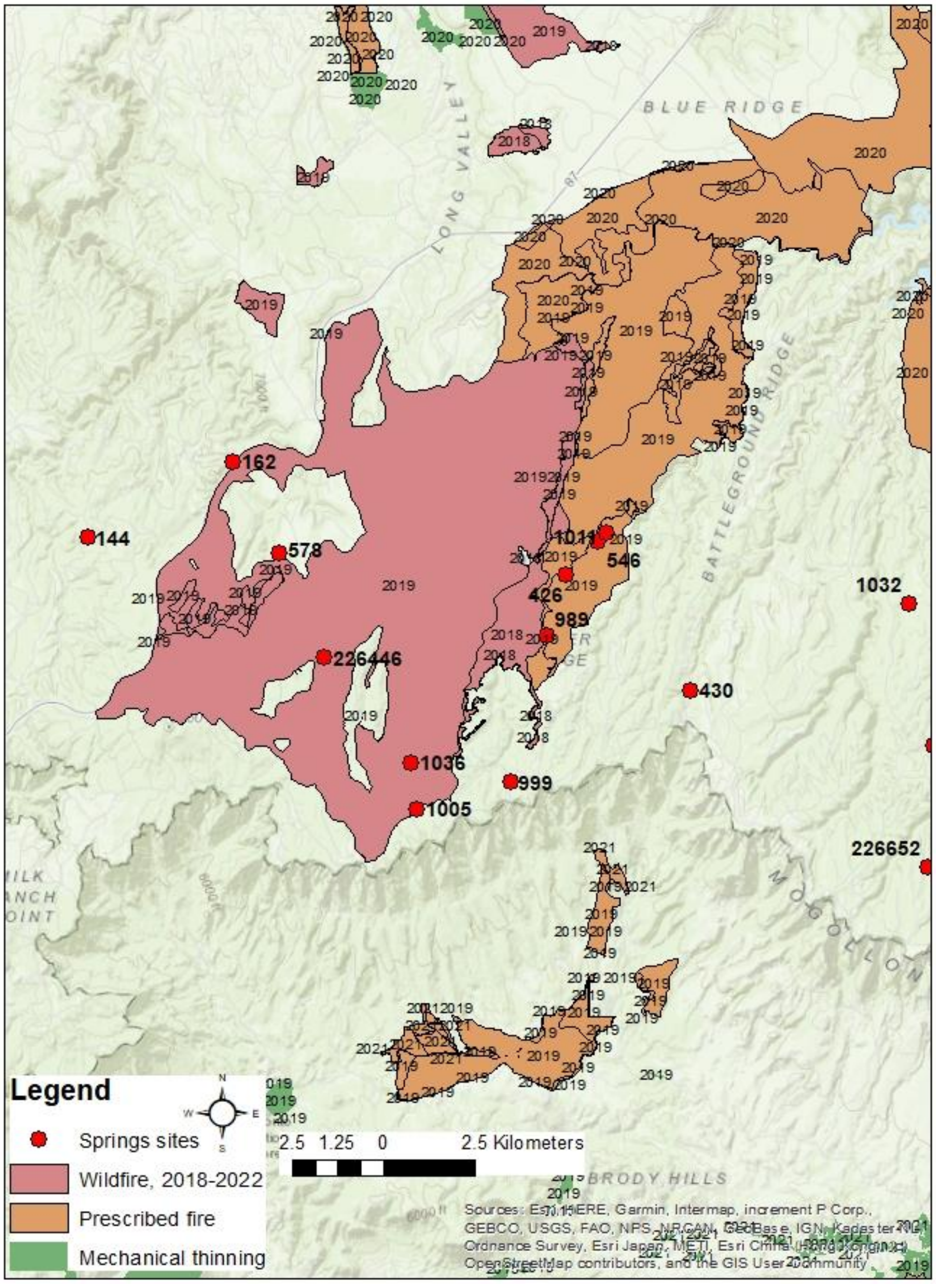
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community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Prescribed fire
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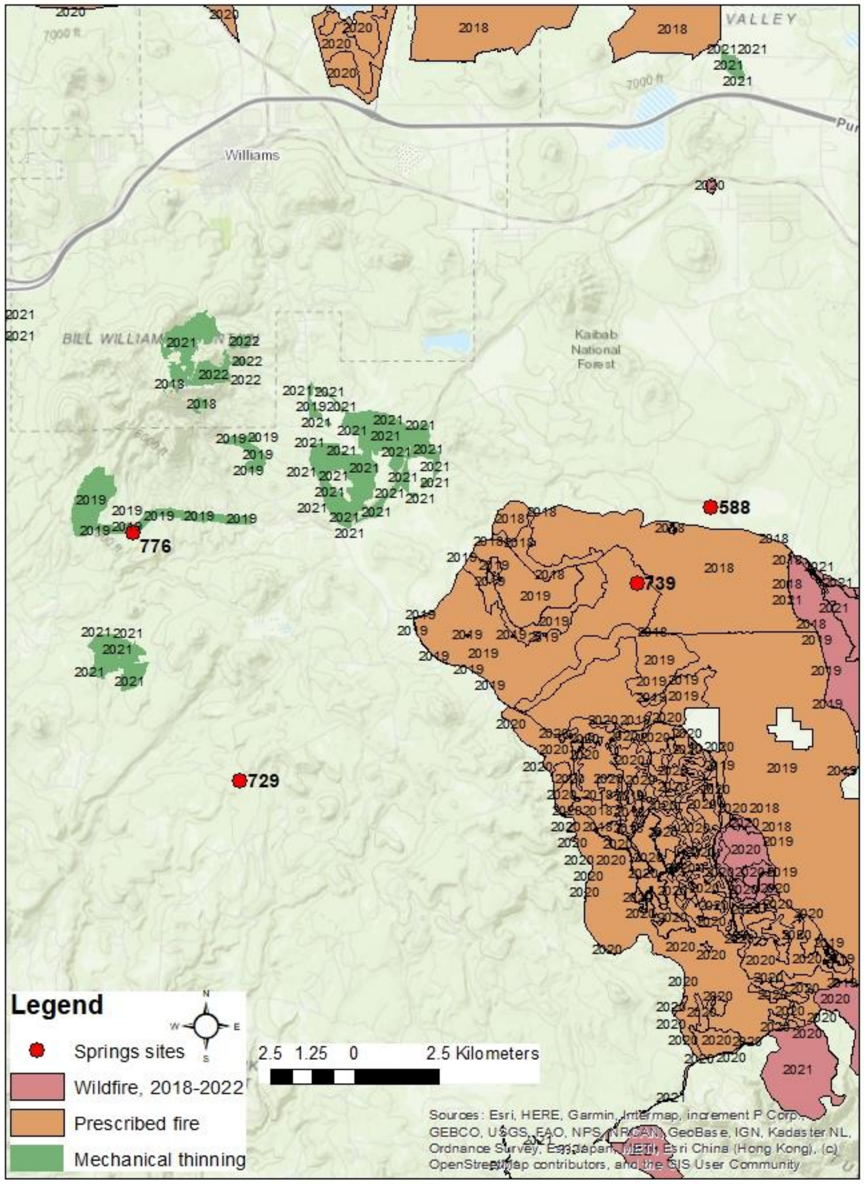
BLUE RIDGE
LONG VALLEY
BATTLEGROUND RIDGE
MOGOLLON
BRODY HILLS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Springs sites
Wildfire, 2018-2022
Prescribed fire
Mechanical thinning
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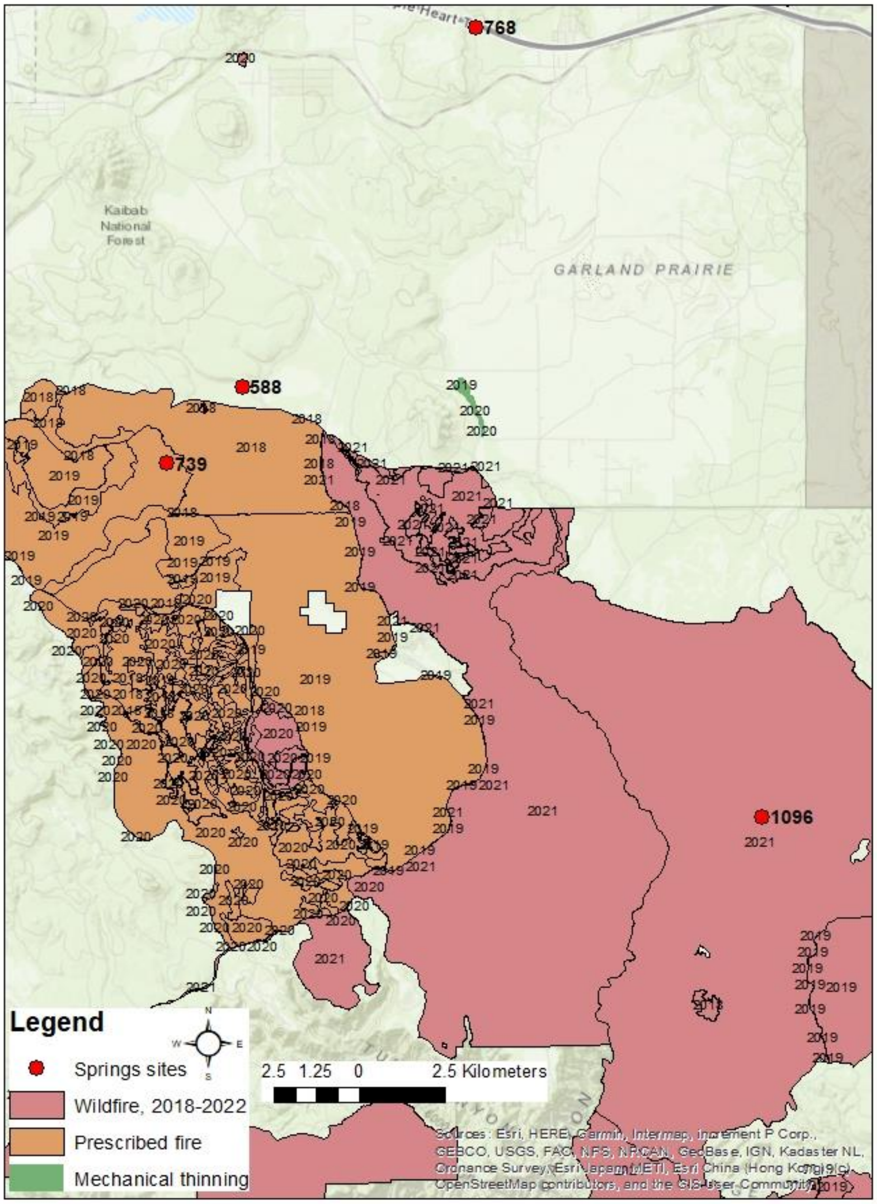
Kaibab National Forest
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community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Legend
Springs sites
Wildfire, 2018-2022
Prescribed fire
Mechanical thinning
2.5 1.25 0 2.5 Kilometers

Appendix C. Flow data by springs type, geology, landscape position, and Treatment status.

Site ID	Spring Name	Measured Spring Flow Rate (L/s), Baseline Year	Measured Spring Flow Rate (L/s), 2020	Measured Spring Flow Rate (L/s), 2021	Measured Spring Flow Rate (L/s), 2022
Helocrene Springs					
29	Banfield Spring	0.15	0.07	0.00	0.00
1	Clark Spring	0.00	0.00	0.00	0.00
30	Coyote Spring	0.20	0.59	0.06	0.07
31	Driftfence Spring	0.17	0.61	0.06	0.10
2	East Twin Spring	---	0.00	0.00	0.00
32	Fain Spring	0.00	0.25	0.00	0.00
33	Foster Canyon Spring	0.11	0.47	0.10	0.18
3	General Springs	0.00	0.48	0.04	0.00
4	Immigrant Spring	0.00	0.00	0.07	0.00
5	Kehl Spring	0.10	0.97	0.41	0.30
34	Lee Spring	0.00	0.00	0.00	0.00
6	Lower McDermit Spring	0.00	0.00	0.00	0.00
35	Meadow Spring	0.01	0.04	0.01	0.00
36	Merritt Springs	0.05	0.29	0.04	0.02
7	Middle Kehl Meadow Spring	0.08	1.10	0.17	1.92
37	Mineral Spring	0.01	0.04	0.02	0.00
38	Monkshood Spring	0.05	0.05	0.01	0.01
39	Moonshine Spring	0.40	1.20	0.00	0.00
40	Mud Springs	0.00	0.00	0.00	0.00
8	Overhang Spring	---	0.80	0.00	0.03
9	Rosilda Spring	0.00	0.00	0.07	0.00
10	Smith Spring	0.12	1.40	0.04	0.71
11	Spitz Spring Lower	0.00	0.02	0.02	0.01
12	Trotting Turkey Spring	0.00	0.00	0.00	0.00
13	T-Six Spring	0.01	0.00	0.00	0.04
41	Whistling Springs	0.16	0.12	0.06	0.00
14	Willard Spring	0.00	0.04	0.00	0.00
42	Wilson Spring	0.01	3.10	0.00	0.00
Hillslope Springs					
15	Bear Seep Tank	0.00	0.00	0.00	0.00
43	Big Spring	1.00	2.69	0.82	0.76
16	Bone Dry Springs	0.00	0.00	0.11	0.00
44	Bootlegger Spring	0.02	0.04	0.01	0.03
45	Carla Spring	0.57	0.51	0.18	0.13
17	Clover Spring West	0.00	6.79	0.16	1.46
18	Dairy Spring	1.50	22.00	0.33	3.09

Site ID	Spring Name	Measured Spring Flow Rate (L/s), Baseline Year	Measured Spring Flow Rate (L/s), 2020	Measured Spring Flow Rate (L/s), 2021	Measured Spring Flow Rate (L/s), 2022
46	Derrick Spring	0.92	1.70	0.36	0.28
19	Double Springs (East)	0.18	4.50	0.50	1.74
47	Dove Spring	0.03	4.40	0.00	0.00
48	George Spring	0.62	1.40	0.18	0.15
49	Goshawk Spring	0.09	0.10	0.02	0.03
50	Grapevine Spring	0.06	0.03	0.03	0.02
20	Griffiths Spring	0.42	0.31	0.04	0.05
21	Homestead Spring	0.02	0.18	0.00	0.00
22	Hunter Springs	0.00	0.14	0.00	0.00
51	Jones Springs	0.70	0.00	0.01	0.00
23	Keller Spring	0.15	1.40	0.35	0.03
24	Lauren Spring	0.04	0.39	0.21	0.004
52	Leopard Frog Spring	0.19	0.12	0.08	0.04
25	McFarland Spring	0.09	0.31	0.08	0.06
26	North of Willard Springs	0.14	1.00	0.03	0.04
27	One Hundred One Spring	0.15	0.33	0.03	0.01
53	Pivot Rock Spring	0.80	13.00	0.33	0.77
54	Rock Top Spring	0.00	0.01	0.01	0.00
28	Sawmill Spring	0.00	0.03	0.00	0.00
55	Spikerush Spring	0.03	0.06	0.02	0.01
56	Strahan Spring	0.08	0.68	0.29	0.13

Site ID	Spring Name	Measured Spring Flow Rate (L/s), Baseline Year	Measured Spring Flow Rate (L/s), 2020	Measured Spring Flow Rate (L/s), 2021	Measured Spring Flow Rate (L/s), 2022
Sedimentary					
16	Bone Dry Springs	0.00	0.00	0.11	0.00
45	Carla Spring	0.57	0.51	0.18	0.13
1	Clark Spring	0.00	0.00	0.00	0.00
17	Clover Spring West	0.00	6.79	0.16	1.46
30	Coyote Spring	0.20	0.59	0.06	0.07
46	Derrick Spring	0.92	1.70	0.36	0.28
31	Driftfence Spring	0.17	0.61	0.06	0.10
3	General Springs	0.00	0.48	0.04	0.00
48	George Spring	0.62	1.40	0.18	0.15
49	Goshawk Spring	0.09	0.10	0.02	0.03
21	Homestead Spring	0.02	0.18	0.00	0.00
4	Immigrant Spring	0.00	0.00	0.07	0.00

Site ID	Spring Name	Measured Spring Flow Rate (L/s), Baseline Year	Measured Spring Flow Rate (L/s), 2020	Measured Spring Flow Rate (L/s), 2021	Measured Spring Flow Rate (L/s), 2022
5	Kehl Spring	0.10	0.97	0.41	0.30
23	Keller Spring	0.15	1.40	0.35	0.03
24	Lauren Spring	0.04	0.39	0.21	0.004
52	Leopard Frog Spring	0.19	0.12	0.08	0.04
25	McFarland Spring	0.09	0.31	0.08	0.06
35	Meadow Spring	0.01	0.04	0.01	0.00
36	Merritt Springs	0.05	0.29	0.04	0.02
7	Middle Kehl Meadow Spring	0.08	1.10	0.17	1.92
38	Monkshood Spring	0.05	0.05	0.01	0.01
39	Moonshine Spring	0.40	1.20	0.00	0.00
27	One Hundred One Spring	0.15	0.33	0.03	0.01
8	Overhang Spring	---	0.80	0.00	0.03
53	Pivot Rock Spring	0.80	13.00	0.33	0.77
55	Spikerush Spring	0.03	0.06	0.02	0.01
12	Trotting Turkey Spring	0.00	0.00	0.00	0.00
41	Whistling Springs	0.16	0.12	0.06	0.00
Igneous					
29	Banfield Spring	0.15	0.07	0.00	0.00
15	Bear Seep Tank	0.00	0.00	0.00	0.00
43	Big Spring	1.00	2.69	0.82	0.76
44	Bootlegger Spring	0.02	0.04	0.01	0.03
18	Dairy Spring	1.50	22.00	0.33	3.09
19	Double Springs (East)	0.18	4.50	0.50	1.74
47	Dove Spring	0.03	4.40	0.00	0.00
2	East Twin Spring	---	0.00	0.00	0.00
32	Fain Spring	0.00	0.25	0.00	0.00
33	Foster Canyon Spring	0.11	0.47	0.10	0.18
50	Grapevine Spring	0.06	0.03	0.03	0.02
20	Griffiths Spring	0.42	0.31	0.04	0.05
22	Hunter Springs	0.00	0.14	0.00	0.00
51	Jones Springs	0.70	0.00	0.01	0.00
34	Lee Spring	0.00	0.00	0.00	0.00
6	Lower McDermit Spring	0.00	0.00	0.00	0.00
37	Mineral Spring	0.01	0.04	0.02	0.00
40	Mud Springs	0.00	0.00	0.00	0.00
26	North of Willard Springs	0.14	1.00	0.03	0.04
54	Rock Top Spring	0.00	0.01	0.01	0.00
9	Rosilda Spring	0.00	0.00	0.07	0.00
28	Sawmill Spring	0.00	0.03	0.00	0.00
10	Smith Spring	0.12	1.40	0.04	0.71
11	Spitz Spring Lower	0.00	0.02	0.02	0.01

Site ID	Spring Name	Measured Spring Flow Rate (L/s), Baseline Year	Measured Spring Flow Rate (L/s), 2020	Measured Spring Flow Rate (L/s), 2021	Measured Spring Flow Rate (L/s), 2022
56	Strahan Spring	0.08	0.68	0.29	0.13
13	T-Six Spring	0.01	0.00	0.00	0.04
14	Willard Spring	0.00	0.04	0.00	0.00
42	Wilson Spring	0.01	3.10	0.00	0.00

Site ID	Spring Name	Measured Spring Flow Rate (L/s), Baseline Year	Measured Spring Flow Rate (L/s), 2020	Measured Spring Flow Rate (L/s), 2021	Measured Spring Flow Rate (L/s), 2022
Mogollon Rim Springs					
45	Carla Spring	0.57	0.51	0.18	0.13
17	Clover Spring West	0.00	6.79	0.16	1.46
30	Coyote Spring	0.20	0.59	0.06	0.07
46	Derrick Spring	0.92	1.70	0.36	0.28
31	Driftfence Spring	0.17	0.61	0.06	0.1
3	General Springs	0.00	0.48	0.04	0.00
48	George Spring	0.62	1.40	0.18	0.15
49	Goshawk Spring	0.09	0.10	0.02	0.03
22	Hunter Springs	0.00	0.14	0.00	0.00
5	Kehl Spring	0.10	0.97	0.41	0.30
23	Keller Spring	0.15	1.40	0.35	0.03
24	Lauren Spring	0.04	0.39	0.21	0.004
52	Leopard Frog Spring	0.19	0.12	0.08	0.04
25	McFarland Spring	0.09	0.31	0.08	0.06
35	Meadow Spring	0.01	0.04	0.01	0.00
7	Middle Kehl Meadow Spring	0.08	1.10	0.17	1.92
27	One Hundred One Spring	0.15	0.33	0.03	0.01
8	Overhang Spring	---	0.80	0.00	0.03
53	Pivot Rock Spring	0.80	13.00	0.33	0.77
55	Spikerush Spring	0.03	0.06	0.02	0.01
41	Whistling Springs	0.16	0.12	0.06	0.00

Site ID	Spring Name	Measured Spring Flow Rate (L/s), Baseline Year	Measured Spring Flow Rate (L/s), 2020	Measured Spring Flow Rate (L/s), 2021	Measured Spring Flow Rate (L/s), 2022
Treatment Springs					
739	Big	1.00	2.69	0.82	0.76
426	Bone Dry	0.00	0.00	0.11	0.00
182083	Clark	0.00	0.00	0.00	0.00
776	East Twin	0.00	0.00	0.00	0.00
989	Homestead	0.02	0.18	0.00	0.00
545	Hunter	0.00	0.14	0.00	0.00
546	Keller	0.15	1.40	0.35	0.03
1011	Lauren	0.04	0.39	0.21	0.00
1036	Middle Kehl Meadow	0.08	1.10	0.17	1.92
425	Moonshine	0.40	1.20	0.00	0.00
226446	Overhang	---	0.80	0.00	0.30
1096	Strahan	0.08	0.68	0.29	0.13
250584	Trotting Turkey	0.00	0.00	0.00	0.00

Appendix D. Field water quality parameters at study springs.

Baseline field water quality parameters (specific conductance, pH, and alkalinity) at study springs. For specific conductance, the higher the value, the greater the mineralization in the water. pH is the measurement of acidic or basic properties. Water alkalinity measures the buffering capacity of spring water.

Site Name	Site ID	Survey Date	Specific conductance (µS/cm)	pH	Alkalinity (mg/L)
Banfield Spring	896	9/27/2019	211	8.04	90
Bear Seep Tank	899	9/18/2019			
Big Spring	739	7/30/2019	124	7.26	60
Bone Dry Springs	426	9/27/2019			
Bootlegger Spring	909	10/12/2016	184		65
Carla Spring	921	7/19/2017	324	7.16	176
Clark Spring	182083	10/8/2019			
Clover Spring West	162	9/18/2019			
Coyote Spring	437	9/26/2019	288	6.97	160
Dairy Spring	946	9/18/2019	142	5.93	56
Derrick Spring	951	7/19/2017	468	7.03	172
Double Springs (East)	955	9/8/2019	79	6.48	
Dove Spring	956	9/7/2016	136	7.84	
Driftfence Spring	226460	7/19/2017		7.26	132
East Twin Spring	776	7/29/2019	188	8.5	76
Fain Spring	963	9/19/2019	341	7.26	125
Foster Canyon Spring	972	9/20/2019	155	5.78	56
General Springs	430	9/19/2019	166	5.74	
George Spring	978	6/26/2019	320	6.83	148
Goshawk Spring	982	7/8/2017	333	8.11	98
Grapevine Spring	983	10/2/2019	574	8.09	216
Griffiths Spring	855	5/29/2019	814	6.26	42
Homestead Spring	989	6/24/2017	222	6.44	72
Hunter Springs	545	9/26/2019			
Immigrant Spring	999	10/13/2019			
Jones Springs	1004	9/20/2019	190	5.69	80
Kehl Spring	1005	6/2/2017	50	5.7	
Keller Spring	546	9/19/2019	537	7.18	
Lauren Spring	1011	8/5/2017	303	6.925	145
Lee Spring	1013	10/1/2019	253	8.21	65
Leopard Frog Spring	1014	7/7/2017	344	6.65	100

Site Name	Site ID	Survey Date	Specific conductance (µS/cm)	pH	Alkalinity (mg/L)
Lower McDermit Spring	582	9/19/2019	312	5.98	140
McFarland Spring	1032	7/19/2017	275	7.24	230
Meadow Spring	1033	8/7/2017	342	6.77	180
Merritt Springs	411	6/26/2019	319	7.34	148
Middle Kehl Meadow Spring	1036	6/23/2017	145	6.54	53
Mineral Spring	768	8/27/2020	3137	7.185	
Monkshood Spring	544	9/26/2019	432	7.77	155
Moonshine Spring	425	6/25/2019	43.5	5.825	24
Mud Springs	729	7/29/2019	147	6.645	64
North of Willard Springs	181912	9/11/2019	121	6.28	70
One Hundred One Spring	578	9/20/2019	277	6.98	
Overhang Spring	226446	6/22/2017	154	6.49	76
Pivot Rock Spring	144	9/20/2019	190	7.1	
Rock Top Spring	1075	9/19/2019	274	8	110
Rosilda Spring	588	7/29/2019	205	7.295	84
Smith Spring	1089	9/8/2019	105	6.12	
Spikerush Spring	226652	7/8/2017	415	7.63	123
Spitz Spring Lower	770	6/11/2018	159	6.08	80
Strahan Spring	1096	10/3/2019	416	7.83	188
T-Six Spring	1113	6/12/2018	533	6.29	
Trotting Turkey Spring	250584	10/9/2019			
Whistling Springs	412	6/26/2019	169	6.645	108
Willard Spring	1131	9/11/2019	163	6.16	70
Wilson Spring	1052	10/5/2019	117	5.98	

APPENDIX E: HISTORICAL FLOW RATES AT 56 STUDY SPRINGS

Igneous	<2009	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
															0.00
Banfield						0.16						0.15	0.07	0.00	
Bear Seep Tank					0							0	0.00	0.00	0.00
Big					0.62				0.17		0.35		2.69	0.82	0.76
Bootlegger Spring									0.022				0.04	0.01	0.03
Dairy						0.59						1.5	22.00	0.33	3.09
Double (East)						0.43			0			0.18	4.50	0.50	1.74
Dove Spring									0.023				4.40	0.00	0.00
East Twin						0			0			0	0.00	0.00	0.00
Fain	0.03											0	0.25	0.00	0.00
Foster Canyon										0.11		0.11	0.47	0.10	0.18
Grapevine						0.026						0.059	0.03	0.03	0.02
Griffiths				0.008	0.029		0.047		0.051			0.42	0.31	0.04	0.05
Hunter			0.052		0							0	0.14	0.00	0.00
Jones					0.51					0		0.01	0.00	0.05	0.00
Lee									0	0		0.01	0.00	0.00	0.00
Lower McDermitt					0.001				0			0	0.00	0.00	0.00
Mineral							0.014		0.018				0.04	0.02	0.00
Mud					0.00014							0	0.00	0.00	0.00
North of Willard									0.47			0.14	1.00	0.03	0.04
Rock Top										0		0	0.01	0.01	0.00
Rosalida					0.29				0.17			0	0.00	0.07	0.00
Sawmill					0				0			0	0.03	0.00	0.00
Smith							0.28		0.1			0.12	1.40	0.00	0.71
Spitz					0.037						0.0027		0.02	0.02	0.01
Strahan						0.23						0.079	0.68	0.29	0.13
Tsix					0.099				0				0.00	0.00	0.04
Willard									0.09	0		0	0.04	0.00	0.00
Wilson									5.2				3.10	0.00	0.00

Sedimentary	<2009	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Bone Dry					0							0	0.00	0.11	0.00
Carla										0.57			0.51	0.18	0.13
Clark												0	0.00	0.00	0.00
Clover West						0.45						0	6.79	0.16	1.46
Coyote		0.31										0.2	0.59	0.06	0.07
Derrick										0.95		0.92	1.70	0.36	0.28
Driftfence										0.17			0.61	0.10	0.10
General		0										0	0.48	0.04	0.00
George										0.315		0.62	1.40	0.18	0.15
Goshawk										0.086			0.10	0.02	0.03
Homestead					0					0.022			0.18	0.00	0.00
Immigrant										0		0	0.00	0.07	0.00
Kehl										0.1			0.97	0.41	0.30
Keller			0.33									0.15	1.40	0.35	0.03
Lauren										0.035		0.0075	0.39	0.21	0.00
Leopard Frog						0.1				0.19			0.12	0.08	0.04
McFarland					0.1					0.085			0.31	0.08	0.06
Meadow										0.014			0.04	0.01	0.00
Merritt		0.44										0.045	0.29	0.04	0.02
MKehl					0.1					0.79			1.10	0.17	1.92
Monkshood			0.074									0.045	0.05	0.01	0.01
Moonshine		0										0.4	1.20	0.00	0.00
One Hundred One			0.154									0.15	0.33	0.03	0.01
Overhang													0.80	0.00	0.30
Pivot Rock			2.77									0.8	13.00	0.33	0.77
Spikerush										0.033			0.06	0.02	0.01
Trotting Turkey												0	0.00	0.00	0.00
Whistling		0.48										0.16	0.12	0.00	0.05

APPENDIX F. 4FRI MONITORING PROTOCOL

Schenk et al. 2019. Groundwater Yield and Springs Monitoring Plan in Forest Thinning Treatments of the Four Forest Restoration Initiative (4FRI). ***Appendix F is attached as a separate document.***