Groundwater Yield and Springs Monitoring Plan in Forest Thinning Treatments of the Four Forest Restoration Initiative (4FRI)

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Photo caption: 4FRI forest treatment in progress near the Fort Valley Trail System north of Flagstaff, AZ, November 2018, Edward Schenk

Front cover caption: LO Spring on the Kaibab National Forest, photo from the Springs Stewardship Institute 2015.

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EXECUTIVE SUMMARY

The Four Forest Restoration Initiative (4FRI) is a joint project between Coconino, Kaibab, Tonto, and Apache-Sitgreaves National Forests to restore forests at a landscape level to a more natural and sustainable stand density. One secondary benefit expected by the project is the increase in surface and groundwater flow due to the reduction in vegetation. There are few studies on the impact of changes in vegetation density and composition on groundwater recharge and yield, despite several decades of previous studies of the impacts on surface water and riparian areas (Wyatt 2013, Acharya et al. 2018). The purpose of this report is to provide a framework to model, detect, and monitor the effect of 4FRI vegetation treatments on groundwater yield and springs ecosystems. The report is separated into two general sections, a section on modeling approaches and another on an empirical field monitoring plan.

Process based modeling is an important tool for predicting environmental change at a landscape scale. A modeling approach is appropriate for landscape scale projects such as the 4FRI treatment, and the relatively modest budget allowed for environmental monitoring on Forest Service units. This report evaluated several models eventually discarding some common eco-hydrologic models that were not suited for the northern Arizona landscape. The Water Supply Stress Index (WaSSI), Soil and Water Assessment Tool (SWAT), and HYDRUS models were not fully evaluated in this report due to data limitations or the resolution of model outputs. The Regional Hydro-Ecologic Simulation System (RHESSys) model, TIN-Based Real-Time Integrated Basin Simulator (tRIBS), coupled groundwater and climate modeling, and empirical statistical relational techniques were evaluated. This report presents a table with the data requirements of each model, allowing readers to decide if concurrent model runs are desired to evaluate the precision of the predictions and detect areas with diverging results. This report also provides a list of relevant climatic and hydrologic datasets for model implementation. Unfortunately, there is still several large data gaps making high resolution modeling difficult. New, and ongoing, research in northern Arizona on local groundwater recharge, water balances, and basic data collection may assist in long-term trend analysis but are still relatively immature.

The second portion of the report details an empirical field-based monitoring plan based on springs previously monitored for physical and biological character. The majority of this data is stored in Springs Online (SpringsData.org) while some of the continuous data is housed at Northern Arizona University (NAU) with Dr. Abraham Springer or the Salt River Project (SRP). Twenty eight springs with prior flow data were identified within the 4FRI five year treatment areas. Another twenty eight springs were selected at random within 20 km of treatment areas but upgradient or parallel to groundwater flow paths as potential control sites. Springs for both treatment and control areas were categorized by geology (igneous or sedimentary) and by spring type (hillslope or helocrene/wet meadow). Ten springs of high ecological value were identified for intensive study of microtopography, continuous flow, and restoration potential.

Due to budget constraints only three of these springs complexes were selected for intensive study (Hoxworth, Hart Prairie, and Clover). A total of 80 springs were selected for an ideal (non-budget restrained) version of monitoring, either as intensive sites with restoration potential or as sites appropriate to build a pseudo paired watershed monitoring network. These sites for both monitoring techniques are provided in the appendix in the event that future funding is appropriated for a larger study. All springs were classified by elevation, aspect, and flow using ArcGIS and the Springs Online relational database (SpringsData.org). The general design is similar to that of paired watersheds used for surface water forest studies.

A discussion is provided on the best model selection for the project and how to select a sub-set of the highlighted springs sites for long-term monitoring. The lack of long term data in the 4FRI project area makes any modeling exercise difficult at best. At this time the authors recommend a pseudo paired watershed study, allowing empirical comparisons of treatment and control springs to determine the impact of forest thinning. A cost estimate for both intensive monitoring, provided by NAU, and a pseudo paired watershed design, provided by SSI, is provided for the readers. A brief discussion of appropriate springs assessment protocols for detecting change is also included.

INTRODUCTION

The Four Forest Restoration Initiative (4FRI) is a ~600,000 acre landscape-scale forest restoration program in northern Arizona focused on the restoration of healthy ponderosa pine forests (Figure 1; Wyatt et al. 2015). The primary purpose of the project is to reduce the likelihood of severe forest fires created by dense fire-suppressed forest stands (e.g. Schultz Fire). This is particularly timely as this report was being written during and shortly after the Camp Fire largely destroyed the town of Paradise, CA and less than a year after the Tinder Fire destroyed over 30 homes near the Blue Ridge Reservoir in the Coconino National Forest. One of the secondary objectives is to provide for wildlife and plant diversity. One method of increasing diversity is to increase surface water and groundwater yields for wildlife and society by reducing evapotranspiration (ET) rates, rainfall-snow intercept by dense tree canopies, and hydrophobic soil creation by intense wildfires (O'Donnell et al. 2016). This objective is also timely as the Southwest persists in a drought state, making water resources in this semi-arid landscape even more valuable than usual. The 4FRI treatment areas are in watersheds that directly provide water to the Verde Valley, Phoenix, and numerous small communities in Arizona. Expectations of large increases in water yield from forest thinning should be tempered by previous studies indicating nominal increases in yield or short term benefits that are rapidly eclipsed by vegetation re-growth (Neary et al. 2008, Wyatt 2013, Acharya et al. 2018). Previous studies focused on groundwater recharge or yield but did not include monitoring of springs ecosystems or detailed analyses of groundwater yield at springs.

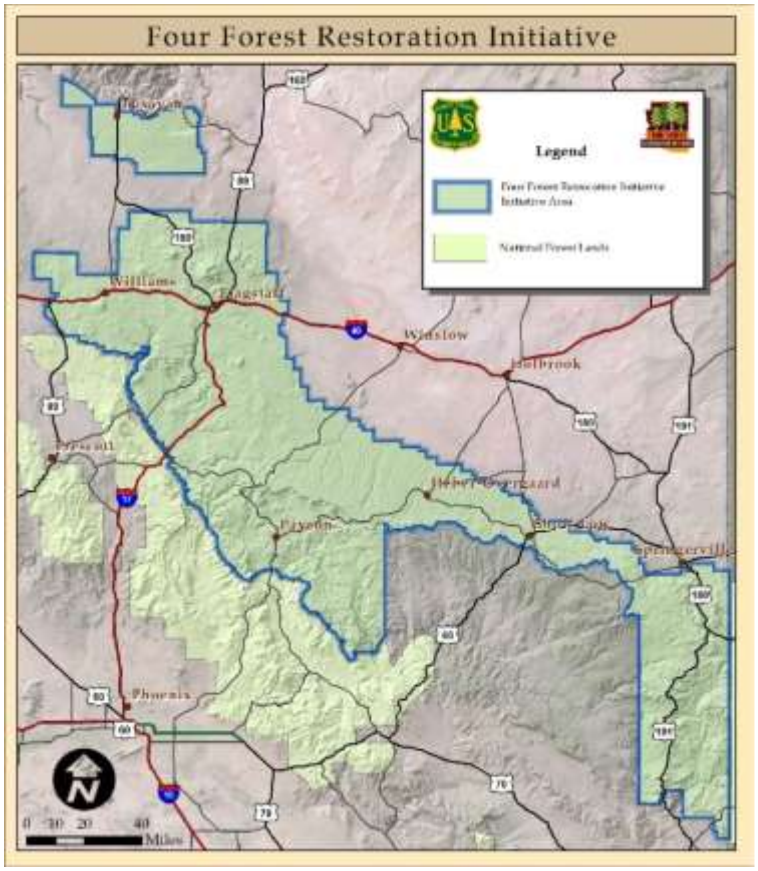

Figure 1. Map of the Four Forest Restoration Initiative (4FRI) project. Figure from the Forest Service 4FRI project website (https://www.fs.usda.gov/4fri).

Groundwater yields are expressed at springs, groundwater dependent ecosystems that exist at the intersection of the groundwater table and the surface (Stevens and Meretsky 2008). Springs are hot spots of biodiversity in the Arizona landscape, often with orders of magnitude more diversity than the surrounding landscape (Stevens et al. 2016). Springs ecosystems are used by springs dependent species, such as springsnails, upland animals as a watering source, and humans. Many springs contain cultural sites showing the long history of human use, contemporary use often includes watering locations for livestock and game animals and occasionally domestic use. Springs flow has lowered in the past decade as on-going droughts across the Southwest has begun to effect some springs (Schenk et al. 2018). Groundwater extraction, combined with drought, has also dried up, or reduced flow, at springs throughout Arizona (e.g. Blasch et al. 2006, Leake and Haney 2010, Tobin et al. 2018). Understanding the potential beneficial impact of 4FRI treatments on springs flow is important for quantifying ecosystem and societal benefits (Neary et al. 2008).

Previous hydrologic studies within the 4FRI project area include a groundwater-flow model for the Verde Valley section of the 4FRI area (Wyatt et al. 2015), a physical model for predicting surface water flow in the Verde-Tonto-Salt section of 4FRI (Moreno et al. 2016), and a modified empirical model for the Verde-Salt drainages based on the Beaver Creek experimental watershed (Robles et al. 2014). Recently a paired rainfall-runoff statistical model with climate and vegetation process modeling was used in the nearby Kaibab Plateau section of the Kaibab National Forest (O'Donnell et al. 2018). The amount of thinning required to detect a response in surface or groundwater varies by treatment and area. In general, a 20 to 40% reduction in forest basal area is required for detectable increases in water yield (Neary et al. 2008, Wyatt 2013, O'Donnell et al. 2016). The long-term benefits of forest thinning are questionable as vegetation re-growth and climate change may rapidly mask any gains in water yield (Wyatt et al. 2015, O'Donnell et al. 2018). To date there have been very few studies of the impacts of vegetation management on groundwater, or groundwater dependent ecosystems (GDE), either within the 4FRI project or on a global scale (Wyatt 2013, Wyatt et al. 2015, Acharya et al. 2018). While the hydrologic response may be marginal there is the potential for real lasting benefits for groundwater dependent ecosystems (i.e. springs) if the increase in water yield crosses an environmental threshold (Cartwright and Johnson 2018).

A systematic review of hydrologic responses to forest thinning was conducted by Wyatt (2013) as part of his master's thesis at Northern Arizona University. Wyatt synthesized 37 previous studies showing that surface yield tended to increase by up to 50% post-treatment but that results were often short-lived due to vegetation growth. Groundwater results were inconclusive and were summarized in less than half of the studies (Wyatt 2013). A more recent review of the impact of forest encroachment on groundwater recharge also highlighted the relative lack of scientific studies on groundwater responses to vegetation change (Acharya et al. 2018). The review article listed six general methods for determining groundwater change related to vegetation including: simple water balances, changes in water table, water isotopic signatures, chloride mass balance, electrical geophysical imaging of the water table, and physical and process modeling (Acharya et al. 2018). A new review of the existing literature was conducted by the authors' building on the previous reviews, a total of 35 groundwater studies related to forest management were summarized. A statistically significant difference in groundwater response to forest thinning was found between clear cut treatments and selective treatments ($p = 0.09$, $\alpha = 0.10$). Selective treatment areas showed greater increases in groundwater recharge than clear cut treatments, possibly due to the higher sublimation and evaporation in un-shaded clear cut treatments. To date there have been no known studies of the impacts of forest thinning on springs ecosystems, although the potential is great to conduct these studies by leveraging some existing, unpublished datasets from springs within the 4FRI treatment areas. This potential study, therefore, is unique in scope as it would determine the impact of forest thinning treatments not only on groundwater yield (by way of springs) but also of the impact on the individual springs ecosystems, thereby incorporating valuations of ecological integrity, water resource benefit, and hydrogeologic response.

MODELING APPROACHES

We analyzed each of the six general techniques listed in the review articles above to determine which techniques have merit for the 4FRI project. A water balance model can be constructed with groundwater recharge calculated as precipitation minus evapotranspiration (ET), surface runoff, and change in soil water storage. This method has been used in semi-arid rangelands in the US (Weltz and Blackburn 1995, Wilcox et al. 2006), but is of limited usefulness for the 4FRI project due to the large uncertainties in ET and soil water storage across the project area. Previous ET studies in the region show uncertainties of up to 92% with average model uncertainty of 11 to 14% (Ha et al. 2015). However, the predicted change in groundwater recharge is likely only 3% over the short term (Wyatt et al. 2015). The large amount of error inherent in a water balance approach makes it unfeasible for the 4FRI project, especially since the 4FI partners have not conducted efforts to monitor the energy and mass balance of the ecosystems planned to be restored. For this reason Ha et al. (2017) published models using off-site meteorologic data appropriate for simulating ET.

Empirical monitoring approaches that measure change in water table elevations between treatment and control areas has been used extensively to predict changes in groundwater recharge (Acharya et al. 2018). This method however has numerous uncertainties and potential errors. Factors including local groundwater pumping, location of monitoring wells relative to karst conduit features and/or preferential groundwater paths, and the aquifer system that the well is monitoring, all need to be considered and fully understood. Springs flow can be used as a surrogate for wells because springs exist at the intersection of the water table and the surface. Instrumenting a large network of springs and wells should provide some understanding of the change in groundwater recharge but may still include considerable error due to under or over sampling perched versus regional aquifers, differences in groundwater age, proximity to groundwater diversions and pumping, and unknown extent of the contributing zone to the monitoring site (Scanlon et al. 2005, Pool et al. 2011, Acharya et al. 2018, Tobin et al. 2018). An empirical monitoring approach alone may be inadequate for understanding the impact of forest thinning on the groundwater system, unless a robust study design is implemented that accounts for the potential weaknesses of monitoring groundwater yields.

Groundwater isotopes including hydrogen, oxygen, carbon, chloride, and nitrogen have been used to determine the provenance of groundwater (e.g. Fontes 1980). Isotopic analyses have been used to determine vegetative impacts on the water table in only a few studies, some of which have been inconclusive (Acharya et al. 2018). Several local studies have utilized isotopes to determine the source of groundwater, the relative contributions of snowpack, and the age of groundwater supplies (e.g. Johnson et al. 2012, Springer et al. 2017, Asante and Kreamer 2018). The cost of isotopic dating across the large, complex 4FRI treatment landscape render this method untenable for determining changes in groundwater recharge for this project.

Chloride, in groundwater, is a stable anion that neither leaches from sediment nor is adsorbed to particles. As such it can be used in mass balance calculations to determine the change in groundwater recharge (Gaye and Edmunds 1996, Acharya et al. 2018). The method is relatively low in cost for a small watershed but has numerous caveats including the necessity for constant land use over the period of study, the assumption that chloride mass flux is constant, and that there are no inputs or outputs of chloride other than that brought about by precipitation and groundwater discharge (Gaye and Edmunds 1996, Sibanda et al 2009, Acharya et al. 2018). The chloride mass balance approach was used by Aldridge (2015) to measure groundwater recharge in meadows, ephemeral channels, and thinned and un-disturbed ponderosa pine forests characteristic of 4FRI treatments. Aldridge (2015) found the chloride mass balance technique was capable of providing seasonal estimates of groundwater recharge within the range of estimates included in the Northern Arizona Regional Groundwater Flow Model of Pool et al. (2011). A chloride mass balance study was initiated by NAU in one of the 4FRI experimental watersheds in Upper Lake Mary (LM5 watershed; O'Donnell et al. 2016) in 2017 and is ongoing as of this writing.

Geophysical methods, particularly electrical resistivity mapping, can be used to quickly map the depth to the water table. Electrical resistivity has been used extensively throughout the world, including locally (e.g. Adams et al. 2006), to map the water table, changes in water table depth, and local geologic structure (Michot et al. 2003, Kirsch and Yaramanci, 2009). While this method is highly precise for shallow aquifers it is of limited utility for multiple, perched, or deep aquifers (e.g., the Redwall aquifer). Mapping the entirety of the 4FRI project would be time consuming. This method would be best used for shallow localized aquifers and near high elevation springs and wells that have shallow relatively uncomplicated groundwater paths.

Coarse-resolution, gravity-based groundwater monitoring from the twin GRACE satellites has indicated that depletion of groundwater storage within the Colorado River basin may exceed the rate of depletion of the large storage reservoirs (Lake Mead and Lake Powell), with the sharpest decline occurring over the past four years of severe drought (Castle et al. 2014). Unfortunately, the resolution of GRACE (100-200 km per "pixel") is insufficient to describe local depletions of aquifer storage and variability of groundwater recharge within the 4FRI area (Alley and Konikow 2015; Scanlon et al. 2015). Previous studies in the southwestern U.S. have demonstrated recharge is not uniform across the landscape but instead narrowly focused in stream channels during runoff events (e.g., Stonestrom et al. 2007). The rapidly-growing repeat microgravity method for monitoring recharge through thick unsaturated zones has great potential for being demonstrated within the 4FRI area. The repeat gravity method could be verified with two independent techniques, the chloride mass balance technique, and storage changes from water-level changes in regional wells (or springs flow).

The final method listed by Wyatt (2014) and Acharya et al. (2018) is physical and process based modeling. Several models have been used to predict the impact of vegetation removal (or vegetation encroachment) on groundwater recharge. Each model has strengths and weaknesses, and all require at least some amount of high precision data to provide a realistic and usable product to the user. A brief description of some of the models used in the past for similar studies is presented in both Wyatt (2013) and Acharya et al. (2018). These models are particularly useful for large landscapes where empirical monitoring alone may be cost or labor prohibitive. The data needs for each of the models is presented later in this report and is generally summarized in Acharya et al. (2018).

The majority of previous forest management-groundwater yield studies used an empirical approach, usually a paired-watershed design (Figure 2). Other approaches previously used include groundwater numerical modeling, process modeling, chloride mass balance, and water balances. The majority of studies have occurred in the last 15 years, indicating the recent interest in finding non-traditional means to increase groundwater yield (Figure 2).

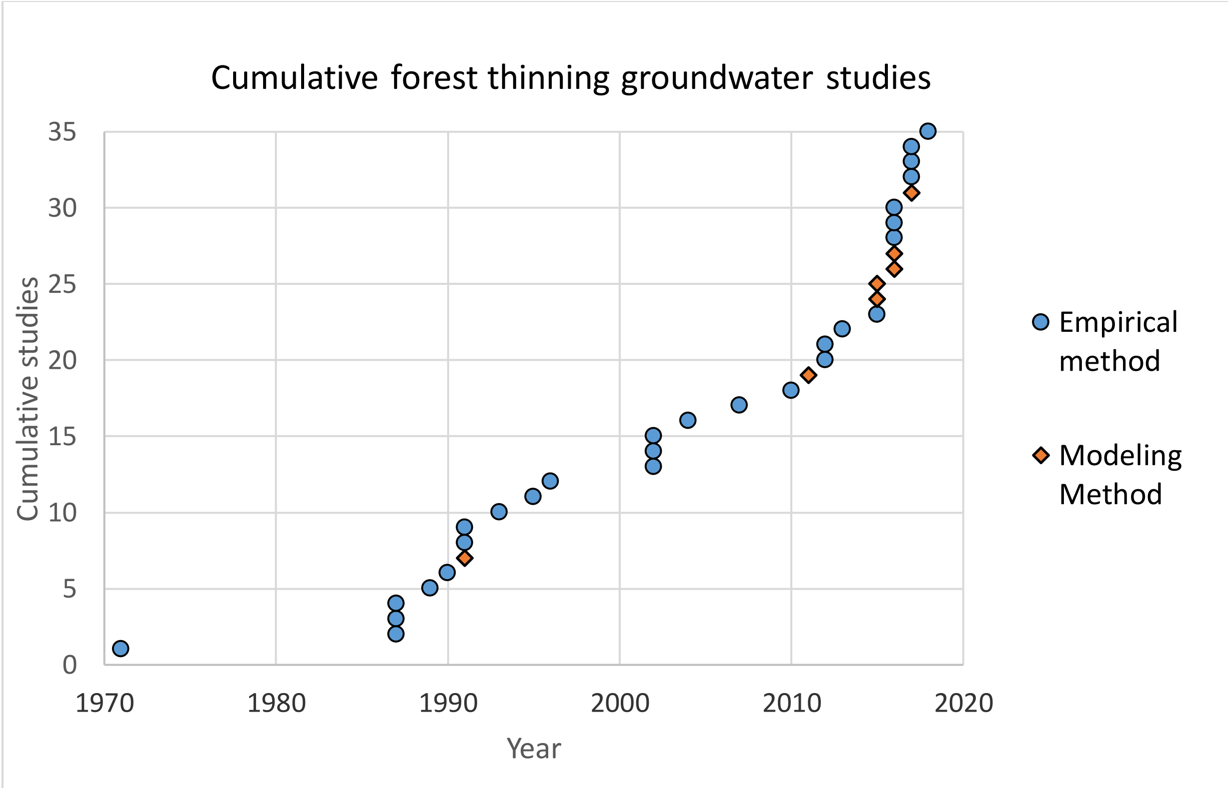

Figure 2. Cumulative graph of forest management-groundwater studies by general method.

The purpose of this study is to advise the 4FRI management team on the best methods for accurately and precisely determining, or predicting, the impacts of forest thinning on groundwater recharge and springs outflow in the 4FRI project, and to provide an understanding of the variables required to successfully run such a model. A second objective is to provide a comprehensive field monitoring plan of springs and wells influenced by 4FRI treatments, including possible springs and well sites for monitoring, monitoring techniques, and general timelines of pre- and post-treatment monitoring windows.

General Physical Components to Forest Thinning and Groundwater Yield Modeling

Geology

The 4FRI project spans the high lands of northern Arizona including sections of the Coconino Plateau, the Little Colorado Plateau, and the White Mountains. The majority of the study area is within, or on the edge, of the Colorado Plateau. Soils are largely mineral, shallow, and closely related to the local bedrock (Taylor 1983). Regional aquifers include the “C” aquifer comprised primarily of Kaibab Formation and Coconino Sandstone and the “R” aquifer comprised of the Redwall Formation and Muav Limestone (Hart et al. 2002, Blasch et al. 2006, Pool et al. 2011, Tobin et al. 2018). Localized perched aquifers in the discontinuous fractured igneous rocks associated with the San Francisco Volcanic Field and in the Supai Formation, among others (Billingsley et al. 1980). A simplified stratigraphic column for the Mogollon Rim section of the 4FRI project is included in Figure 3. Many of the models included in this report require geologic data including soil depth, soil moisture, depth to water table, and various aquifer characteristics. The needs of each model is listed later in this report.

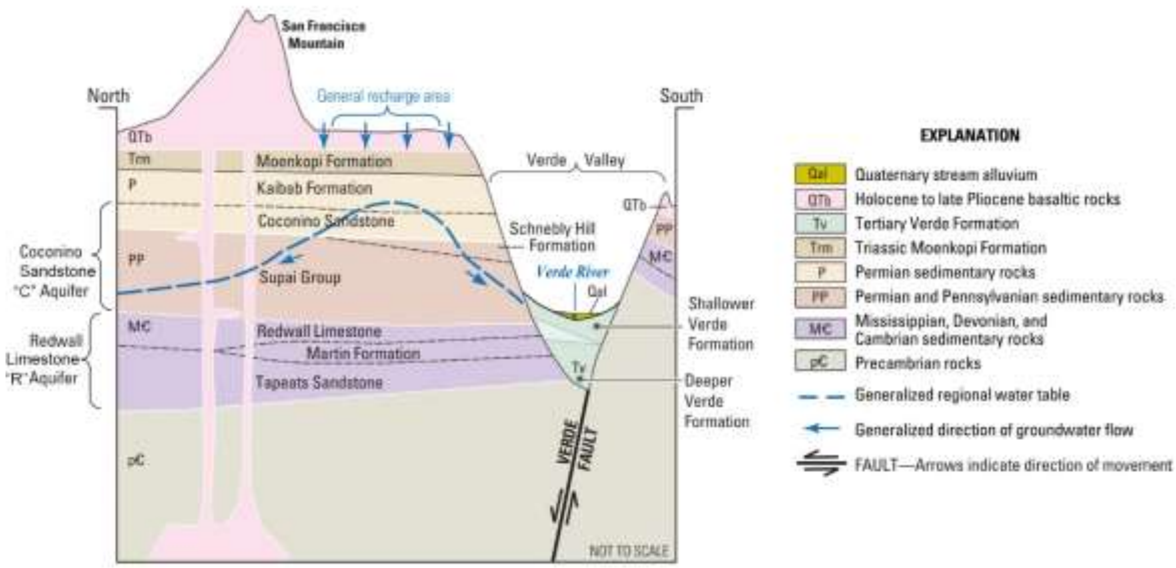

Figure 3 A hydrogeologic cross section from the San Francisco Mountains south to the Verde River basin, including major aquifers (Blasch et al. 2006, modified in Garner et al. 2013).

Hydrologic Cycle

The following section is a very brief description of some of the components of the hydrologic cycle relevant to this project. A summary figure was provided in Moreno et al. (2016) that has been modified and included as Figure 4. A more comprehensive discussion of the relevant components of the hydrologic cycle for forest thinning studies is provided in a recent chapter to the Colorado Plateau Science Biennial Conference Proceedings (O'Donnell et al. 2016).

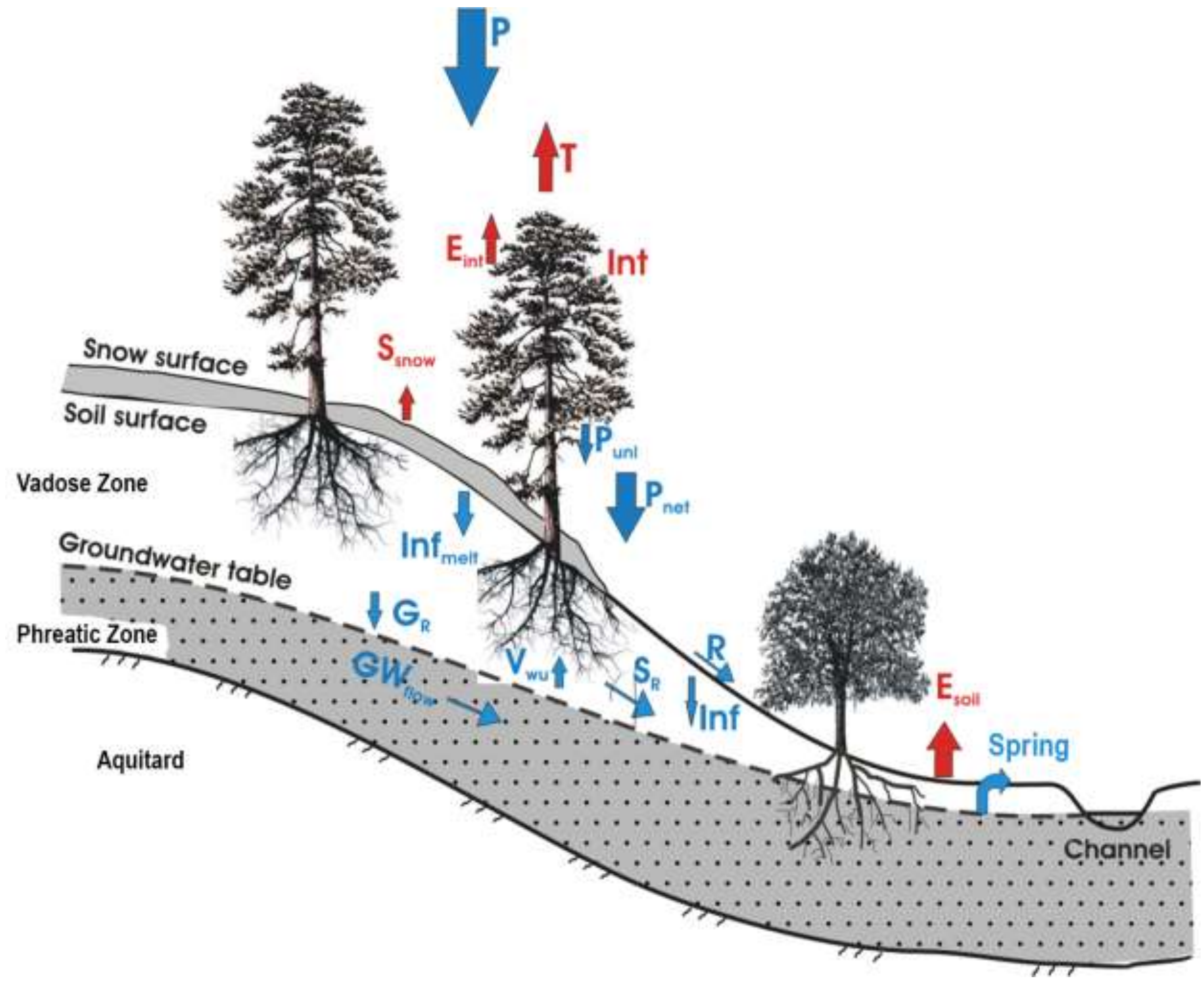

Figure 4. Components of the hydrologic cycle and water balance, modified from Moreno et al. 2016. Precipitation (P) can include either snow or rain and can be intercepted (Int) by vegetation allowing for net precipitation (P_{net}) to reach the ground as well as unloading (P_{unl}) from the vegetative canopy. Some portion of the precipitation in the canopy evaporates (E_{int}), evaporates from the soil surface (E_{soil}) or sublimates (S_{snow}). Surface runoff (R) can also occur. Some portion of the water infiltrates the soil either as rain (Inf) or as snowmelt (Inf_{melt}). Once in the unsaturated zone (vadose zone) water can either move laterally (S_r) or recharge the aquifer (G_r). Once in the aquifer water is constrained by the lower aquitard and moves down gradient as groundwater flow (GW_{flow}) and is expressed at the surface as either a spring or as baseflow in a stream channel.

Precipitation:

Precipitation in Northern Arizona can be generally characterized by winter snow events and summer monsoon rains. Monsoon rains are typically short duration events with the majority of water becoming surface runoff due to the intensity of the rainfall event overwhelming the ability of the water to infiltrate the soil. Most of the water that does infiltrate the soil is taken up by vegetation due to the short duration of rainfall. Most groundwater recharge, therefore, occurs due to the gradual melting of winter snowpack (Earman et al. 2006; Tobin et al. 2018). Measuring snow water equivalent (SWE) is essential for understanding the water balance in northern Arizonan watersheds (Baker 1986, O'Donnell et al. 2016).

Evapotranspiration (ET):

ET is the sum of processes that move water from the surface, and near surface, back to the atmosphere. Inherent in the term is both evaporation and transpiration, though ET often also includes sublimation. Measuring ET flux is inherently difficult due to the multiple pathways for evaporation, transpiration, and sublimation to occur as well as the environmental variables that control the flux of water from the surface and near-surface to the atmosphere (e.g. Verstraeten et al. 2008; Montes-Helu et al. 2009; Ha et al. 2017). Understanding these rates, however, are critical for understanding the impact of forest management on the groundwater recharge, aquifer storage, and spring flow.

Snow Sublimation:

Sublimation, the process where water transforms from a solid to a gas skipping the liquid phase, is especially important in Northern Arizona where the majority of precipitation is in the form of snow. The high elevations of Northern Arizona forests coupled with low humidity provides the conditions to readily sublimate snow on sunny days. The rate of water loss due to sublimation is a factor of climate, elevation, aspect, shading provided by trees (less water loss) and increased surface area of snow trapped within a tree canopy (increased water loss). Most ET models account for sublimation, as do direct measurements such as those taken at eddy-covariance towers (Verstraeten et al. 2008). Previous ET measurements in Northern Arizonan dense forests, burned areas, and thinned forests already fundamentally include sublimation in their calculations (e.g. Ha et al. 2015). A study dedicated to measuring canopy effects on snow sublimation in Central Arizona confirms the importance of sublimation in water budgets but also came to the result that snowpack throughout the region did not persist long enough into spring to experience substantial amounts of ground sublimation. Only areas above 2900m (9500 ft) elevation would see large changes in ground sublimation due to differences in canopy cover (Svoma 2016).

Groundwater Recharge:

Groundwater recharge is defined as the downward movement of water from the unsaturated (vadose) zone of soil or rock into the groundwater saturated (phreatic) zone (Fetter 2001). For groundwater studies the use of the term “recharge” can be synonymous with “net infiltration”, “percolation”, or “groundwater input” (Scanlon et al. 2002, Acharya et al. 2018). Groundwater recharge is controlled by a number of variables including precipitation, snow depth and snow water equivalent (SWE), water infiltration (controlled by vegetation, microclimate, and soil properties), soil porosity, permeability, and depth, root zone uptake, and depth to water table. Soil moisture is a key variable in most semi-arid water cycles and can be measured using a variety of probes (O’Donnell et al. 2016). This list is far from comprehensive and individual variables can be influenced by several other physical and biological factors. Measuring groundwater recharge can be difficult, especially for projects such as 4FRI where a high resolution, high precision, time sensitive product is required (Scanlon et al. 2002), and because recharge is ephemeral (usually only occurring during snow melt of average to above average snow melt years) and is focused (generally to ephemeral channels, fractures, faults, and sinkholes).

Groundwater Flow:

Groundwater flow is controlled by aquifer character including permeability, aquifer thickness, slope, fracture or dissolution conduits, and the rate of groundwater recharge, among other things (Fetter 2001). Northern Arizona is generally modelled by the USGS Northern Arizona Regional Groundwater Flow Model (NARGFM; Pool et al. 2011). While this model works reasonably well for coarse resolution simulations it does not include an accurate portrayal of karst features that may influence groundwater flow paths and residence times of some large karst springs in northern Arizona (Jones et al. 2018).

Surface Water Runoff:

Surface water runoff, also called overland flow, is defined by water that flows along the surface of the landscape following precipitation or snowmelt (Fetter 2001). The proportion of precipitation or snowmelt that becomes surface water runoff is controlled by the permeability of the soil surface, soil storage and draining capacity, the intensity and length of rain or snow inputs, and surface roughness (a proxy for residence time or pooling; Dunne and Black 1970). In Arizona the majority of surface water runoff occurs during monsoon storms, where high intensity, short duration storms overwhelm the ability of soils to drain leading to flash floods. Low intensity, long duration snow melt events usually produce less surface water runoff and a higher proportion of groundwater recharge.

MODELING HYDROLOGIC RESPONSES TO THINNING AND FIRE

Overview:

Predicting the impact of forest management (thinning and prescribed fire) on the hydrologic cycle at a large temporal or spatial scale requires modeling. Previous forest management studies have employed either brute force models based on statistical relations among long-term climatic and hydrologic datasets, or process-based models developed from a mixture of spatial and temporal physical and biological variables. To date a minority (17%) of groundwater-forest management studies have opted to use process or numerical models instead of empirical based statistical techniques. While some techniques or models may be more useful than others, all modeling techniques have inherent assumptions and data limitations that must be recognized for the user to understand the utility, and limitations, of the results (Box and Draper 1987).

In this report we provide the background on an eco-hydrologic model, RHESSys, and physical modeling suites, tRIBS and MODFLOW-precipitation/runoff modeling, that have the capability to predict groundwater recharge and surface runoff changes in relation to vegetation thinning. A third general method, empirically driven statistical/stochastic modeling, is presented at the end of this section. Several coarse resolution process models (e.g. WaSSI) have been used in other studies but would not be relevant for this project due to the high resolution prediction capability required for individual springs. The commonly used USDA Soil and Water Assessment Tool (SWAT) was likewise not evaluated for this report due to the difficulty in calibrating the model in complex terrain or extreme snow or rain events (e.g. monsoon events; Shope et al. 2013). SWAT may, however, be capable for rapidly modeling simplified events within the 4FRI project, specifically the impact of vegetation removal on snow driven groundwater recharge on relatively homogenous land forms. HYDRUS, a finite-element model, has been used in some vegetation thinning-hydrology studies (e.g. Wine et al. 2015; Acharya et al. 2018) but was not evaluated for this report due to the model's inability to accurately portray the landscape without data on spatially detailed plant rooting depth (Acharya et al. 2018).

Ideally multiple models will be utilized to provide a range of results, giving the Forest Service an idea of the precision of the results as well as an understanding of the uncertainty in the results. Running multiple models is common for environmental predictions including hurricane tracking, oil exploration, and climate change predictions. The models described below have considerable overlaps in data requirements, allowing for concurrent model development and runs. Land managers should understand that each of these models were developed with different goals in mind. The ecohydrologic model was designed primarily with surface runoff and shallow groundwater components while the MODFLOW derived model is much more detailed with groundwater components but lacks fine detail in surface processes. None of the modeling techniques described below will provide a perfect representation of the complexity of the northern Arizonan landscape, empirical monitoring will always be required to verify model results.

RHESSys – Regional Hydro-Ecologic Simulation System:

RHESSys is a process-based model based on a GIS framework that allows the user to assess various hydrologic, vegetative, and biogeochemical processes within a watershed (Tague and Band 2004). The value of this model is that it requires relatively few input data to provide useful process-based results. This is important for a project like 4FRI where there are few long-term continuous datasets. Calibration datasets can include ET, soil moisture, snowpack/snowmelt, canopy cover and leaf area index (LAI), and stream gauge discharge. A flow chart of components that can feed into a RHESSys model of forest thinning impacts on hydrology is provided in a study of climate and land use changes in North Carolina Forest Service lands (Martin et al. 2017).

Relevant studies that used RHESSys include a headwaters of the Yakima River studied where the researchers paired a RHESSys model with a covariance matrix adaptation evolution strategy (CMA-ES) to calibrate the model. Future work within that study will pair RHESSys with MODFLOW and RiverWare (Nguyen 2015). RHESSys also was used in the headwaters of the American and Merced Rivers in California to determine the impact of forest thinning on runoff, LAI, canopy cover, and shrub cover (Saksa et al. 2017). That model has snowpack applications, as demonstrated in a study that showed stream baseflow losseas a function of reduced snowpack and snowmelt in the West (Tague and Grant 2009). RHESSys is also used to simulate land use changes including forest harvest and road development in Western Oregon (Tague and Band 2000) and to predict climate impacts on forest stand growth and streamflow (Martin et al. 2017).

tRIBS – TIN-Based Real-Time Integrated Basin Simulator:

A previous 4FRI study assessed the impact of program treatments on surface water runoff using calibrated datasets from paired research watersheds. The focus of the study was on the Verde, Tonto, and Salt watersheds along the Mogollon Rim (Moreno et al. 2016). The tRIBS model was employed using paired data from the reference and treatment watersheds. While this method previously was used for the 4FRI project area, it is likely less robust than other techniques due to the reliance on purely physical parameters (climate, topography, precipitation), vegetative character has to be simulated. A user guide for tRIBS can be found online at: http://vivoni.asu.edu/tribs/userManual.html.

Coupled Groundwater Model with Precipitation-Runoff (e.g. MODFLOW-PRMS):

The Northern Arizona Regional Groundwater Flow Model (NARGFM) is a regional numerical model running on the MODFLOW base code (Pool et al. 2011). The model has been used for a previous study of impacts of 4FRI on surface water runoff (Wyatt et al. 2015). The model was fed data from the Basin Characterization Model that provided recharge values (Flint and Flint 2008) and a Forest Vegetation Simulator (FVS; Dixon 2002) to simulate vegetation re-growth. Since MODFLOW does not model vegetation explicitly the authors had to make adjustments to the recharge flux property by hand to simulate changes in ET (Wyatt et al. 2015). Similar models could combine groundwater flow models (e.g. MODFLOW) to climate and precipitation run-off models (e.g. Precipitation-Runoff Modeling System; PRMS). Any model should incorporate conduit flow modules as the 4FRI study area includes well developed karst features. Newer versions of MODFLOW (after 2016) can include the Conduit Flow Pathway (CFP) module to help simulate rapid conduit flow pathways. Adapting the NARGFM model to simulate the real-world karst heterogeneity in the C and R aquifers would be helpful for modeling hydrologic responses for springs relatively close to treatment areas. Springs that draw from a larger region can still be accurately modeled using a porous media model like NARGFM due to the masking factor of mixed waters from different sources and flowpaths (Scanlon et al. 2003).

Empirically-based Statistical Modeling:

The authors conducted a review of the existing literature; the results indicate that the majority (29 out of 35) of forest management studies that quantified groundwater impacts used empirical based statistical modeling. The majority of studies implemented a paired watershed approach. While very data intensive, this technique is useful in areas that do not have existing long term datasets of climate, geology, vegetation, soils, and hydrology. Previous local hydrology-vegetation studies have usually relied on collecting project specific field data to come to conclusions.

Rainfall-runoff regressions were used to create a statistical model describing the impact of fire, climate change, and forest thinning on the Kaibab Plateau (O'Donnell et al. 2018). Other inputs included a vegetation model based on Climate-FVS and LANDIS II. The model was calibrated using experimental forest (paired watershed) studies at Thomas Creek, Willow Creek, Workman Creek, Beaver Creek, Castle Creek, and Corduroy Creek (O'Donnell et al. 2018). A similar 4FRI study was conducted in the Verde-Salt watersheds using a series of regression models to determine groundwater yield (Robles et al. 2014). This study assessed the relative increase in surface water flow following thinning using a modified Baker-Kovner logistical regression technique (Brown et al. 1974) and data from the Beaver Creek experimental paired watersheds. The modified equation was most strongly informed by tree basal area, total winter precipitation, years after treatment, and predicted increase in precipitation (Robles et al. 2014). The model was particularly useful because the study encompassed the Beaver Creek experimental watershed where the original Baker-Kovner model was developed.

Regression modeling techniques can be useful to predict the impact of 4FRI treatments on groundwater recharge and springs flow. The model used by O'Donnell et al. did not account for groundwater inputs or output. A more refined model would need to include soil moisture, ET, depth to water table, and preferential groundwater flow paths. Once completed it would require similar inputs as the RHESSys or MODFLOW-PRMS modeling techniques (Table 1).

Table 1. A comparison of generic model inputs required to successfully predict hydrologic impacts of forest thinning.

Study:	Saksa et al. 2017	Moreno et al. 2016	Wyatt et al. 2015	O'Donnell et al. 2018
Model:	**RHESSys**	**tRIBS**	**MODFLOW-PRMS**	**Empirical modeling**
			NARGFM/FVS/BCM/CMIP3	*(& Climate FVS/LANDIS-II/GCM)*
	Precipitation	Precipitation	Precipitation	Precipitation
	Snow depth	Snow depth		ratio of snow/rain
	temperature	temperature		temperature
	solar radiation	solar radiation		solar radiation
	wind speed/direction	wind speed/direction		wind speed/direction
	soil moisture	soil moisture		
	streamgauges	streamgauges	streamgauges	streamgauges
	aspect	aspect		aspect
	slope	slope		slope
	elevation	elevation		elevation
	vegetation composition			vegetation composition
	vegetation vertical structure	vegetation height		
	basal area		basal area	basal area
	canopy cover	canopy cover		
	leaf area index	leaf area index		
	soil type	soil type		
	soil conductivity/permeability			soil conductivity/permeability
		depth to bedrock	depth to bedrock	
		aquifer depth	aquifer depth	aquifer depth
		Surface channel density	Surface channel density	Surface channel density
			hydraulic conductivity	
			transmissivity	
			anisotropy	
			specific storage	
			specific yield	
			groundwater recharge	
			groundwater pumping	
			evapotranspiration	evapotranspiration
			conduit flow paths	conduit flow paths
				relative humidity
				fire history

Accounting for Climate Variability

Climate variability, including anthropogenic climate change, should be accounted for in any long term monitoring and change detection study. The Southwest is predicted to experience greater droughts, more intense monsoon rain events, and a transition of snow to rain events in the winter over then next century (e.g. O'Donnell et al. 2018). The timeline of the plan described in this report, however, is on a short time scale where natural climate variability will likely mask any long term climate trends (see confidence intervals of climate variability in O'Donnell et al. 2018). Additionally, the study design described in the next section of this report should account for climate variability by pairing treatment and control sampling populations within the same climatic zones.

Field Data Collection Plan

4FRI Hydrologic Data

The field data collection plan for the 4FRI hydrologic studies can be divided into two basic components: 1) empirical data needed for calibrating, running, and verifying the eco-physical modeling outlined under the previous section; and 2) empirical data to measure trends in springs ecosystem function, both in control conditions and springs affected by 4FRI treatments (e.g. a paired watershed approach). Data collection for the hydrologic model(s) will depend on the model(s) selected, the boundary conditions of the models, and the modeling domain. In general data could include synoptic sampling of soil depth, moisture, actual ET, and additional data to supplement long-term datasets including water discharge, groundwater depth, wind speed and direction, and vegetation stand character. Due to budget constraints, at the time of this report's creation, there is no intention to initiate the modeling portion of this plan. Empirical data could be stored and used if future funding is secured to model the impacts of landscape scale forest thinning on groundwater resources.

O'Donnell et al. (2016) designed a comprehensive paired watershed study to measure the hydrologic effects of the first analysis area of the 4FRI. The proposed portions of the paired watershed study related to rainfall:runoff relationships were instrumented in the Middle Sycamore and the Upper Lake Mary watersheds. Stream flow and precipitation have been continuously monitored by NAU since 2015 in Middle Sycamore and since 2016 in Upper Lake Mary in a control watershed and watersheds designed to receive low-, medium-, and high-intensity mechanical thinning treatments. Additionally, a COSMOS continuous soil moisture sensor was installed in the Upper Lake Mary 5 watershed along with lysimeters to conduct a chloride mass balance study. The current chloride mass balance study was started in 2017 with data collection ongoing (as of this writing). Data is managed by NAU researchers.

Paffett et al. (2018) conducted assessments of 200 randomly selected springs across the Coconino and Kaibab National Forests, many within 4FRI. Data within the report includes springs discharge, biological inventories, and springs assessments that could be useful as pre-treatment springs condition dataset (Paffett et al. 2018). Monthly springs discharge data for select springs in the Verde River drainage is available in the appendices of two NAU master's theses (Flora 2004; Rice 2007). These data have yet to be summarized in a peer reviewed article or in Springs Online yet would be very helpful for determining long-term trends in springs flow and water quality and could be included in landscape scale modeling and 4FRI monitoring efforts. In general a paired watershed, or paired groundwater contribution area, method would be appropriate for measuring change derived by forest thinning (e.g. Baker 1999, O'Donnell 2016). This section of the report provides the basic framework for developing an effective monitoring plan based on the general method of evaluating treatment area sites to nearby control sites of comparable size and character (e.g. a pseudo paired watershed approach).

Long term climate records, both for conceptual and process based modeling, can be found at the National Oceanic and Atmospheric Administration (NOAA) website under the Global Historic Climatology National Database (GHCND). Relevant long term climate sites include Flagstaff, Tusayan, Oak Creek, Verde, and Payson, AZ. The list of sites, and sites ID, are listed below (Table 2). The Merriam Powell Research Center, on the campus of NAU, also maintains an elevational gradient climate network, this data is not publicly available but could be used for this project if requested. Long term snow telemetry (SNOTEL) precipitation and

SWE data is available online at: https://www.wcc.nrcs.usda.gov/snow/snow_map.html. Local sites that may be useful for model inputs include stations at Mormon Lake, Bar M, Happy Jack, Promontory, and Heber.

Table 2. Long term climate data from the National Oceanic and Atmospheric Administration (NOAA) Global Historical Climatology Network (GHCND) database.

Site Name	Site Custodian	Site ID (GHCND)
Flagstaff, AZ	NOAA	USR0000AFLG
Tusayan, AZ	NOAA	USR0000ATUS
Oak Creek, AZ	NOAA	USR0000AOAK
Verde, AZ	NOAA	USR0000AVER
Payson, AZ	NOAA	USR000APAY

Long term hydrologic data are important for both conceptual- and process-based modeling. The majority of long term data can be accessed from the U.S. Geological Survey's National Water Information System (NWIS), although there are proprietary datasets held by NAU, the National Park Service, and various other organizations. A search of the Groundwater Site Inventory (GWSI), a database maintained by the Arizona Department of Water Resources (ADWR), shows the lack of long-term publicly available monitoring wells in the region (Figure 5). Non-public wells (e.g. Rowe Well in Grand Canyon National Park) may be of use if the data can be procured. A partial list of potential hydrologic sites relevant to this project are included below, eight digit identifiers are USGS IDs relatable in NWIS (water.usgs.gov; Table 3). A second table (Table 4) shows all USGS streamgauges within 50 kms of a treatment site that has at least 1000 records up until the time of this writing. Sites labeled as "downstream" are down gradient of treatment sites and no further than 50 km, sites that are "parallel" could be used as control sites and are within 20 kms of a treatment area. Three passive wells have recently (2017) been instrumented near Lake Mary by the City of Flagstaff and NAU. This data is currently not publicly available but would likely be useful to obtain for model calibration and empirical monitoring of treatment effects on groundwater. Additional data may also be found at the Salt River Project (SRP) web portal (https://streamflow.watershedconnection.com/Map). The expanded tables below, as well as access to any non-public datasets, would be useful for theoretical or conceptual modeling or for regional level model calibration.

Table 3. Long-term continuous hydrologic datasets appropriate for the 4FRI project. Some sites contain multiple datasets from different organizations, these are denoted under the Site Custodian column.

Site Name	Site Custodian	Type	Site ID (as labeled by custodian)
Bubbling Springs	AZGFD, SRP	Surface	
Campbell Ranch	SRP	Surface	
Clover Spring	NAU	Surface	
Cottonwood Spring+	USGS, NAU, NPS	Surface	9402450 (USGS)
Del Rio Springs	USGS, SRP	Surface	9502900
Hart Prairie	NAU	Surface	
Hermit Creek	USGS, NPS	Surface	9403043 (USGS)
Hoxworth Springs	NAU	Surface	
Oak Creek near Sedona	USGS	Surface	9504420
Page Springs	AZGFD	Surface	
Payson Obervation Well	ADWR, City of Payson	Well	A-10-10 11ACB
Payson Obervation Well	ADWR, City of Payson	Well	A-10-10 04ABB
Payson Obervation Well	ADWR, City of Payson	Well	A-10-10 06DCC
Payson Obervation Well	ADWR, City of Payson	Well	A-11-10 26DAB
Payson Obervation Well	ADWR, City of Payson	Well	A-11-10 32BBB
Payson Obervation Well	ADWR, Compass Bank	Well	A-10-10 03CCD
Pump House Wash*	USGS, NPS	Surface	9403013 (USGS)
Rowe Well	NPS	Well	
Skunk Canyon Well	City of Flagstaff	Well	A-20-07 03ACA
Sterling Spring	AZGFD, SRP	Spring/Surface	
West Clear Creek	USGS	Surface	9505800
Wet Beaver Creek	USGS	Surface	9505200
* (near Indian Garden in Grand Canyon)			
+ (spring in Grand Canyon near Horseshoe Mesa)			

Table 4. Potential USGS streamgauges for conceptual modeling or regional groundwater model calibration.

Site Name	Type	USGS ID	Installation date	n	Classification
FILLER DITCH AT GREER, AZ	Surface	9383300	8/1/1960	9871	Down gradient
LITTLE COLORADO RIVER AT GREER, AZ	Surface	9383400	8/1/1960	11784	Down gradient
SOUTH FORK LITTLE COLORADO RIVER NEAR GREER, AZ	Surface	9383409	7/21/2011	2541	Control
NUTRIOSO CREEK ABV NELSON RES NR SPRINGERVILLE, AZ	Surface	9383500	6/22/1967	8159	Control
SHOW LOW CREEK NEAR LAKESIDE, AZ	Surface	9390500	5/1/1953	23806	Control
CHEVELON FORK BELOW WILDCAT CANYON, NR WINSLOW, AZ	Surface	9397500	5/1/1947	16866	Down gradient
NEWMAN CANYON ABOVE UPPER LAKE MARY, AZ	Surface	9400815	8/22/2014	1413	Control
CHERRY CREEK NEAR GLOBE, AZ	Surface	9497980	5/4/1965	19174	Down gradient
TONTO CREEK ABOVE GUN CREEK, NEAR ROOSEVELT, AZ	Surface	9499000	12/21/1940	28320	Down gradient
VERDE RIVER NEAR CLARKDALE, AZ	Surface	9504000	4/15/1965	19074	Down gradient
OAK CREEK NEAR SEDONA, AZ	Surface	9504420	10/1/1981	13426	Down gradient
OAK CREEK NEAR CORNVILLE, AZ	Surface	9504500	7/1/1940	27709	Down gradient
WET BEAVER CREEK NEAR RIMROCK, AZ	Surface	9505200	10/1/1961	19199	Control
DRY BEAVER CREEK NEAR RIMROCK, AZ	Surface	9505350	10/1/1960	21096	Down gradient
WEST CLEAR CREEK NEAR CAMP VERDE, AZ	Surface	9505800	12/5/1964	19570	Down gradient
FOSSIL CREEK NEAR STRAWBERRY, AZ	Surface	9507480	9/30/2010	2835	Down gradient
EAST VERDE R DIV FROM EAST CLEAR CR NR PINE, AZ	Surface	9507580	10/21/1965	19250	Control
EAST VERDE RIVER NEAR CHILDS, AZ	Surface	9507980	9/1/1961	19871	Down gradient
VERDE RVR BLW TANGLE CREEK, ABV HORSESHOE DAM, AZ	Surface	9508500	8/22/1945	19672	Down gradient

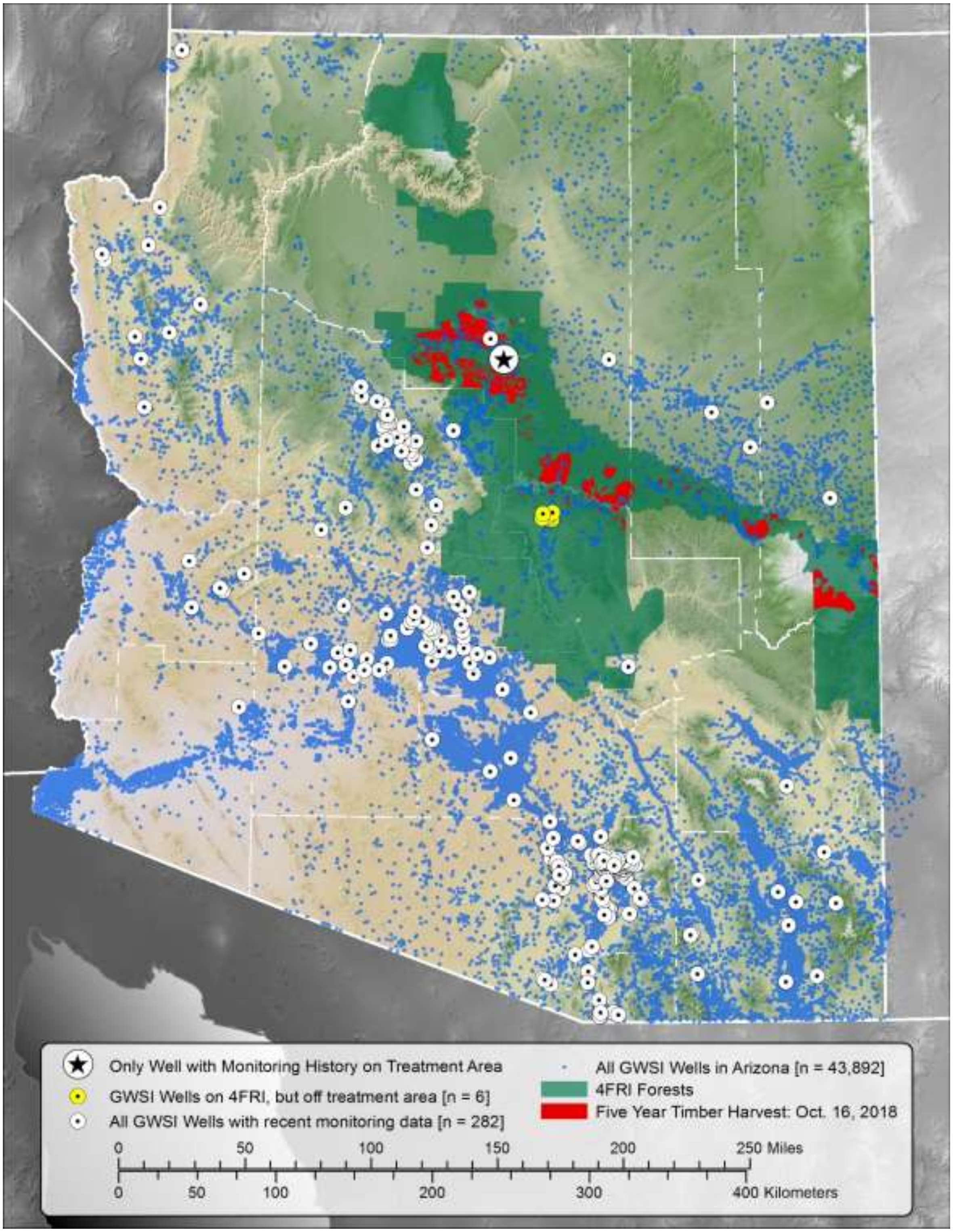

Figure 5. Wells registered in the Groundwater Site Inventory (GWSI) state database. Note the lack of long term datasets, especially in the 4FRI project area. The 4FRI planned thinning areas are marked in red. The one well that resides within the 4FRI thinning area is Skunk Canyon, owned by the City of Flagstaff. The three newly (2017) monitored wells by the City of Flagstaff and NAU do not currently show up in the GWSI database.

Selecting Springs for Monitoring

Springs ecosystems should be routinely monitored to determine the influence of 4FRI treatments on springs flow and water quality. A key component to the study design is the determination of an appropriate sample size. A statistical power analysis can be conducted to determine an appropriate sample design using known values of effect size, number of population groupings, and detection sensitivity (Faul et al. 2009). Two types of power analyses were utilized for this plan, a simple one-way ANOVA power analysis using the free software package R and a repeated measures ANOVA using the free G*Power software suite (see Appendix D for results). Repeated measures ANOVA (multiple measurements of each site during the study) indicate that a minimum of 28 springs within treatment areas and 28 control springs (56 springs total) should be selected to determine if there is a noticeable signal from 4FRI treatments. Springs should be clustered by control springs (outside of the treatment area and upstream or parallel to groundwater flow from treatment areas) and treatment springs. Treatment springs should ideally be in shallow groundwater paths so that the impact of treatments can be observed, low elevation springs are likely to include a mix of old and new groundwater making detection of changes in groundwater recharge problematic. Control springs should be within 20 km of treatment areas to allow for easy field access to both control and treatment sites and to mirror local microclimate and ecotones. Springs of both types (treatment and control) should ideally be classified by elevation, geology, springs flow, springs type (sphere of discharge), and aspect. Due to budget restrictions we have simplified the springs study to an analysis of geology (igneous and sedimentary) and springs type (hillslope or helocrene/wet meadow). See Appendix A and B for a list of potential springs for monitoring in the vicinity of Flagstaff and Williams, AZ.

A sub-set of ten springs were selected by SSI and Dr. Springer for intensive monitoring (Appendix C). These springs were selected based on having high restoration potential, high ecological value, and high cultural value. Evaluations were completed using Springs Online and personal knowledge of springs in the 4FRI project area by Dr. Larry Stevens, Dr. Springer, and Jeri Ledbetter. The ten springs should be evaluated by the Comprehensive Implementation Working Group (CIWG) to determine if they are suitable for future restoration under the 4FRI project. Due to budget restraints we currently suggest continuing monitoring at the three existing long-term monitoring springs. These include Hoxworth Spring (currently receiving forest treatments), Clover Spring, and Hart Prairie, a complex of springs that have recently been treated.

Elevation, geology, and the springs types used for monitoring and modeling all influence model output. Elevation can be categorized as montane (greater than 7500 ft), plateau (6000 to 7500 ft), and below the Mogollon Rim (<6000 ft). Geology is tied closely to source aquifer with the potential for cinder/volcanics, C-aquifer springs (primarily Kaibab Limestone, Toroweap Formation, Coconino Sandstone), R-aquifer springs (primarily Redwall Limestone, Muav Limestone), and other localized perched aquifer springs. Springs flow can be binned by orders of magnitude (metric scaling) as described in Springer et al. 2008 and Stevens et al. 2016 (Table 2). The majority of springs within the Coconino and Kaibab National Forests are small, classified between zero and third order springs discharge (Table 5). There are 12 accepted springs types based on spheres of discharge (springs position within the landscape; Springer et al. 2008). Each springs type has unique ecosystem properties (Stevens et al. 2016); monitoring for the 4FRI project should include representative sites from common springs types within the Forest units including hillslope springs, and helocrenes (wet meadows; Springer and Stevens 2009). Rheocrenes (channel springs) should be avoided due to the complication of upstream surface flow contributions. Selecting springs by type that include both north and south aspect is important for understanding the potential difference in springs response to 4FRI treatments by microclimate. North-facing springs are likely to have a cooler, more humid microclimate with more shading and less snow sublimation. In contrast, south-facing springs will be warmer, have warmer drier climate vegetation, and will have lower soil moisture. Due to budget restraints, and the difficulty of comparing springs that are not directly North or South facing, this variable has been ignored for the proposed study.

Table 5. Springs discharge groupings as described in Springer et al. 2008 and Stevens et al. 2016. The majority of 4FRI springs are zero to fourth order springs. The instrument column is related to water discharge measurements and is separate from the long term continuous monitoring equipment described in the report.

Discharge Magnitude	Discharge (English)	Discharge (metric)	Instrument(s)
Zero	No discernable discharge to measure	No discernable discharge to measure	Depression
First	< 0.16 gpm	< 10 mL/s	Depression, Volumetric
Second	0.16 - 1.58 gpm	10 -100 mL/s	Weir, Volumetric
Third	1.58 -15.8 gpm	0.10 - 1.0 L/s	Volumetric, Weir, Flume
Fourth	15.8 – 158 gpm	1.0 - 10 L/s	Weir, Flume
Fifth	158-1,580 gpm; 0.35-3.53 cfs	10. - 100 L/s	Flume
Sixth	1,580 – 15,800 gpm; 3.53 – 35.3 cfs	0.10 - 1.0 m3/s	Current meter
Seventh	35.3 – 353 cfs	1.0 - 10 m3/s	Current meter
Eighth	353 – 3,531 cfs	10 - 100 m3/s	Current meter
Ninth	3,531 – 35,315 cfs	100 – 1,000 m3/s	Current meter
Tenth	>35,315 cfs	>1,000 m3/s	Current meter

SPRINGS MONITORING TECHNIQUES

Continuous springs flow monitoring is complicated by low flows expected at most upper elevation springs in the region. The expected change in flow created by 4FRI treatments is also relatively small (Neary et al. 2008, Wyatt 2013, Wyatt et al. 2015) and can be easily obscured by discharge measurement error during low flows. Due to this potential problem we recommend that small springs (zero to second order springs: Table 5) should include inexpensive thermograph sensors (e.g. Onset TidBits) to determine presence and absence of water and to measure water temperature. Helocrene (wet meadow) springs may require shallow wells (<1m) to be dug to determine hydroperiod. Wells can be instrumented with thermograph sensors and/or be measured regularly using tape measure. Measuring the change in springs perenniality at several ephemeral springs will provide a robust understanding of the effect of 4FRI treatments at the many small springs within the region. Previous hydrologic studies in Arizona have proven the application of thermograph sensors for measuring changes in groundwater yield (Adams et al. 2006). Thermographs provide continuous measurements of temperature, either air or in the water. The sensor can be adapted to determine when the logger is submerged, thereby providing a window for when ephemeral springs, or streams, are flowing. Monitoring the hydroperiod, the pattern and period springs are flowing, can help determine the impacts of forest treatments on groundwater yield and springs ecosystems. Larger springs (third to sixth order: Table 5) can be instrumented using piezometers and traditional water level and field parameter data loggers (e.g. Onset MX2000s, Solinst 3001). We recommend using these traditional methods at the intensive springs sites (Clover, Hart Prairie, and Hoxworth).

The 56 springs not selected for intensive monitoring should include continuous springs flow, through surrogate thermistor methods, and water temperature. Annual measurements of microhabitat size and aquatic macroinvertebrate richness can provide an idea of biological trends and the impact of forest thinning on the springs ecosystem. A subset of springs should be monitored for human, wildlife, and livestock use to determine long-term changes in use and to determine if there are unmeasured variables influencing springs ecosystem function. Monitoring can be completed easily using commercially available game cameras. The current budget does not allow for continuous game camera monitoring, however if future funding becomes available the use of such methods would be greatly helpful for understanding long-term springs use and changes in physical parameters (e.g. flowtography).

We recommend the 4FRI MPMB provide support to NAU to maintain the three existing long term spring discharge monitoring locations (Hoxworth, Hart Prairie, and Clover Spring) and provide resources for analysis and interpretations of the data. These three springs would be selected as part of the 10 intensive high priority springs sites, and due to budget constraints may be the only three continuously monitored springs for springs flow. NAU students could be utilized to establish discharge monitoring at the other 7 intensively monitored springs if funding becomes available. Any intensively monitored site would include quarterly visits to establish new rating curves for discharge measurement stations. All spring discharge measurement locations will be visited quarterly. Discharge will be measured by hand with standard techniques (flumes or weirs) and used to build new or update existing discharge rating curves. Hydrograph responses from Hoxworth and Clover Springs will be analyzed with hydrograph recession curve techniques such as those of Maillet (1905). Hydrograph recession curve analyses for a similar karst aquifer to Clover were successfully demonstrated for springs of the Kaibab Plateau by Jones et al (2017). Responses of the springs to recent climate will be analyzed relative to nearby climate stations (MPCER station in Hart Prairie, NOAA station at Flagstaff airport). The work can be routed through the Master Challenge Cost Share Agreement 18-CS-11030700-12 between NAU and the Coconino National Forest and Kaibab National Forest. One of many benefits of this agreement is that there is a negotiated indirect return rate of 17.5 %.

Ideally all springs (56 spatially distributed and three intensively monitored) should be monitored for water yield, ecosystem function, and springs use for seven years prior to treatment and a minimum of seven years post-treatment based on paired watershed studies in the Verde River drainage (Baker 1986, O'Donnell et al 2016). Prior forest thinning hydrologic studies indicate that groundwater recharge returns to pre-treatment in approximately four years if there are no follow up prescribed burns (Wyatt 2013), monitoring should extend beyond this period to confidently determine the full extent of the impacts of treatments on springs flow.

Springs candidates include sites within the 4FRI treatment areas, and control springs that are "parallel" or just up gradient of 4FRI treatment areas. All springs were identified in the Springs Online database (SpringsData.org), a free secure relational database maintained by the Springs Stewardship Institute. Only springs that had previous springs ecosystem surveys were included in the analysis. Many of these springs were studied by previous studies un-related to the 4FRI project (e.g. Flora 2004, Rice 2007, Stevens 2017). One previous springs inventory was completed for 4FRI by SSI (Stevens and Ledbetter 2017). These previous surveys allow for a pre-treatment baseline condition in cases where the surveys were completed in the last few years: allowing for a fifth year repeat survey for a basic pre/post treatment statistical design (see Appendix D). In some cases the previous survey is too old (> 3 years) to be considered a baseline inventory, in these cases a new Level 2 springs inventory will be completed in the first year to provide a repeatable pre/post ecological design for all 56 sites.

Springs can be compared between the treatment areas, and control sites, by aspect, elevation, and flow using common statistical tests including analysis of variance (ANOVA) and analysis of covariance (ANCOVA) tests. More details about statistical study design appropriate for paired watershed studies is readily available online (e.g. Clausen and Spooner 1993, Grabow et al. 1999, Bishop et al. 2005, O'Donnell et al. 2018). A description of the power analysis design, and recommended study design, is provided in Appendix D.

The five year treatment plan for 4FRI includes 28 springs with prior flow data. An additional 28 "parallel" springs that also have previous flow data and are within 20 km of a treatment area were selected at random as control sites. These two basic classifications of springs can be used for long-term monitoring and assessment of the impacts of forest thinning on hydrologic resources (Figure 5). We do not expect that all 28 springs within the treatment area, or the full suite of springs in the control areas or potential restoration sites, will be selected for monitoring. The list of springs (see Appendix A, B, and C) is the recommended springs to target for monitoring using a basic treatment versus control grouping and sub-groupings of geologic provenance (sedimentary or igneous) and springs type (hillslope or helocrene) and includes alternates in case the primary springs cannot be used. Some springs may not be appropriate for monitoring based on site access, current condition (e.g. if they are now dry), length of pre-treatment measurements, funding, or other considerations. SSI selected sites based on the initial random selection and then further office review that considered previous field visits, Springs Online surveys, and anecdotal evidence from SSI cooperators. Considerations included ease of access, site location (springs directly impacted by roads were excluded), and springs influenced by other human modifications. It should be noted that the springs listed in Appendix E are for an ideal study with a larger study design to improve the statistical power of the analyses and a greater geographic area encompassing the entire 4FRI project.

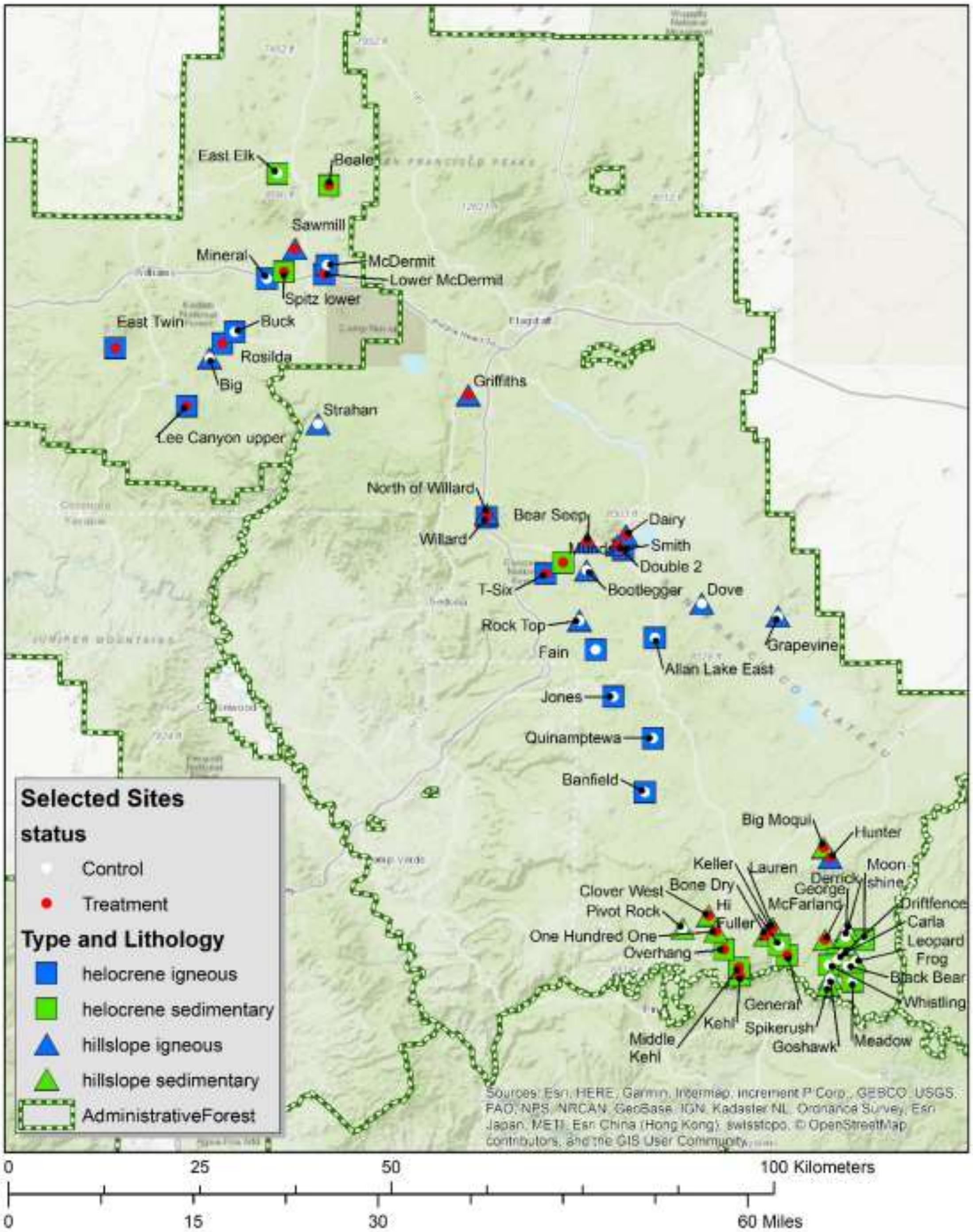

Figure 6. Springs selected for long-term monitoring including the eight groupings selected by control/treatment, springs type (helocrene or hillslope), and local geology (igneous or sedimentary).

Treatment Area Springs

Springs that had previous flow measurements were identified in the 4FRI treatment areas including Clover Spring, an intensively monitored spring site maintained by Dr. Abraham Springer (NAU; Table 3). Hoxworth Springs, a long term NAU monitoring site, is included in this list as it has had partial forest thinning occur within its contributing area in 2017 and 2018. Hart Prairie, another long term NAU monitoring site, could be considered for inclusion based on treatments in 2013 and 2014. None of the springs, or treatment areas, are below the rim with the lowest elevation spring in the treatment area located at 6714 ft (2047 m) and the highest spring located at 7439 ft (2268 m).

Flow at springs within the treatment area ranged from zero (no flow) to 0.86 liters per second (Appendix A). The springs occupy the zero to 3rd order of magnitude shown in Table 5, with four springs of zero magnitude, two 1st order springs, nine 2nd order springs, and eight 3rd order springs (Appendix A). The 28 springs include equal numbers of control and treatment sites as well as igneous versus sedimentary and hillslope versus helocrene spring types (Appendix A).

Springs ecosystems may be preferentially impacted by the local microclimate, as expressed by aspect. Due to budget restraints the study design ignored aspect and focused on helocrene and hillslope springs in either igneous or sedimentary local country rock. All twenty eight treatment area springs were selected within a two hour drive of Flagstaff, AZ to reduce travel costs (Mogollon, Mormon, and Williams Ranger Districts). All springs have had previous Level 2 SSI springs inventories to allow for a pre/post analysis of ecosystem condition, although some springs have not had a recent survey necessitating a new initial survey in year one (Appendix A).

Control Springs

An equal number of springs were selected as control candidates for the springs located in the treatment area (n = 28). Springs were selected from the Springs Online database using a GIS query. Control springs were randomly selected based on flow data (previous flow measurement required), distance from treatment area (less than 20 km from a treatment area), and position on the landscape (must be upstream or parallel to treatment areas). An equal number of springs by geologic context and springs type were selected. The list of potential control springs, with flow and other pertinent information, is available in Appendix B.

Flow ranges from zero (0 order) to 1.04 l/s (4th order) with 6, 0, 13, , 8, and 1 springs in zero to 4th order respectively (Table 3; Appendix B). Due to budget restraints the study design ignores aspect and focused on helocrene and hillslope springs in either igneous or sedimentary local country rock. All twenty eight treatment area springs were selected within a two hour drive of Flagstaff, AZ to reduce travel costs (Mogollon, Mormon, Peaks, and Williams Ranger Districts). All springs have had previous Level 2 SSI springs inventories to allow for a pre/post analysis of ecosystem condition, although some springs have not had a recent survey necessitating a new initial survey in year one (Appendix A).

Intensively Monitored Springs (Potential Restoration Sites)

Funding allows for continued monitoring of the three springs systems that have been monitored in the past. These springs include Clover, Hoxworth, and Hart Prairie. An additional seven springs were selected for monitoring if funding becomes available (Appendix C). These sites are important for biological diversity, historical values, and for calibrating and validating the landscape scale springs monitoring results.

POTENTIAL FINANCIAL COSTS AND TIMELINES

This section provides a general overview of financial costs expected to be incurred using this plan, as such these costs are general, not-inclusive, and may vary greatly due to market conditions. Portions of the tasks were assigned to either SSI or NAU depending on the expertise and skill set of the organization. SSI is qualified to complete the pseudo paired watershed approach (56 springs) due to their experience with large springs monitoring programs related to wildfire effects, grazing, and climate change. NAU (Dr. Springer) is qualified to provide intensive monitoring of the sub-set 10 potential restoration sites due to his previous experiences with restoration monitoring, microtopographic mapping, and change detection.

Optional items - SSI will also provide the 4FRI MPMB and CIWG with a new Springs Ecosystem Assessment Protocol (SEAP) based on an existing assessment protocol that is commonly used in the Southwest (Paffett et al. 2018; Option 1). The new SEAP will provide quantifiable metrics of spring ecosystem health, thereby allowing for change detection at both restoration springs through time and also synoptic assessments of springs ecosystems throughout the 4FRI project footprint. The SEAP will incorporate comments and suggestions from a SSI rapid assessment method project in a neighboring state. The SEAP refinements from this un-related project provide approximately $20,000 worth of project development including an analysis of over 2000 springs conditions in Arizona and Nevada to justify the assessment scoring metrics. Costs associated with the SEAP development for 4FRI build off of this previous 2018 work allowing for the creation of a scientifically defensible and easily repeatable assessment matrix for springs ecosystems in Arizona. The resulting deliverable will provide benefits not only within the 4FRI project but also for any future springs restoration and management provided by the 4FRI partners. We also strongly suggest that funding is found to fund monitoring all 10 keystone springs sites (Option 2). Fully evaluating these sites will provide valuable information about impacts to those high value springs and will also allow for validation and calibration of the larger project.

The costs below have not been vetted by the Museum of Northern Arizona, the non-profit administrator of SSI nor the NAU Office of Sponsored Research (for Dr. Springer and Dr. Sankey's contributions) but are as accurate as possible and provided in good faith. Costs can be broken into tasks outlined below. A breakdown of costs is available in the attached Microsoft Excel sheets.

Goal:	To determine the impact of 4FRI forest thinning on groundwater recharge and springs ecosystems
Methods:	Continuous monitoring of springs hydroperiod at treatment and control sites
	Continuous monitoring of water level at intensive high priority springs ecosytems
	Long term monitoring of groundwater dependent ecosystem health
	Microtopography mapping at intensive high priority springs ecosystems

Methods were selected after an exhaustive review of 35 forest thinning - groundwater recharge study techniques

Task 1: Initial springs site selection and instrumentation,
Task 2: Annual 56 spring revisit (instrument maintenance, data download, annual ecosystem size determination
Task 3: Quarterly intensive site visits (NAU)
Task 4: Data management, import of legacy data, data entry, and QAQC
Task 5: Reporting

Option 1: Develop Springs Ecosystem Assessment Protocol (SEAP) for 4FRI long-term restoration monitoring
Option 2: Seven additional intensive sites to determine flow variability at keystone springs (NAU)

Subtasks

Task 1:	
	Instrument 56 springs with thermisters to determine hydroperiod
	Level 2 Springs Inventory at 56 springs (if a Level 2 survey has not been completed in the last 3 years)
Task 2:	
	Annual visit of 56 springs for thermister download
	Annual visit of 56 springs for discharge, microhabitat mapping, and macroinvertebrate diversity sampling
Task 2 (year 5):	
	Final visit of 56 springs for thermister download and instrument removal
	Final visit of 56 springs for Level 2 SSI survey
Task 3:	
	Continuous flow measurements at Hoxworth, Hart Prairie, and Clover spring complexes
	Quarterly visits for downloads and flow measurements for stage-discharge rating curve
Task 4:	
	Data management of biological and geographic data (Springs Online)
	Data management of thermisters (HoboLink, Excel)
	Data management of pressure transducers and intensive site flow measurements (NAU)

Field monitoring of the pseudo paired watersheds will consist of instrumenting springs for flow detection using Onset MX series thermisters, routine springs ecosystem inventorying and assessments, and data compilation and analysis. Continuous monitoring of intensive sites will include pressure transducers (OTT series water level loggers). Springs ecosystem surveys, at a SSI Level 2 inventory level (Stevens et al. 2016), could be conducted for less than $1000 per spring if sites are close together and have easy field access. We strongly suggest using experienced springs surveyors to avoid poorly collected and compiled data. Data compilation and analysis costs will depend on whether it is conducted in-house, by Springs Stewardship Institute, NAU, or independent consultants. The attached cost estimate assumes springs ecosystem data management by SSI and continuous springs flow data management by NAU.

Field monitoring should include a minimum of seven years of pre and post monitoring as described in previous paired watershed studies (e.g. Baker 1986, Wyatt et al. 2015, O'Donnell 2016). Some sites already have extensive monitoring that would reduce the required amount of pre-treatment monitoring. Costs for long-term monitoring should decrease after initial setup as the overhead, staff training, site access development, and equipment costs are generally expressed in the first year of installation. A summary of costs using a Forest Service five year budget cycle is provided in Table 6; a detailed cost estimate is available in the attached Excel worksheets. A fully funded budget is also provided in Appendix E with the potential full study plan.

Table 6. Cost summary for the five year groundwater yield and springs ecosystem monitoring effort. More detail is included in the attached Microsoft Excel spreadsheet.

Budget Summary:			
	SSI	**NAU**	**Total**
FY19	$39,565.00	$14,400.00	
FY20	$25,993.60	$9,600.00	
FY21	$24,778.60	$9,888.00	
FY22	$24,898.60	$10,185.00	
FY23	$30,200.00	$10,491.00	
Total	$145,435.80	$54,564.00	$199,999.80

CONCLUSION

The five year 4FRI treatment area is extensive, ranging from near Flagstaff, AZ to the New Mexico border (Figure 1). Modeling the effects of the treatment is likely the most cost effective method for determining landscape scale changes in surface and groundwater flow created by forest thinning. This report highlights four general modeling methods and discusses the difficulty in implementing each of the modeling techniques in northern Arizona. Unfortunately there is a lack of long-term high resolution datasets within the 4FRI footprint to provide high resolution spatial and temporal predictive models. For this reason the only modeling technique that may work for this project is a process based model (RHESSys) to provide general hydrologic trends. The general process based model can be paired with a more robust groundwater specific model such as the Northern Arizona Groundwater Flow Model (NARGFM) paired with vegetative and climate components, similar to Wyatt et al. (2015). On-going local studies on groundwater recharge, including chloride mass balance and repeat micro gravity techniques, should be explored for the possibility of collaboration to help inform and calibrate the models.

Long term empirical monitoring at springs, wells, and streamgauges will allow not only for model calibration and verification but also for paired site comparisons between treated and non-treated surface watersheds and groundwater catchment areas. The majority (>80%) of previous forest thinning-groundwater studies have used a paired site approach due to the ability to control for environmental variables and to craft a data plan specific to a treatment area. This report provides a list of potential springs sites in both control and treatment areas as well as intensive high priority springs that could be useful for monitoring for regional aquifer effects. We recommend scouting each site for ease of access to help narrow down potential monitoring sites. Some springs sites may not be conducive to monitoring due to the potential for surface water interactions (e.g. rheocrenic springs). All springs should be scouted not only for ease of access but also monitoring feasibility, appropriate monitoring techniques (e.g. thermographs versus pressure transducers versus annual spot monitoring), and to determine the accuracy of previous site reports. A minimum of 28 control and 28 treatment springs will be required for a paired study approach. Previous studies indicate that a minimum of seven to nine years of monitoring will be required to understand the effects of forest thinning, and re-growth, on springs ecosystems (O'Donnell et al. 2016). Treatment and control springs groups can be compared using standard multivariate statistical techniques including analyses of covariance (ANCOVA) as well as regressional analysis to determine trends and correlations.

Studies indicate that measurable changes in surface and groundwater yields will not be noticeable until 20 to 25% of forest cover has been removed (Neary et al. 2008 and the authors' review of existing literature). Water yields will likely only change by a few percent with the largest gains immediately after forest thinning before re-vegetation begins (e.g. Wyatt 2013). The monitoring plan should take into account the expected modest change in water yield and select monitoring techniques that reduce both human and environmental error and variability. For stream flow this would include the use of thermographs to determine the presence and absence of water at ephemeral sites. Measuring the period of flow at many ephemeral sites would reduce the variability inherent in discharge or stage measurements in non-uniform channels. Likewise using an established flume, weir, or pipe at perennial springs will reduce the variability in discharge or stage measurements. Ecosystem surveys should include repeatable methods that reduced variability including set photo points, georeferenced quadrat or transect inventories, and timed macroinvertebrate searches that are repeated during the same season between years using the same survey crew.

This report is intended as a general guide for modeling and monitoring the hydrologic response of the aquifer and springs in the 4FRI project area during and following forest treatments. The plan should be used as a living document, adapted as necessary as treatment timelines change, budgets change, more physical and biological datasets are found, or created, and as the state of the science evolves. The implementation of this plan will require a dedicated budget, scientific expertise, long-term technician support, and data analysis and management.

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APPENDIX A: SPRINGS WITH PRIOR FLOW DATA WITHIN THE 4FRI TREATMENT AREAS

An abbreviated table of the treatment area study design. Elev is elevation in meters above sea level, "rock" indicates local geology, either sedimentary or igneous, "3 yrs" indicates whether a Level 2 springs inventory has occurred in the prior three years, "RD" indicates ranger district.

SiteID	Name	SpringType	Elev(m)	Flow (l/s)	Rock	3 yrs	RD
162	Clover West	hillslope	2092	0.86	sed	no	Mogollon
425	Bone Dry	hillslope	2095	0.32	sed	yes	Mogollon
430	General	helocrene	2182		sed	no	Mogollon
438	Big Moqui	hillslope	2185	0.02	sed	yes	Mogollon
545	Hunter	hillslope	2203	0.03	ign	no	Mogollon
546	Keller	hillslope	2175	0.33	sed	yes	Mogollon
578	One Hundred One	hillslope/gushet	2180	0.10	sed	No	Mogollon
582	Lower McDermit	helocrene	2176	0.00	ign	no	Williams
588	Rosilda	helocrene	2047	0.17	ign	yes	Williams
899	Bear Seep Tank	hillslope	2211		ign	yes	Williams
649	Lee Canyon Upper	helocrene	2139	dry	ign	no	Williams
770	Spitz lower	helocrene	2128	0.08	sed	yes	Williams
774	Beale	helocrene	2255	0.00	sed	no	Williams
776	East Twin	Helocrene	2150	0.01	ign	no	Williams
782	Sawmill	hillslope	2211	0.00	ign	no	Williams
855	Griffiths	hillslope	2091	0.03	ign	no	Mormon
946	Dairy	hillslope	2180	0.31	ign	no	Mormon
954	Double 2	hillslope	2190	0.67	ign	no	Mormon
1005	Kehl	helocrene	2268	0.10	sed	yes	Mogollon
1011	Lauren	hillslope	2177	0.04	sed	yes	Mogollon
1032	McFarland	hillslope	2224	0.09	sed	yes	Mogollon
1036	Middle Kehl Meadow	helocrene			sed	yes	Mogollon
1047	Munds	Helocrene	2110	0.00	sed	no	Mormon
1089	Smith	helocrene			ign	no	Mormon
1113	T-Six	helocrene	2070	0.10	ign	yes	Mormon
1131	Willard	helocrene	2054	0.09	ign	sorta	Mormon
181912	North of Willard	hillslope	2057	0.47	ign	no	Mormon
226446	Overhang	helocrene			sed	yes	Mogollon

Appendix B: A List of Control Springs for the 4FRI Treatment Areas

An abbreviated table of the control area study design. Distance is distance to a treatment area, "rock" indicates local geology, either sedimentary or igneous, "3 yrs" indicates whether a Level 2 springs inventory has occurred in the prior three years, "RD" indicates ranger district.

SiteID	Name	Distance (km)	SpringType	Flow (l/s)	Rock	3 yrs	RD
741	Buck Spring	0.11	helocrene	0.02	ign	no	Williams
768	Mineral Spring	0.14	helocrene	0.02	ign	no	Williams
783	McDermit Spring	0.09	Helocrene	0.02	ign	no	Williams
887	Allan Lake East Unnamed	1.16	helocrene		ign	no	Mormon
896	Banfield Spring	2.87	helocrene	0.16	ign	no	Mogollon
963	Fain Spring	2.28	Helocrene	0.03	ign	no	Mormon
1065	Quinamptewa Spring	2.11	helocrene		ign	no	Mogollon
429	Hi Fuller Spring	0.11	Helocrene	0.01	sed	no	Mogollon
576	Black Bear Spring	3.53	helocrene	0.07	sed	no	Mogollon
580	East Elk Spring	2.45	helocrene	1.05	sed	yes	Williams
739	Big Spring	0.36	hillslope	0.40	ign	no	Williams
909	Bootlegger Spring	2.09	hillslope	0.02	ign	yes	Mormon
956	Dove Spring	10.23	hillslope	0.03	ign	yes	Mogollon
983	Grapevine Spring	9.01	hillslope	0.01	ign	no	Mogollon
1004	Jones Springs	2.26	helocrene	0.51	ign	no	Mogollon
1075	Rock Top Spring	3.86	hillslope	0.04	ign	no	Mormon
1096	Strahan Spring	0.29	hillslope	0.23	ign	no	Peaks
921	Carla Spring	2.54	hillslope	0.57	sed	yes	Mogollon
951	Derrick Spring	1.41	hillslope	0.95	sed	yes	Mogollon
982	Goshawk Spring	1.45	hillslope	0.09	sed	yes	Mogollon
1014	Leopard Frog Spring	3.77	hillslope	0.15	sed	yes	Mogollon
1033	Meadow Spring	0.93	helocrene	0.01	sed	yes	Mogollon
226460	Driftfence Spring	2.13	helocrene	0.17	sed	yes	Mogollon
226652	Spikerush Spring	1.59	hillslope	0.03	sed	yes	Mogollon
144	Pivot Rock		hillslope/cave		sed	yes	Mogollon
978	George		hillslope/cave		sed	no	Mogollon
412	Whistling		helocrene		sed	no	Mogollon
425	Moonshine		helocrene		sed	no	Mogollon

APPENDIX C: LIST OF POTENTIAL RESTORATION SPRINGS FOR INTENSIVE MONITORING

These springs were selected by NAU and SSI as "keystone" springs, sites of high biological value and relatively high flow. This plan calls for continuing monitoring at Clover, Hoxworth, and Hart Prairie. Additional funding will be needed to monitor the other seven priority springs.

Spring	Continuous discharge
Clover	NAU since 2013
Hoxworth	NAU Since 2014
Hart Prairie	NAU since 1994
Big	SRP since 2013
Private in Kachina Village?	
Derric	
Audra	
Lauren	
Georges	
Jones	
East Elk	
Little Elden	

APPENDIX D: STATISTICAL DESIGN

Power Analysis results – using R, PWR package, and a balanced one-way ANOVA power analysis

Eight treatments = control: hillslope, helocrene, basalt, limestone; treatment: hillslope, helocrene, basalt, limestone. All sites should be within a half day's drive of Flagstaff to keep costs and logistics down. Control sites should be within 20 kms of treatment areas. All springs should be "low flow" marginally perennial. Statistical tests were completed using RStudio and the PWR package (available on CRAN). More specifically the balanced one-way ANOVA power calculation (pwr.anova.test) was used to determine the appropriate sample size needed to avoid both a Type 1 and Type 2 statistical error. Results are as follows:

```
> pwr.anova.test(k=8,n=10,sig.level=0.05,power=0.8)
     Balanced one-way analysis of variance power calculation
              k = 8
              n = 10
              f = 0.4443177
      sig.level = 0.05
          power = 0.8
NOTE: n is number in each group
```

To have 8 treatments and a total n of 80 (10 per treatment) we would need an effect size of 0.44 (high effect). This is at an alpha of 0.05 and a power level of 0.8 (80% probability of not committing a Type 2 error). I completed an effect size test using O'Donnell's surface water model results (O'Donnell et al. 2018) which leads to an effect size (f) of 0.5. I then used this value in the ANOVA power test:

```
> pwr.anova.test(k=8,f=0.5,sig.level=0.05,power=0.8)
     Balanced one-way analysis of variance power calculation
              k = 8
              n = 8.0971
              f = 0.5
      sig.level = 0.05
          power = 0.8
NOTE: n is number in each group
```

This result indicates that **72 total springs are needed** assuming a high (f=0.5) effect, results are always rounded up when using a power analysis (9 springs per population, 8 populations). Each treatment type will require 9 spring sites to determine forest treatment effects. High effect is predicted using mean surface water runoff predictions and standard deviations from O'Donnell et al. 2018. **I would recommend making the study 80 springs to allow for one extra spring per treatment type in case a data logger is lost or destroyed or a spring site is impacted by non-4FRI related impacts.** I also did a model run using 10 populations (perhaps low versus high elevation) which resulted in the need for a minimum of 80 springs (90 springs if one contingency spring was selected). Next I computed the effect size using an analysis of 38 prior studies and the effect of forest treatments on depth to water table, the effect size was much smaller which results in an extremely large sample size:

```
> pwr.anova.test(k=8,f=0.08,sig.level=0.05,power=0.8)
     Balanced one-way analysis of variance power calculation
              k = 8
```

```
              n = 281.1641
              f = 0.08
      sig.level = 0.05
          power = 0.8
NOTE: n is number in each group
```

We would need **282 springs per group (2256 springs) if the effect is extremely low** (0.08) as predicted if using only changes in depth to groundwater, using a synthesis of 38 results from previous groundwater recharge studies. I don't think that this is a reasonable analysis, depth to groundwater is not analogous to groundwater yield and is likely a highly insensitive variable for computing landscape scale dynamics.

Effect Size calculations:

Effect size (f statistic in the balanced one-way analysis of variance power model) is determined by subtracting the mean control value by the mean experimental value and dividing by the total standard deviation. For this study the values were either surface water runoff or change in depth to groundwater level. Values for surface water runoff were taken from model runs in O'Donnell et al. 2018s paper on Ponderosa Pine forest (high-mid elevation) treatment in the Kaibab National Forest. Results were standardized at the 2020 model year for control and high restoration potential, standard deviation was estimated from Figure 4 in the paper (O'Donnell et al. 2018).

Change in groundwater depth was summarized from 38 previous examples of forest thinning and forest encroachment studies. Standard deviation was calculated from both control and experimental depths to water table. The resulting effect size is likely not useful for determining a sampling design since the depth to water table is not a surrogate for springs flow or available groundwater but merely a measure of depth to local perched groundwater.

Raw data table, DTW = depth to water table (mm) from 38 prior studies. Median surface water (SW) runoff modeling is from O'Donnell et al. 2018 paper on forest restoration in Kaibab National Forest. The effect size is an order of magnitude higher for surface water impacts than for changes in depth to water table.

14987.2	Mean change (5 yr) DTW
13614.72	Mean DTW, historic
17564.02	stdev
0.08	**effect size**

*median annual runoff in 2020 (mm)	
High-mid elevation	
109	Restoration
100	Control
18	stdev
0.5	**Effect Size**
*O'Donnell et al. 2018 SW runoff	

Other assumptions:

The power calculation assumes that an alpha of 0.05 and power level of 0.8 is appropriate for determining the sample size. An alpha of 0.05 (p value) is a standard but could be adjusted to be more lenient or more restrictive depending on stakeholders' sensitivity. A power level of 0.8 (f value) is also touted as a standard, a higher or lower f value can be assigned depending on stakeholders' interests. A higher f value would increase confidence that the study will correctly determine the effect of forest thinning but will also greatly increase the needed sample size. For example a power level of 0.9 (90% confidence) would require 11 sites per treatment, or 88 springs. Adding at least one spring per treatment type as a factor of safety would make the study consist of 96 springs (assuming 8 treatment types and p=0.05).

Power analysis results – repeated measures

The power analysis conducted above does not take into account repeated measures (multiple measurements of the same variable). A repeated measures ANOVA power analysis was conducted in the free G*Power software suite (available here: https://stats.idre.ucla.edu/other/gpower/). A description of the statistical design is available on the website and in a peer reviewed article (Faul et al. 2009). The repeated measures ANOVA was conducted assuming four measurement periods (annual) for the eight potential springs groupings using the effect size calculated using the O'Donnell 2018 paper (explained in the prior section). The result is the need for 48 springs sites to have the statistical power to statistically show the difference between treatments. As a factor of safety we recommend adding one additional spring per group in case of unforeseen issues with a site, this leads to a total of 56 spring sites.

Study design

(not including optional increases in intensive or landscape scale sites):

Continuous data:

Springs perenniality (TidBit)
Water and air temperature (TidBit)
Springs flow at intensive sites (water level corrected to discharge using a rating curve)

n = 5 (repeated measures statistical design):

Flow
Basic water chemistry (pH, conductivity, alkalinity)
repeat photographs (potentially a semi-quantitative riparian health metric)
Springs use/abuse (change in fencing, trails, etc)
Pool or depth to groundwater (manual piezometers at helocrenes; preferably measured quarterly for an n of 16 to 20)
Macroinvertebrate richness
botanical richness
springs ecosystem polygon size

n = 2 (insufficient for a standard deviation or SE but still usable for averaged analyses, e.g. ANOVAs)

Level 2 Springs Survey including:
springs ecosystem assessment (SEAP or modified SEAP)
available solar radiation (SPF)
tree canopy cover analysis
botanical diversity
invertebrate and vertebrate diversity

APPENDIX E: PROPOSED FULLY FUNDED STUDY DESIGN

The following detail is provided as a guide for a fully funded statistical design. The details were provided to the 4FRI MPMB in February of 2019 and was later pared down to the study design listed in the plan. This fully funded study includes a larger sampling design over the entire 4FRI geographic area, thereby providing a higher likelihood of accurately determining impacts of forest thinning on the region's groundwater resources.

A minimum of 30 paired springs (60 springs total) should be selected to determine if there is a noticeable signal from 4FRI treatments. Springs should be clustered by control springs (outside of the treatment area and upstream or parallel to groundwater flow from treatment areas) and treatment springs. Treatment springs should ideally be in shallow groundwater paths so that the impact of treatments can be observed, low elevation springs are likely to include a mix of old and new groundwater making detection of changes in groundwater recharge problematic. A second type of treatment springs, those that are down gradient of treatment areas, could be used to try to determine larger aquifer effects. Springs of both types (treatment and control) should be classified by elevation, geology, springs flow, springs type (sphere of discharge), and aspect.

Elevation, geology, and the springs types used for monitoring and modeling all influence model output. Elevation can be categorized as montane (greater than 7500 ft), plateau (6000 to 7500 ft), and below the Mogollon Rim (<6000 ft). Geology is tied closely to source aquifer with the potential for cinder/volcanics, C-aquifer springs (primarily Kaibab Limestone, Toroweap Formation, Coconino Sandstone), R-aquifer springs (primarily Redwall Limestone, Muav Limestone), and other localized perched aquifer springs. Springs flow can be binned by orders of magnitude (metric scaling) as described in Springer et al. (2008) and Stevens et al. (2016). Monitoring for the 4FRI project should include a representative number of control and treatment springs for each of the springs discharge classes. The majority of springs within the Coconino and Kaibab National Forests are small, classified between zero and third order springs discharge. There are 12 accepted springs types based on spheres of discharge (springs position within the landscape; Springer et al. 2008). Each springs type has unique ecosystem properties (Stevens et al. 2016); monitoring for the 4FRI project should include representative sites from common springs types within the Forest units including rheocrenes (channel springs), hillslope springs, and helocrenes (wet meadows; Springer and Stevens 2009). Selecting springs by type that include both north and south aspect is important for understanding the potential difference in springs response to 4FRI treatments by microclimate. North-facing springs are likely to have a cooler, more humid microclimate with more shading and less snow sublimation. In contrast, south-facing springs will be warmer, have warmer drier climate vegetation, and will have lower soil moisture.

Springs candidates include sites within the 4FRI treatment areas, sites within 50 km down gradient of treatment areas and control springs that are "parallel" or just up gradient of 4FRI treatment areas. All springs were identified in the Springs Online database (SpringsData.org), a free secure relational database maintained by the Springs Stewardship Institute. Only springs that had previous flow measurements were included in the analysis.

The five year treatment plan for 4FRI included 77 springs with flow data. An additional 77 “parallel” springs that contained flow data and were within 20 km of a treatment area were selected at random as control sites. Another random sample of 50 down gradient springs that included flow data and were within 50 kms of treatment areas were selected using a GIS query. These three basic classifications of springs can be used for long-term monitoring and assessment of the impacts of forest thinning on hydrologic resources. We do not expect that all 77 springs within the treatment area, or the full suite of springs in the down gradient and control areas, would be selected for monitoring. The list of springs (see Appendix A, B, and C) is the recommended springs to target for monitoring with the understanding that the final number of monitored sites may be closer to 20 per treatment class. Some springs may not be appropriate for monitoring based on site access, current condition (e.g. if they are now dry), funding, or other considerations.

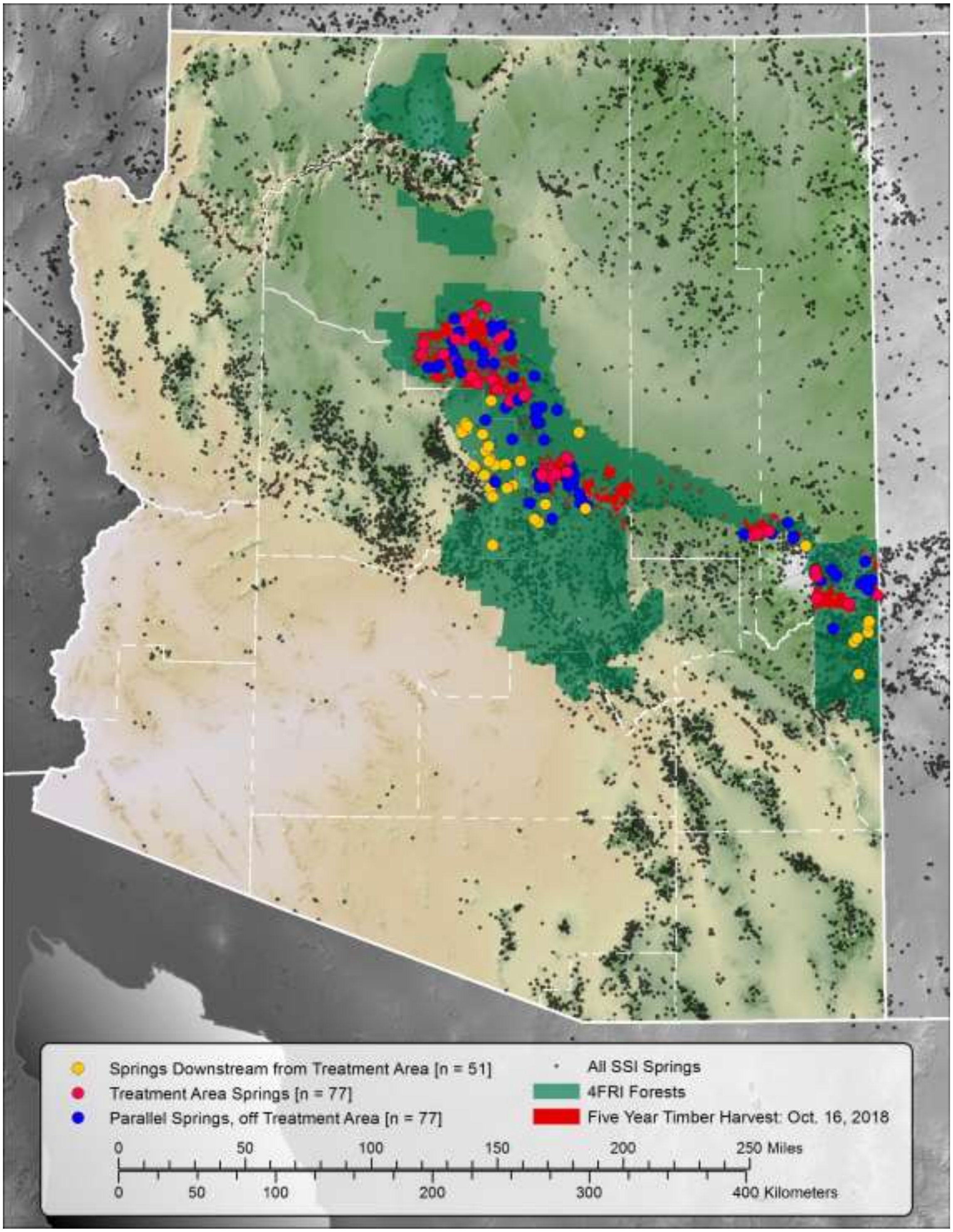

Figure E1. Potential springs for long-term monitoring related to forest thinning. Down gradient ("downstream") springs are within 50 km of treatment areas, "parallel" springs are potential control sites within 20 km of treatment areas.

Treatment Area Springs

Seventy seven springs that had previous flow measurements were identified in the 4FRI treatment areas including Clover Spring, an intensively monitored spring site maintained by Dr. Abraham Springer (NAU). None of the springs, or treatment areas, are below the rim with the lowest elevation spring in the treatment area located at 6634 ft (2010 m) and the highest spring located at 9730 ft (2948 m). Fifteen springs are classified as montane springs (>7500 ft) while 62 springs are classified as plateau springs (6000 to 7500 ft).

Flow at the 77 springs within the treatment area ranged from zero (no flow) to slightly over one liter per second. The springs occupy the zero to 4th order of magnitude, with 12 springs of zero magnitude, four 1st order springs, 32 2nd order springs, 27 3rd order springs, and two 4th order springs. The majority of springs are hillslope springs (36%) followed closely by stream channel springs (rheocrenes; 31%), and wet meadows (helocrenes; 14%). Other springs types include caves, gushets, and anthropogenic springs.

Springs ecosystems may be preferentially impacted by the local microclimate, as expressed by aspect. For the treatment area 18 springs had a southern aspect (drier and warmer climate), 23 springs had a northern aspect (colder and humid climate), and 36 springs had neither aspect. Springs can be compared between the treatment areas, control sites, and downstream sites by aspect, elevation, and flow using common statistical tests (e.g. ANOVA, ANCOVA).

Control Springs

An equal number of springs were selected as control candidates for the springs located in the treatment area (n = 77). Hoxworth Springs, a long term NAU monitoring site, is included in this list. Springs were selected from the Springs Online database using a GIS query. Control springs were randomly selected based on flow data (previous flow measurement required), distance from treatment area (less than 20 km from a treatment area), and position on the landscape (must be upstream or parallel to treatment areas). Hart Prairie, another long term NAU monitoring site, could be considered for inclusion, though it was not randomly selected following the protocols mentioned above.

Elevation at control springs ranged from 4100 ft (1243 m) to 10,140 ft (3073 m) with 11 springs classified as below the rim (< 6000 ft), 34 springs classified as plateau site (6000 to 7500 ft), and 32 springs classified as montane (> 7500 ft). Flow ranges from zero (0 order) to 85 l/s (5th order) with 8, 4, 30, 21, 11, and 3 springs in zero to 5th order respectively (Table 3). The majority of springs types were hillslope springs (40%) with a smaller proportion of rheocrene springs than the treatment area (16%) and an equal proportion of helocrene springs (14%). Eight sites had a southern aspect, 31 with a northern aspect, and 38 with neither aspect.

Down Gradient Springs

Forest thinning will likely impact not only springs within the treatment area but springs that emanate from aquifers that receive groundwater recharge from the treatment area. Springs monitoring down gradient ("downstream") of treatment areas should be monitored to provide a holistic understanding of the impacts of vegetation treatments on groundwater dependent ecosystems. For this project a random selection of 50 springs with flow data was selected from the Springs Online database. Springs were selected in areas up to 50 km down gradient from treatment areas as identified using a GIS analysis. Note that some of these springs may be on non-Federal lands and that some springs may be receiving a mix of "old" and “new” water making detection of 4FRI treatment impacts difficult. Springs monitoring of down gradient springs should be selective and done with the advisement of a hydrogeologist with local and regional knowledge. The list of selected sites includes Page Springs and Bubbling Pond, both listed in Table 3 as sites with long term hydrologic data.

The down gradient springs selected vary in elevation from the control and treatment springs groups. The range of elevations of down gradient springs is from 2093 ft (634 m) to 9200 ft (2788 m) with the majority (47) of springs located below the rim (< 6000 ft). Springs flow ranged from zero to over 1000 l/s (Secret Garden Spring, a source for Fossil Creek). The spring flow orders range from zero order to 7th order with the majority of sites in the 2nd, 3rd, and 4th order classes. Most of the springs do not have recorded data on springs type, but of those that do the majority are rheocrene springs. Slightly over a quarter of the springs had a southern aspect (28%) with 22% of the springs located with a northern aspect and half of the springs with neither aspect.

Springs with Prior Flow Data within the 4FRI Treatment Areas

SiteID	ShortName	SpringType	Elevation (m)	Flow (l/s)	Aspect_Class
771	Spitz Upper	anthropogenic	2130	0.025	Flat or East/West
917	Burnt	cave	2204	0.031	Flat or East/West
551	Pinchot West	cave	2162	0.32869	Flat or East/West
552	Pinchot East	cave	2146	1.5	Flat or East/West
1047	Munds	Helocrene	2110	0	Flat or East/West
591	Windfall	Helocrene	2220	0.03771	Flat or East/West
770	Spitz lower	helocrene	2128	0.0754333	Flat or East/West
1131	Willard	helocrene	2054	0.09	Flat or East/West
524	Buckshot	helocrene	2940	0.188	Flat or East/West
13595	Chipmunk	helocrene	2204	0.24	Flat or East/West
1083	Scott	hillslope	2010	0	Flat or East/West
419	Poverty	hillslope	2193	0	Flat or East/West
549	Drier	hillslope	2194	0	Flat or East/West
782	Sawmill	hillslope	2211	0	Flat or East/West
945	Curley Seep	hillslope	2319	0.003786	Flat or East/West
989	Homestead	hillslope	2212	0.022	Flat or East/West
545	Hunter	hillslope	2203	0.025865	Flat or East/West
855	Griffiths	hillslope	2091	0.0331033	Flat or East/West
1344	Little 44	hillslope	2151	0.05055	Flat or East/West
13587	Thompson	hillslope	2185	0.092	Flat or East/West
1113	T-Six	hillslope	2070	0.099	Flat or East/West
946	Dairy	hillslope	2180	0.3073333	Flat or East/West
181912	North of Willard	hillslope	2057	0.47	Flat or East/West
162	Clover West	hillslope	2092	0.856	Flat or East/West
582	Lower McDermit	hypocrene	2176	0.001	Flat or East/West
1120	Upper Hull	rheocrene	2055	0	Flat or East/West
226448	East Clear Creek Headwaters	rheocrene	2190	0.0075	Flat or East/West
967	Fortyfour	rheocrene	2151	0.043	Flat or East/West
226457	Homestead Channel	rheocrene	2207	0.076	Flat or East/West
592	Long Valley South Lower	rheocrene	2134	0.08417	Flat or East/West
1036	Middle Kehl Meadow	rheocrene	2250	0.0895	Flat or East/West
1037	Middle Kehl	rheocrene	2244	0.099	Flat or East/West
594	Little 44 Upper	rheocrene	2159	0.126575	Flat or East/West
993	Houston Draw	rheocrene	2254	0.455	Flat or East/West
141	Poison	rheocrene	2030	0.666	Flat or East/West
744	Newman		2581	0.631	Flat or East/West
598	Kinder	anthropogenic	2175	0.03155	Northerly
1345	Aspen	cave	2194	0.20525	Northerly
578	One Hundred One	gushet	2180	0.10214	Northerly
774	Beale	helocrene	2255	0	Northerly
525	Burro Creek Headwaters	helocrene	2854	0.22	Northerly
17704	Wind	helocrene	2948	0.41	Northerly
426	Bone Dry	hillslope	2179	0	Northerly
438	Big Moqui	hillslope	2185	0.019	Northerly

Treatment Springs (cont'd)

SiteID	ShortName	SpringType	Elevation (m)	Flow (l/s)	Aspect_Class
1011	Lauren	hillslope	2177	0.035	Northerly
559	Stone Fir	hillslope	2853	0.0756	Northerly
1032	McFarland	hillslope	2224	0.0925	Northerly
955	Double	hillslope	2190	0.3125	Northerly
546	Keller	hillslope	2175	0.3308	Northerly
954	Double 2	hillslope	2190	0.67	Northerly
1072	Riordan Overpass	limnocrene	2195	0	Northerly
1146	Mud	rheocrene	2222	0.014	Northerly
492	Pinchot Channel	rheocrene	2145	0.03248	Northerly
226445	Stump Glen	rheocrene	2191	0.066	Northerly
950	Delinator	rheocrene	2159	0.12	Northerly
920	Buzzard	rheocrene	2070	0.1262	Northerly
1089	Smith	rheocrene	2178	0.145	Northerly
593	Clover	rheocrene	2090	1.39232	Northerly
738	Clover		2189	0.0631	Northerly
754	NE	anthropogenic	2184	0	Southerly
776	East Twin	anthropogenic	2150	0.00631	Southerly
745	Twin	anthropogenic	2130	0.0631	Southerly
1005	Kehl	helocrene	2268	0.1	Southerly
588	Rosilda	helocrene	2047	0.1674257	Southerly
804	Orion	hillslope	2487	0	Southerly
527	Dump	hillslope	2871	0.02487	Southerly
541	Clearcut	hillslope	2848	0.02866	Southerly
13593	Danstone	hillslope	2317	0.096	Southerly
1022	Lockwood	hillslope	2103	0.09723	Southerly
557	Thompson Ranch	hillslope	2696	0.17778	Southerly
802	Chimney	rheocrene	2276	0	Southerly
179644	Lacewing	rheocrene	2407	0.068	Southerly
179647	Porpoising	rheocrene	2469	0.08	Southerly
19773	Crossing	rheocrene	2281	0.12	Southerly
226449	Miller	rheocrene	2171	0.26	Southerly
1016	Lindbergh	Rheocrene	2103	0.3852667	Southerly
226450	Mashed Potato	rheocrene	2221	0.5	Southerly

A List of Control Springs for the 4FRI Treatment Areas

SiteID	ShortName	SpringType	Elevation (m)	Flow (l/s)	Aspect_Class
144	Pivot Rock	cave	2129	1.43	Flat or East/West
648	weed	helocrene	2143	0.00	Flat or East/West
17759	Nine Unnamed 2	helocrene	2613	0.00	Flat or East/West
17400	Two Pond	helocrene	2742	0.00	Flat or East/West
1052	Wilson	helocrene	2664	2.76	Flat or East/West
948	Deep Lake	hillslope	2156	0.00	Flat or East/West
916	Burn	hillslope	2195	0.02	Flat or East/West
13602	Los Burros	hillslope	2386	0.05	Flat or East/West
938	Coneflower	hillslope	2265	0.06	Flat or East/West
746	Dow	hillslope	2044	0.07	Flat or East/West
1014	Leopard Frog	hillslope	2270	0.15	Flat or East/West
446	Veit	hillslope	2626	0.17	Flat or East/West
392	Dane	hillslope	2243	0.30	Flat or East/West
979	Geronimo	hillslope	1612	0.42	Flat or East/West
445	Bob Thomas Upper	hillslope	2564	0.55	Flat or East/West
13769	Welch	hillslope	2824	0.87	Flat or East/West
17758	Nine Unnamed 1	hillslope	2610	2.30	Flat or East/West
714	Rim	hypocrene	2233	0.00	Flat or East/West
15464	Alpine Dry	hypocrene	2516	0.30	Flat or East/West
1264	Bear (tnf)	Rheocrene	1842	0.02	Flat or East/West
990	Horseshoe	Rheocrene	2386	0.03	Flat or East/West
901	Bell Rock	Rheocrene	1305	0.06	Flat or East/West
1086	Seven Anchor	Rheocrene	2371	0.08	Flat or East/West
1313	Turkey	Rheocrene	1783	0.24	Flat or East/West
118	Gray	Rheocrene	2044	0.36	Flat or East/West
898	Bear Paw		3073	0.01	Flat or East/West
807	Elden		2151	0.03	Flat or East/West
13671	CC Franey		2712	0.09	Flat or East/West
13674	CC		2714	0.13	Flat or East/West
997	Hoxworth At The Fault		2139	0.17	Flat or East/West
11706	Turkey		1500	0.32	Flat or East/West
1161	Woods		1929	1.58	Flat or East/West
10587	Landon		2097	1.92	Flat or East/West
18885	Henturkey		1691	3.79	Flat or East/West
18847	A-21-05 10aaa unnamed		2163	3.79	Flat or East/West
18853	R-C		1684	50.48	Flat or East/West
13586	Big		2049	69.41	Flat or East/West
1126	Wet Beaver East		1558	85.19	Flat or East/West
435	Quail	exposure	2093	0.40	Northerly
749	Holloway	helocrene	2100	0.03	Northerly
1087	Sheep	helocrene	2191	0.07	Northerly
793	Tappen	Helocrene	2232	0.07	Northerly
17511	Tres Coyotes	helocrene	2792	0.61	Northerly
393	West Moonshine	hillslope	2220	0.00	Northerly

Control Springs (cont'd)

SiteID	ShortName	SpringType	Elevation (m)	Flow (l/s)	Aspect_Class
1039	Mint Lower West	hillslope	2329	0.00	Northerly
1070	Red Squirrel	hillslope	2285	0.01	Northerly
427	Hidden	hillslope	2309	0.01	Northerly
909	Bootlegger	hillslope	2225	0.02	Northerly
416	Cliffside	hillslope	2309	0.02	Northerly
956	Dove	hillslope	2241	0.03	Northerly
1145	Maple	hillslope	2300	0.03	Northerly
423	Dora	hillslope	2314	0.04	Northerly
439	Royal Bull	hillslope	2317	0.07	Northerly
448	Above Jackson 1	hillslope	2497	0.08	Northerly
17762	Nine Unnamed 5	hillslope	2612	0.09	Northerly
786	Little	hillslope	2233	0.38	Northerly
412	Whistling	hillslope	2297	0.48	Northerly
951	Derrick	hillslope	2213	0.95	Northerly
773	West Elk	hillslope	2197	1.47	Northerly
1123	Weatherford Canyon	rheocrene	2306	0.00	Northerly
1124	Wee Stead Seep	rheocrene	2341	0.00	Northerly
764	Hat Tank Upper	rheocrene	2060	0.06	Northerly
10743	Three Pipe	rheocrene	2555	0.13	Northerly
1060	Phroney	Rheocrene	1243	0.14	Northerly
894	Babes Hole	rheocrene	1805	0.27	Northerly
13614	Buckelew		2282	0.01	Northerly
10586	Aspen		2257	0.06	Northerly
161	Tonto Natural Bridge Upper		1415	6.31	Northerly
16326	Indian Gardens		1656	6.31	Northerly
1147	Oak	hanging garden	2490	1.26	Southerly
768	Mineral	helocrene	2117	0.02	Southerly
1081	Schell	helocrene	2360	0.02	Southerly
13752	Bottom	helocrene	2693	0.20	Southerly
1135	Wingfield Corral	hillslope	2076	0.00	Southerly
983	Grapevine	hillslope	2092	0.01	Southerly
748	Garland	hillslope	2052	0.02	Southerly
18899	Winters no 1		1925	0.06	Southerly

A List of Downstream Springs for Monitoring Related to the 4FRI Treatments

SiteID	ShortName	SpringType	Elevation (m)	Flow (l/s)	Aspect_Class
15028	Page Cave	cave	1067	443.16	Flat or East/West
164110	Secret Garden	gushet	1313	1174.29	Flat or East/West
505	Bush Creek Cabin	helocrene	1802	0.38	Flat or East/West
495	Dutch Oven	hillslope	1969	0.07	Flat or East/West
936	Big	hillslope	1280	0.30	Flat or East/West
1286	Lower Gould	Rheocrene	1217	0.01	Flat or East/West
153	Grimes	Rheocrene	1402	0.02	Flat or East/West
508	Raspberry Trail West	rheocrene	1641	0.02	Flat or East/West
1314	Verde Hot	Rheocrene	827	0.70	Flat or East/West
18803	A-14-06 29dad		1171	0.06	Flat or East/West
987	Hance		1122	0.13	Flat or East/West
11655	Bear Flat		1520	0.25	Flat or East/West
18819	Cottontail		1022	0.32	Flat or East/West
18886	Columbine Sp		1522	0.32	Flat or East/West
18858	A-13-05 16bba 1 Unnamed		928	0.57	Flat or East/West
18874	A-13-05 16bbd 2 Unnamed		923	0.82	Flat or East/West
18868	Catfish		923	1.39	Flat or East/West
18851	Frey ranch		1091	3.79	Flat or East/West
18946	Beaverhead		1107	5.36	Flat or East/West
18869	A-13-05 16bbd 1 Unnamed		927	5.68	Flat or East/West
18956	Indian gardens		1394	7.26	Flat or East/West
18918	Thompson pasture		1399	11.17	Flat or East/West
18829	Turtle pond		1075	11.39	Flat or East/West
18960	Lolo-mai		1073	18.93	Flat or East/West
18913	Lower newell		1034	32.81	Flat or East/West
18836	Bubbling pond		1075	244.76	Flat or East/West
501	Still	rheocrene	1635	0.01	Northerly
1282	Irving High	Rheocrene	1290	0.18	Northerly
502	Twin	rheocrene	1783	0.25	Northerly
1128	Wet Prong	Rheocrene	1226	0.32	Northerly
498	Maple	rheocrene	2018	0.35	Northerly
18964	A-12-07 21dcd unsurv unnamed		1179	0.19	Northerly
18862	Bull Pen		1214	0.44	Northerly
1166	Soda		1098	2.05	Northerly
13486	XXX Ranch Unnamed		1348	6.31	Northerly
18933	Sheepshead canyon		1074	7.00	Northerly
237577	Mother		1580	10.00	Northerly
926	Chalk Point	hillslope	1425	0.17	Southerly
1115	Turkey Seep	rheocrene	1961	0.00	Southerly
940	Cottonwood Basin Unnamed	rheocrene	939	0.04	Southerly
149	Russell	Rheocrene	1085	0.24	Southerly
1305	Sheep Bridge Hot	Rheocrene	634	1.62	Southerly
11755	Sheep Bridge		635	0.01	Southerly
18818	A-13-05 08dbb unnamed		928	0.06	Southerly
18959	Holly		1065	0.06	Southerly
13682	Beehive lower		2788	0.06	Southerly
18903	Hells canyon		1063	0.25	Southerly
15157	Big		1438	11.04	Southerly
18806	Blue		926	13.88	Southerly
15156	The Grotto		1420	21.45	Southerly
18792	Buckhorn		1543	63.10	Southerly