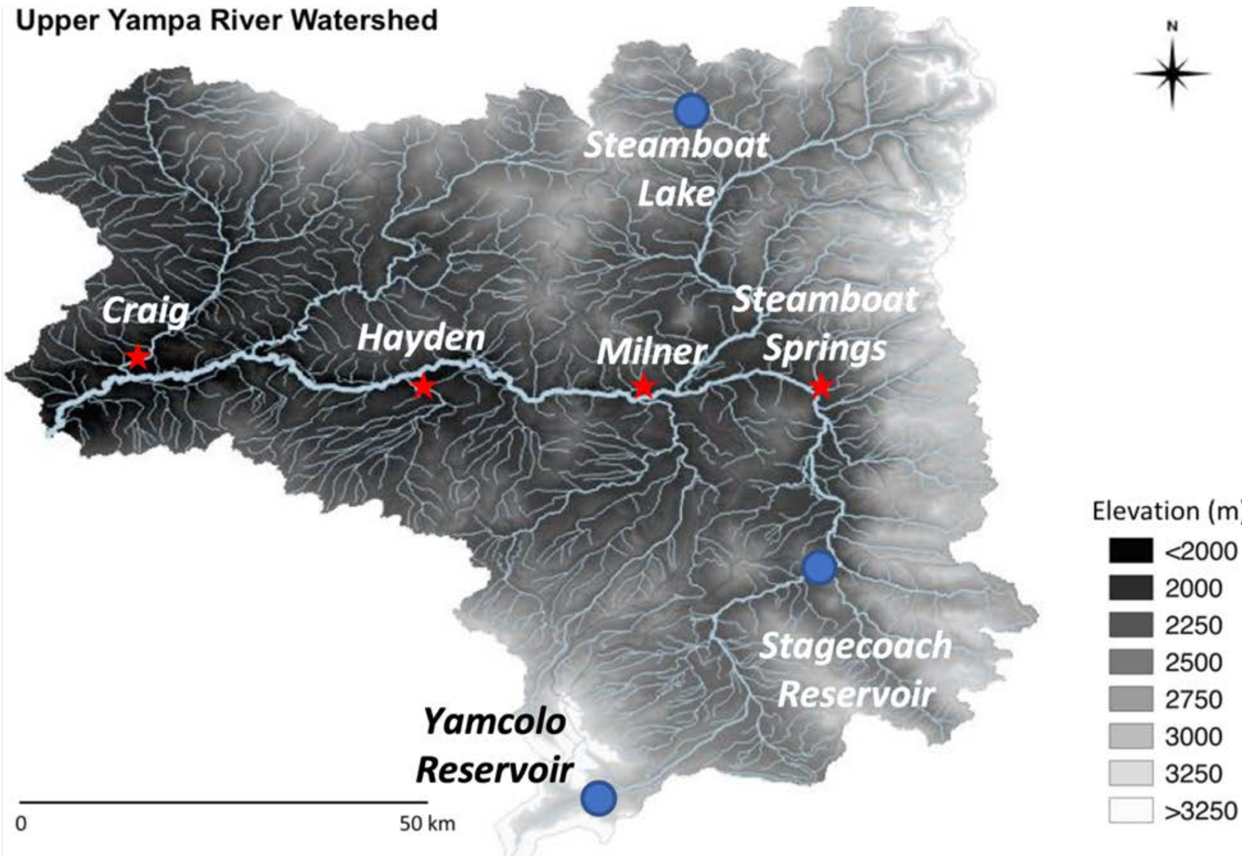
Upper Yampa River Basin Analysis



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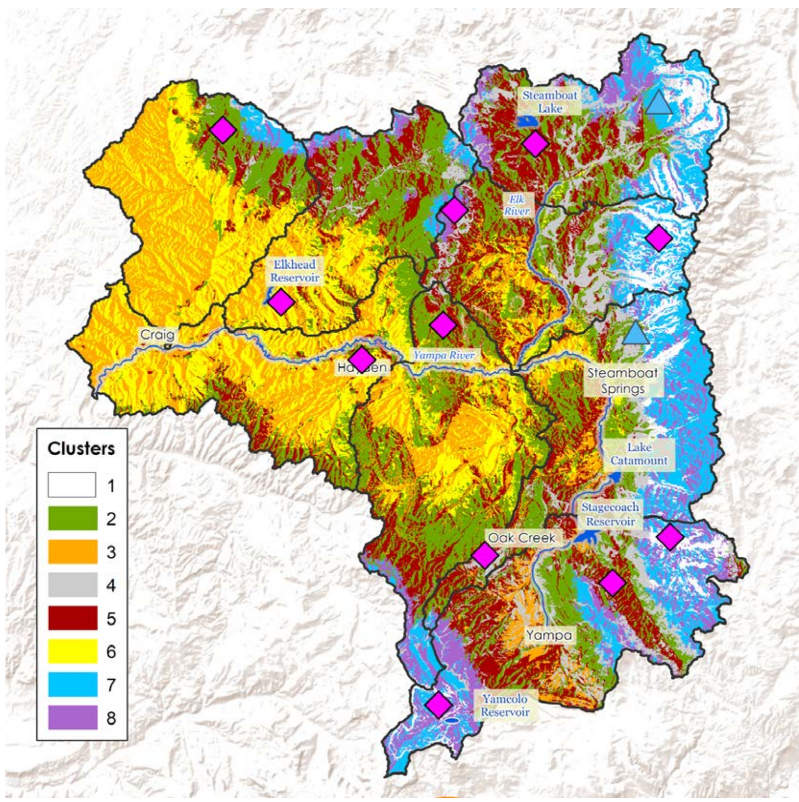
Basin Analysis Executive Summary

Overarching Project Goal: Establish new long-term soil moisture measurements to provide data and scientific insight on the reduction of runoff by dry soils, provide a continuous record of changing landscape conditions with a changing climate, and support operational model and forecast improvements. The goal of this document is to recommend scientifically justified soil moisture station locations and priorities.

Basin Analysis Results and Recommendations

We conducted a basin analysis using available data and stakeholder input to produce a recommendation on soil moisture stations, and identified a top priority for the first station, which will be installed during 2022 as a part of this project. We assessed the atmospheric drivers of soil moisture availability and their changes over time, along with landscape characteristics key to modulating water movement throughout the basin, and incorporated this information with existing station locations and stakeholder input to produce our recommendations. We recommend a minimum of 13 stations within the Upper Yampa. These 13 stations include 2 each covering clusters representing mid to high elevation and precipitation accumulation bands, covering a variety of different aspects, slopes, and landcover, and one each covering the other clusters. Cluster 1 is the highest elevation and precipitation but covers very little of the basin area. Clusters 3 and 6 are lowest elevation and lowest precipitation. Since existing stations within the basin cover two of the clusters, we propose to install 11 new stations in total. The first station we propose installing is in the Headwaters in the Flat Tops. Analysis will be ongoing throughout the installation of the first station to further refine next steps and use the data from the existing stations to continue to refine future proposed installation locations.



1.0 Introduction

The goal of the basin analysis is to support the soil moisture (SM) monitoring effort in the Upper Yampa River Basin (UYRB) by providing the scientific, physically-based justification for proposed SM installation locations. A spatially and temporally high resolution SM observation network will allow for monitoring the antecedent catchment wetness at appropriate scales determined by the initial analysis and ongoing studies (Jasperse et al. 2020). This real-time knowledge of landscape conditions is crucial for runoff and flood forecasts during a precipitation (*P*) or a snowmelt event, as drier soils can act as a buffer for runoff generation during such events (Sumargo et al. 2020). This information may also be useful for seasonal-scale forecasts with additional information on antecedent soil moisture conditions before the start of snowpack accumulation, and drainage of the snowpack into the soils during the season. Over the long-term, the SM monitoring network will benefit the development of distributed hydrologic models, data assimilation systems, and climate change impact assessments.

The basin analysis was completed with stakeholder input. This engagement is meant to ensure the scientific and operational value of the stations, and to ensure the usability of the stations upon installation and accumulation of a period of record relevant for use cases.

This analysis is a key part of the 2-year plan to set up a framework and install a pilot site meant to support stakeholders' decision-making processes and to monitor the potential effects of climate change in UYRB. The work plan includes the design of an SM observing network with a set of recommended numbers of stations and their associated benefits by the end of the 1st calendar year, and installation of a pilot SM observation site in the 2nd calendar year. In future years, key subwatersheds may be a focus of future installations to increase spatial density of stations as appropriate. The pilot site will be installed based upon a balance of high value information and potential to install next year. The permitting process may be started with sites (e.g., National Forests) where the process takes longer, in anticipation of successful fund-raising for more installations. This report outlines the datasets, scope, and methodology used to complete the basin analysis, along with results. Stakeholders' input will also be described.

2.0 Methods

The basin analysis considered the meteorological drivers of SM variability, the land surface factors affecting SM variability, the water collection zones, and land use and stakeholder boundaries. Considering these factors in the analysis helped to identify basin areas that can provide information to support water resources decision making, and are potentially most sensitive to climate change. The analysis identified optimal locations to add new stations where no available soil moisture measurements currently exist. The analysis also provides a set up for future analyses and research pathways, particularly those involving *P*, snowmelt, SM, and runoff processes in UYRB. For this purpose, a compilation of the existing soil moisture observations in

UYRB is essential; they are provided here from SNOTEL, the only source of real time soil moisture information currently available in the watershed.

2.1 Stakeholder Input

Conversations with stakeholders were critical to finalizing the basin analysis. We focused on the Upper Yampa Water Conservancy District (UYWCD), the project sponsor, and the Colorado Basin River Forecast Center (CBRFC), the official forecast provider in the region. While RFC forecasts are not used operationally right now by UYWCD, model improvements throughout the National Weather Service in the coming decades are expected to include capacity to utilize observations like soil moisture as part of efforts to improve forecasts and support water resource decision making.

At the CBRFC, we spoke with Senior Hydrologist Brenda Alcorn and the Decision and Operations Hydrologist John Lhotak. Key takeaways from the interview included that the existing SNOTEL sites in and near the basin often get too wet and are not deep enough to fully understand the hydrologic processes within the soil. Furthermore, the sensor depths used did not correspond well with the model and different depths may be useful in new stations. The CBRFC hydrologists recommended a first look at middle elevations relative to the basin elevation distribution. They provided a link to elevation distributions in their model stratified by zone (found here). In their view, short term benefits of appropriately sited soil moisture stations could include understanding the soil state before the snowpack forms, and understanding how well the model is representing the soil moisture characteristics throughout the year. In the long term, benefits could include utility in next generation models, including with data assimilation of soil characteristics at model initialization.

At the UYWCD, our team spoke with General Manager Andy Rossi and District Engineer Emily Lowell. We learned that current operations successfully use information from two SNOTEL sites near the basin, Ripple Creek and Lynx Pass, in order to predict inflows and make management decisions. This is starting to work less well as the climate changes. In the short and long term, potential benefits from these stations include understanding how much of the water from the snowpack might be draining into the soils throughout the season instead of entering the streams, and how this varies spatially. Soil moisture information would be valuable before the snowpack forms as well as tracking the moisture from the snowpack during snowmelt, and understanding soil moisture drainage throughout the rest of the year. This information could initially be used for situational awareness. In the longer term, information from these stations may be added directly into the planning process, similar to how the two SNOTEL sites are currently used.

2.2 Atmospheric drivers of soil moisture variability

Atmospheric processes strongly influence SM variability. In a snow-dominated basin like the UYRB, *P* and temperature (*T*) are dominant drivers of the surface water budget. The relative contributions of these quantities to the SM fluctuations vary depending on the season. For example, *P* is the dominant moisture source in fall and winter, while *T* is a dominant source in the spring through driving snowmelt-runoff processes (Bales et al. 2006). *T* and other quantities, such as solar radiation and humidity, can modulate the SM during the summer through evapotranspiration (Hanson 1991). Consequently, analyses of the basin hydrometeorology and hydroclimatology can provide essential support for the SM instrumentation effort, and in this phase of the project we focus on *P* and *T*.

The annual and daily 4-km gridded Parameter-elevation Regressions on Independent Slopes Model (PRISM: PRISM Climate Group 2004) datasets were used for the *P* and *T* analyses. We computed the mean (μ), standard deviation (σ), and coefficients of variation (CV) of annual-total (*P)* and seasonal average temperature (*T*) for the 30-year period of 1981-2010. The 1981-2010 period is an established baseline for “climate normals” (NOAA NCEI 2021). CV refers to the ratio of the standard deviation (σ) to the mean (μ) of each variable, i.e., the interannual variability relative to the climatological average. This metric is especially useful when multiple variables with different μ states are considered or compared. These were compared to the mean, standard deviation, and coefficient of variation during 2011-2019 to understand how these atmospheric drivers of soil moisture variability may be changing with climate. We included the 4-month period March-June in addition to other seasons (here defined as Jan/Feb/Mar; Apr/May/Jun; Jul/Aug/Sep; Oct/Nov/Dec). The March-June period represents the snowmelt/water supply operation season in the region.

2.3 Cluster Analysis

In the cluster analysis, we used atmospheric and land surface variables to explore where SM stations will be most useful to capture the basin scale soil moisture on event, seasonal, and climate scales. This approach was used successfully in northern California’s Russian River watershed (Sumargo et al. 2020) and is currently being replicated for other Forecast Informed Reservoir Operations (FIRO) projects, which require state of the art monitoring to support successful water resource management. The Russian River watershed covers approximately 1500 mi^2, while the Upper Yampa covers about 2000 mi^2. However, the portion covered by the additional soil moisture stations funded through FIRO was a single subwatershed covering just 105 mi^2. Here, we start the process with the entire watershed. As these stations begin to accumulate observations and start to provide critical information, key subwatersheds may be a focus of future installations to increase spatial density of stations as appropriate.

The first step in this analysis is to identify appropriate variables. Here, with the help of stakeholder input described in Section 2.1, we consider *P*, vegetation, and terrain features such as elevation, slope, aspect, and land cover (Table 2.3.1). Other variables, such as soil type, were considered for their usefulness in identifying the cluster areas relevant for the SM observation installation.

Table 2.3.1 Variables considered in the cluster analysis. Note that gray shade and italics indicates that the variables were evaluated based on the clusters identified by the other variables.

Variable	**Resolution**	**Source**	**Reasoning**
Total Annual Precip - 30 Year Norm	800m	PRISM	necessary to understand water input to soils
Digital Elevation Model (DEM)	30m	USGS	topographic characteristics critical to understanding how water moves through the landscape
Slope	30m	USGS	
Aspect	30m	USGS	
Normalized Difference in Vegetation Index (NDVI)	30m	Landsat 8	land surface characteristics that can modulate how much precipitation reaches the soil
National Land Cover Database (NLCD) 2019	*30m*	*NLCD*	
POLARIS Soil Type	*30m*	*POLARIS*	probabilistic soil series map of the contiguous United States

Cluster analysis was conducted using the k-means clustering algorithm, an unsupervised machine learning technique that assigns numerical data to clusters by finding the mean distance between data points (MacQueen 1967). The k-means clustering algorithm is sensitive to varying ranges in variables, such that a variable with a larger range will contribute larger influence to the clustering than a variable with a smaller range. For this reason, data standardization is a recommended step before performing the analysis to transform the variables into a unitless, standardized range of values. We performed a minimum maximum transformation function, a common transformation used for skewed sample data, to reclassify the data to a range of 0 -100. Next we transformed the digital elevation model 30 meter resolution raster grid into points and extracted the values for each of the standardized variables into a single table for use in JMP statistical software.

In JMP we performed a k-means clustering analysis for 2-15 clusters on the 5 reclassified variables. For each k-means the tool calculates the cubic clustering criterion (CCC) value as a method to select the optimal number of clusters by minimizing the sum of squares. The CCC peak value indicated the optimal number of classes for our sample to be 8 (Figure 2.3.1), although additional peaks after that choice indicate potential utility in more stations. We converted the results of the 8 clusters back into a 30 by 30 meter raster grid for spatial analysis.

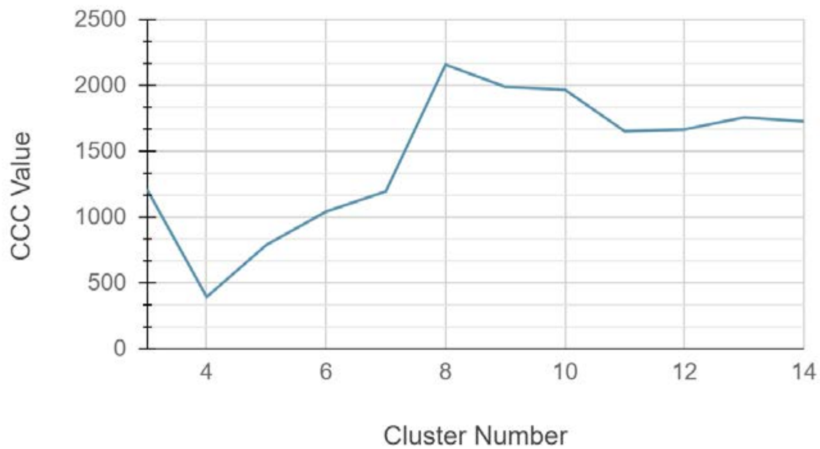


Figure 2.3.1: Cubic Clustering Criterion (CCC) value per total number of clusters.

2.4 Water Collection Zones

To assess areas key to sample for water management support, we combined our results from the stakeholder analysis, atmospheric drivers, and land surface factors. As the project continues we will leverage ongoing modeling efforts and the beginning of our data collection to further understand areas critical to water management - e.g., to answer the question: Where do the soils have the greatest effect on how precipitation enters the tributaries and the main stem of the Yampa River?

3.0 Results

3.1 Atmospheric Drivers of Soil Moisture Variability

First, we assess the climate normals for 1981-2010 and consider basin-scale *P*. The *μ* field exhibits high annual total *P* of up to 2000 mm over the high-elevation areas in the eastern and southern flanks of the basin, reflecting the orographic enhancement. This number is almost 10 times that in the low elevation areas, where the annual *P* is as low as 200 mm. The *σ* field exhibits high variability of up to 300 mm over the high elevation, high *P* zones. In contrast, the CV field shows highest variability of up to 0.2 over the low elevation areas to the western and southwestern flanks (Figure 3.1). A pocket of high CV is also apparent over the northeastern corner of the basin. This CV pattern suggests that the interannual variabilities of *P* over these areas are relatively large compared to their climatological averages. However, other low elevation areas in the north and in the southeast exhibit CV of as low as 0.14. Based on Dettinger et al. (2011), this range of CV is nearly as significant as the difference in *P* variability between Colorado and some other regions in the U.S., such as the Midwest.

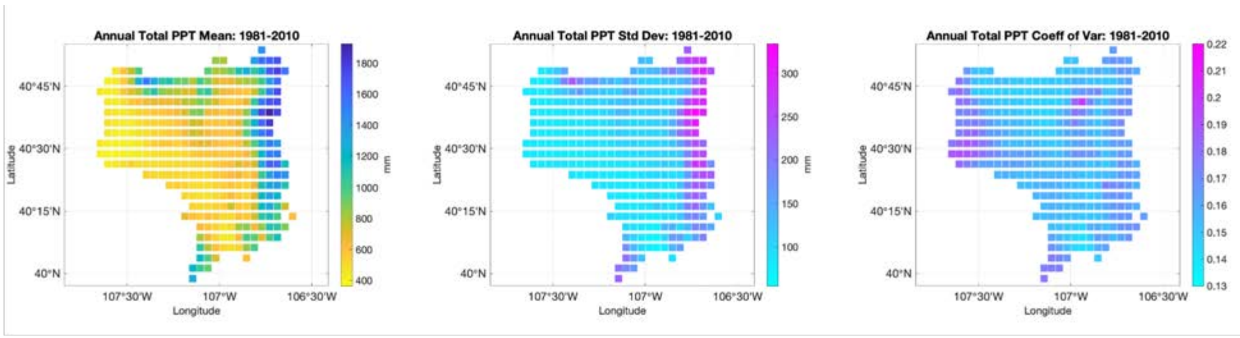


Figure 3.1. The average (left), standard deviation (middle), and coefficient of variation (right) of the annual-total PRISM precipitation for the 1981-2010 period.

For *T,* we present mean and standard deviation only, as the CV spatial patterns did not display any differences from the standard deviation. The μ field, as expected, shows higher average *T* of over 5°C over the lower elevations for Oct-Dec, increasing to over 10°C over Jan-Mar (Figure 3.2). The variability as shown by the σ is as high as 2°C over the far western portions of the basin during Jan-Mar, and under 1°C over the eastern part of the basin in Oct-Dec (Figure 3.3).

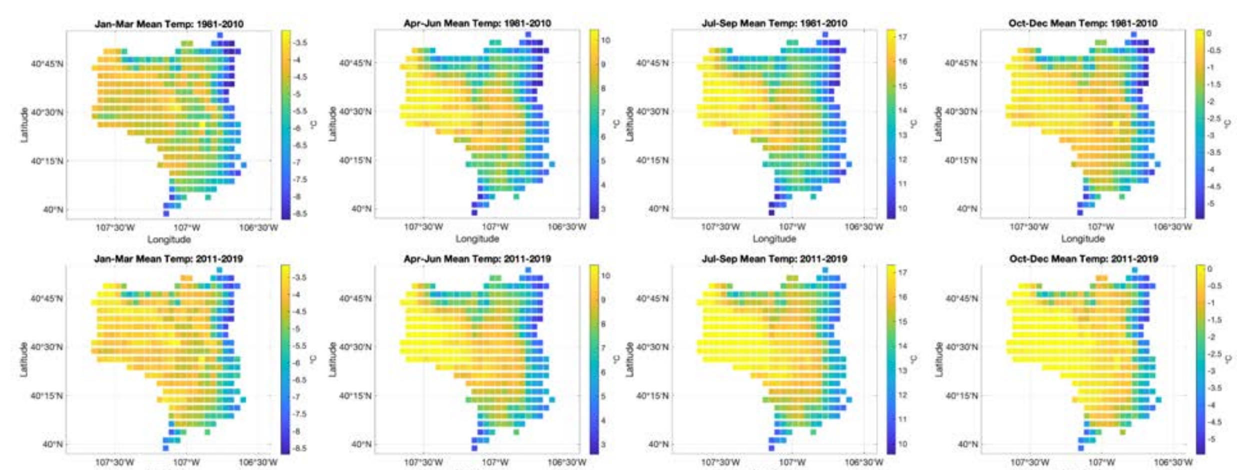


Figure 3.2. Seasonal-mean temperature for both the 30 year period 1981-2010 (top row) and the period 2011-2019 (bottom row). Note the different scales per season (row). Scales are the same for each season (column).

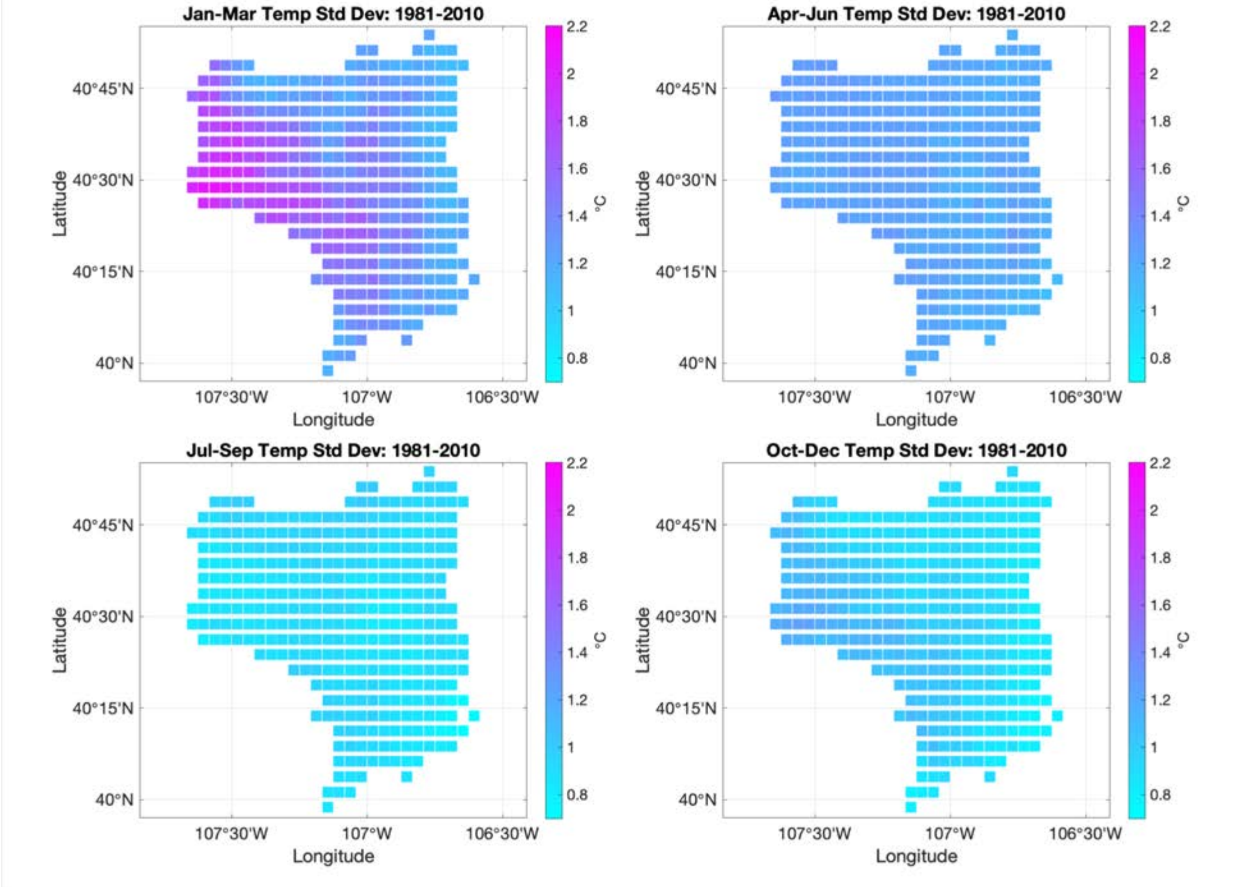


Figure 3.3. Seasonal standard deviations of temperature.

When looking at the change in average over the past decade by season, the temperatures show the largest increase in the higher elevations and far eastern part of the basin in Jul-Sep (Figure 3.4). This could affect the drying out of the soils before the snowpack begins to accumulate in the fall. Unsurprisingly, average temperatures are rising across all grid points in the basin. We also looked at these quantities for the period most critical to snowmelt - the four month period Mar-Jun (Figure 3.5). Compared to Apr-Jun, the average highest temperature is lower. The highest standard deviation is also lower than either period Apr-Jun or Jan-Mar, and there is a small increase in the highest average change in precipitation, closer to Jan-Mar. As noted above, there is no big difference in the pattern of the CV and the σ for this period.

For annual total P, the decade 2011-2019 showed a decrease in almost all grid points over the climate normals from 1981-2010, with some outliers showing decreases of over 250mm/year in the southernmost part of the basin (Figure 3.6).

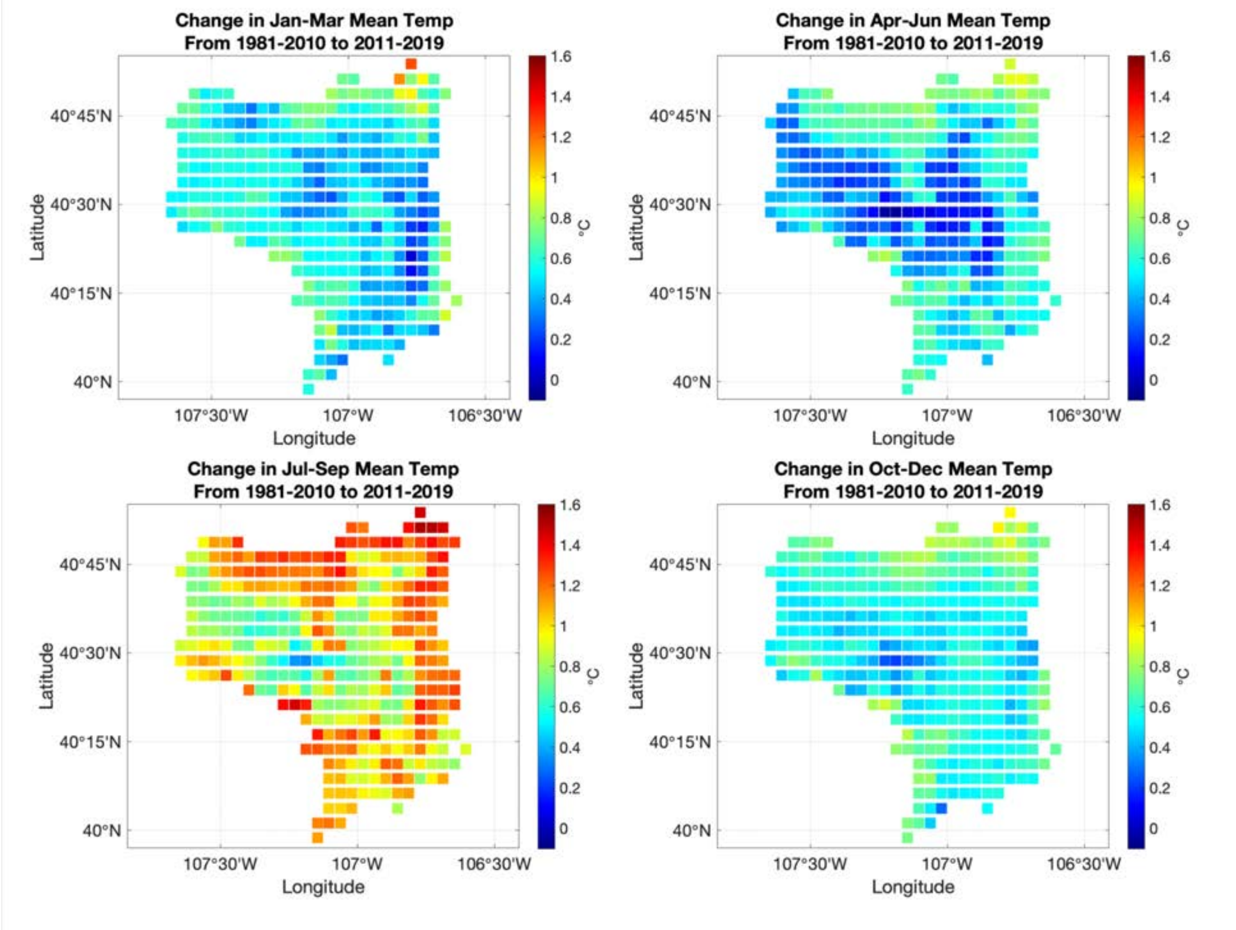


Figure 3.4. Seasonal change in temperature average from 1981-2010 to 2011-2019.

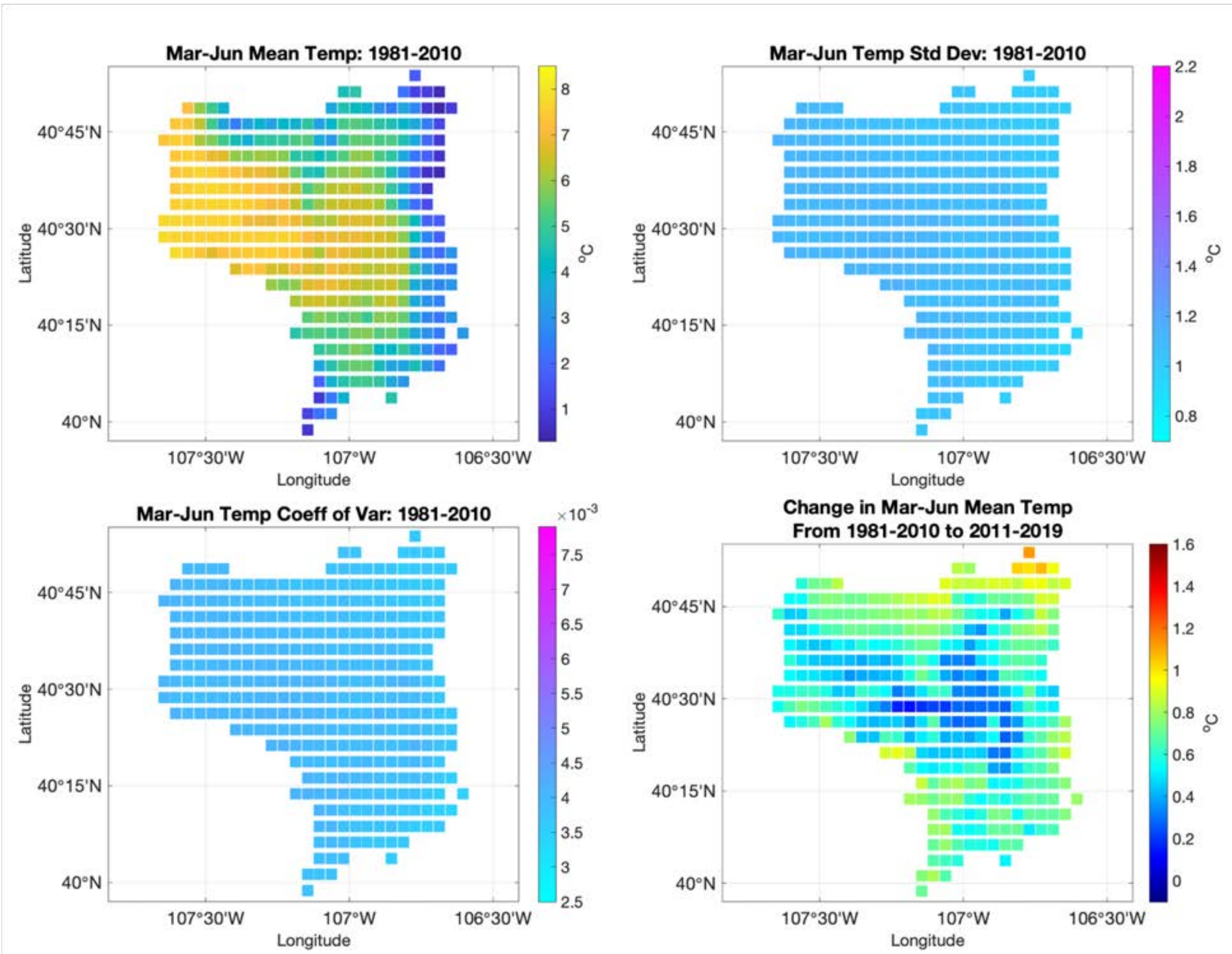


Figure 3.5. Average, standard deviation, coefficient of variation, and change in average temperature during March-June from 1981-2010 to 2011-2019.

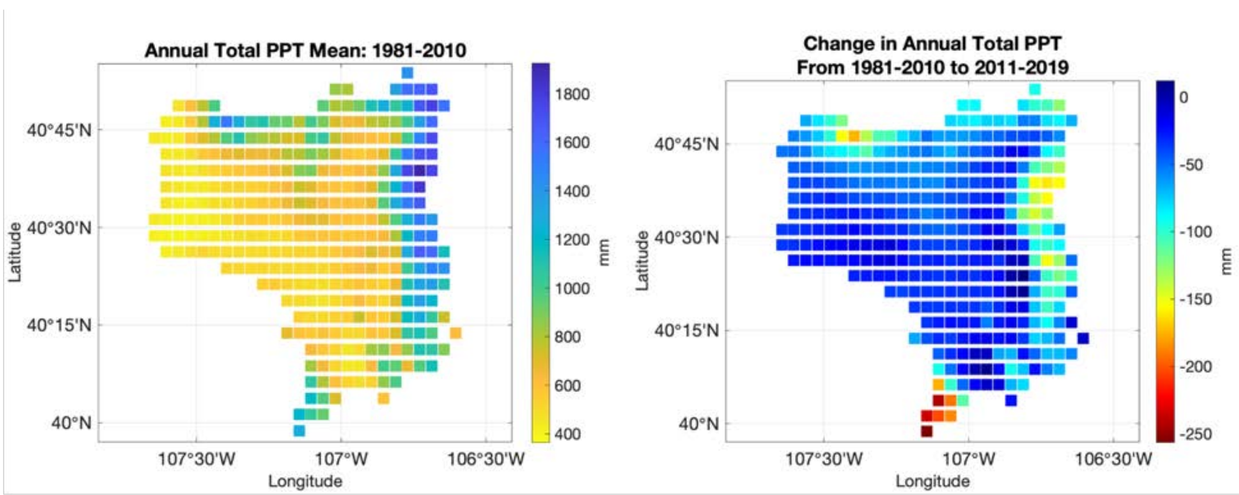


Figure 3.6. Average annual change in precipitation from 1981-2010 to 2011-2019.

3.2 Assessing the Land Surface Factors Affecting the Soil Moisture Variability

Cluster analysis results indicate a robust separation into precipitation bands, elevation bands, and terrain characteristics (Figure 3.2.1, Table 3.2.1). With sufficient resources, each cluster could be covered in every HUC10 (up to 55 stations, see Figure 3.2.2 for the spatial distribution at each cluster), or the cluster analysis could be redone at that spatial scale.

The cluster analysis was also conducted at 800m resolution with, as might be expected, coarser results showing 6 identified clusters as the first reasonable number. Because of the importance of the terrain variables which were available at high resolution, the decision was made to use the results at 30m scale. The analysis was also done with temperature data as well as precipitation, but temperature in particular is so highly correlated with elevation that it was noted as redundant (not shown). Datasets on this analysis can be made available, including Geographic Information System (GIS) layers and databases. Figures can also be made available showing, for example, boxplots of the distribution of the different parameters by cluster.

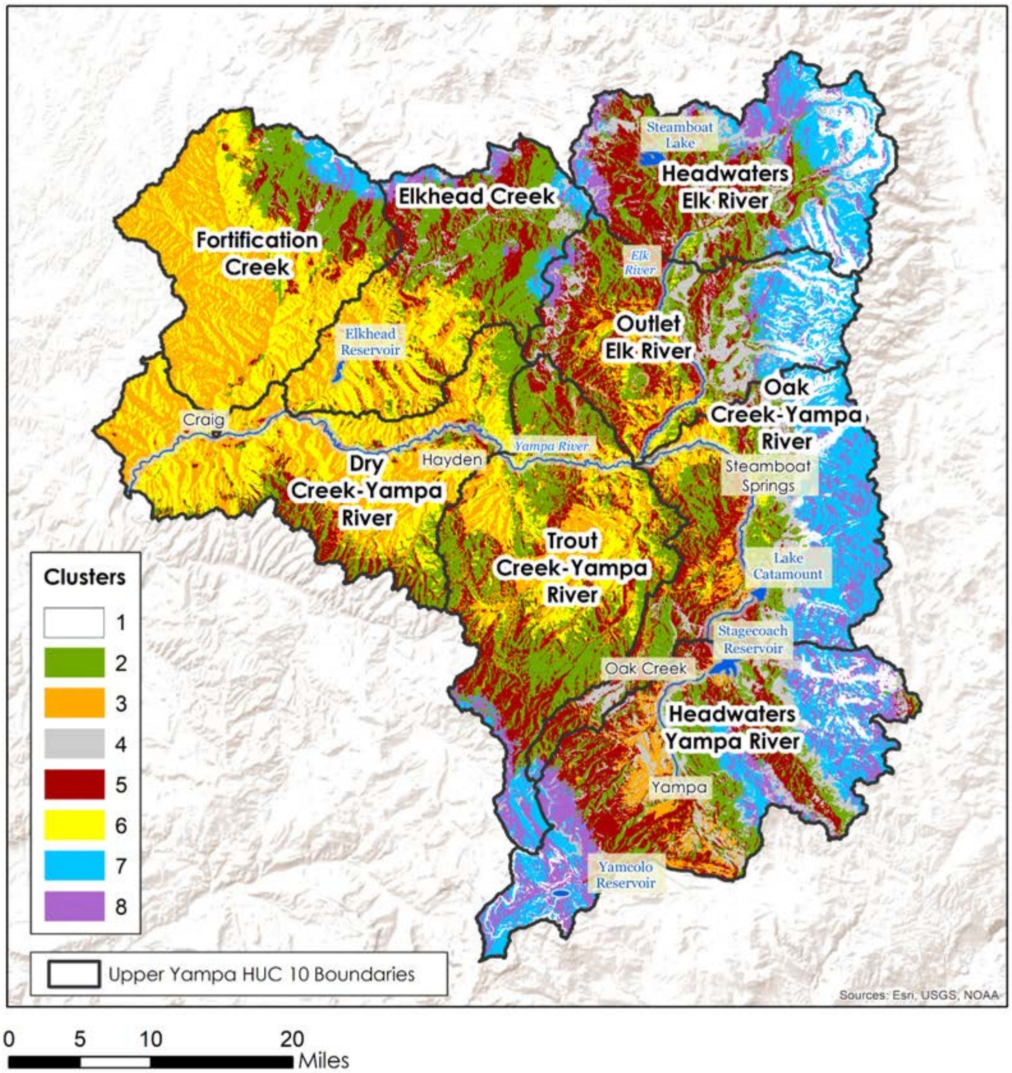


Figure 3.2.1: Spatial map of identified clusters in the Upper Yampa River Basin.

Table 3.2.1 Clusters and their characteristics. Total basin area 2161.4 mi^2. Shaded rows are similar to the same color in terms of precipitation and elevation, with key differences in terrain characteristics.

Cluster	% Basin Area	Precipitation (mm) Percentile: 25th Median 75th	Elevation (m) - Percentile: 25th Median 75th	Characteristics
1	3.8	1211 1407 1594	2978 3140 3304	highest precip/elevation/slope, sandy soil, scrub, less dense forest
2	20	560 645 759	2255 2435 2598	low-mid precip, mid elevation, forested, S/W aspect, low-mod slope, wide mix of soils
3	16	425 479 523	1995 2059 2148	low precip/elevation/slope, NE-SE facing, wide mix of soils, pasture/developed
4	8.6	544 638 790	2255 2421 2614	low-mid precip, mid elevation, lower slopes, S/W facing, sandy soil, forested
5	19	551 617 713	2240 2441 2589	lowest-mid precip, mid elevation, lower slopes, E facing, wide mix of soils and land cover
6	15	432 484 532	2002 2067 2154	low precip/elevation/slope, wide mix of soil, W-facing, developed land/pasture
7	9.8	1071 1223 1418	2880 3012 3165	high-mid precip/elevation, some higher slopes, sandy soil, S/W facing, less dense forest
8	7.8	963 1099 1269	2837 2954 3093	high-mid precip/elevation, some higher slopes, sandy soil, N/E facing, less dense forest

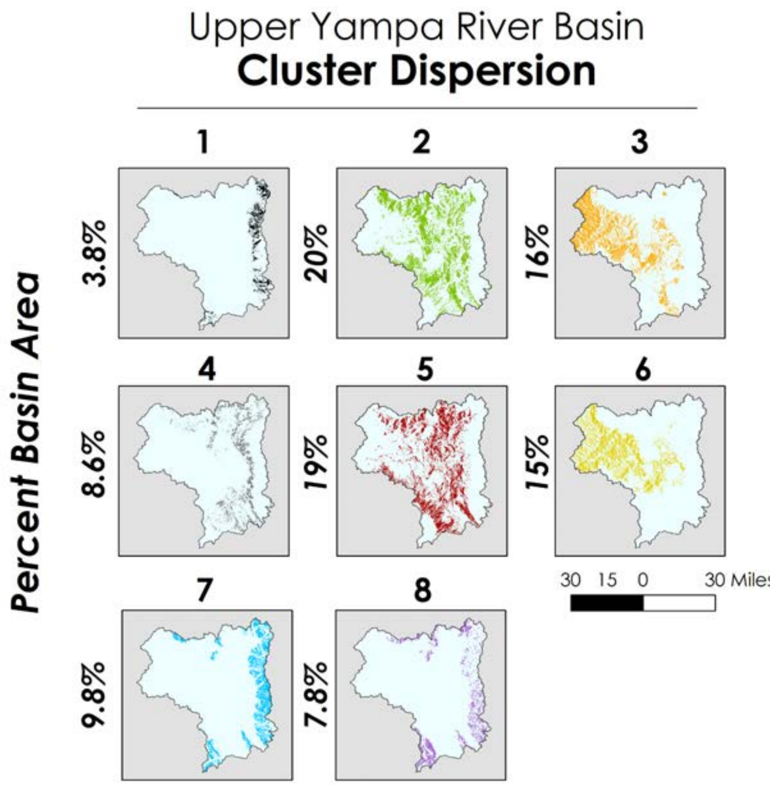


Figure 3.2.2. Spatial maps of each cluster independently, along with percent of basin area.

3.3 Water Collection Zones

Per the combination of stakeholder input on locations where peak snow water equivalent (SWE) information is currently used, and the limitations of existing soil moisture stations, we focus on understanding where we might site new stations to cover both high variability precipitation and temperature, changing precipitation and temperature over the past decade of PRISM data, along with making sure that we adequately cover representative areas as defined by the cluster analysis. We did this via map overlays in GIS. Note that these are currently proxies for the areas that might be most important for water management. As the project continues, we will look at existing soil moisture observations, new observations, and leverage existing modeling studies to understand where the soils have the highest influence on runoff generation.

4.0 Recommendations

We recommend that all of the identified clusters be covered with two stations each. If needed, these can be reduced to one each at Cluster 1, which has a very small overall contribution to basin area (under 5%), and Clusters 3 and 6, which are low elevation and low precipitation. Lost Dog and Lynx Pass already cover Cluster 7 and Dry Lake covers Cluster 2 (see Table 4.1). However, Lynx Pass is slightly outside the watershed, while Lost Dog and Dry Lake are not particularly useful yet as they were sited not for soil moisture but primarily for snowpack measurements (see Section 2.1). Therefore, we still recommend adding one station each in Cluster 7 and 2. This gives a total of 11 recommended additional stations, with one funded to be installed during the course of this project (see Figure 4.1). Within clusters, we recommend a focus on the areas identified in Section 3.1 that show high precipitation variability and large precipitation and temperature changes over the last decade. With this in mind, the priority for Station 1 is located in the Flat Tops at the southwestern end of the Upper Yampa Headwaters basin. The clusters that were identified through this exercise do not correspond with the zones used in the Colorado Basin River Forecast Center model (not shown). However, the recommended area, which contains areas in both Cluster 7 and Cluster 8, is a part of the Yampa-Above Stagecoach zone in the model. Middle elevation in that zone ranges from 8000-9500 feet, and we recommend a site within that band.

If additional funding should become available, more stations, for example one per cluster in each HUC10 within the watershed, could be very useful. This recommendation will gather strength as we enter the second year of the project and begin showing utility in the soil moisture gauges as the period of record lengthens.

Table 4.1 List of SNOTEL stations in and near the Upper Yampa River watershed with soil moisture measurements.

Station Name	Latitude	Longitude	Elevation (ft)	Start Date of soil moisture obs	Cluster
Lynx Pass	40.08	-106.67	8880	25 Sep 2002	7
Lost Dog	40.82	-106.75	9320	9 Sep 1999	7
Dry Lake	40.53	-106.78	8400	29 Jul 2003	2

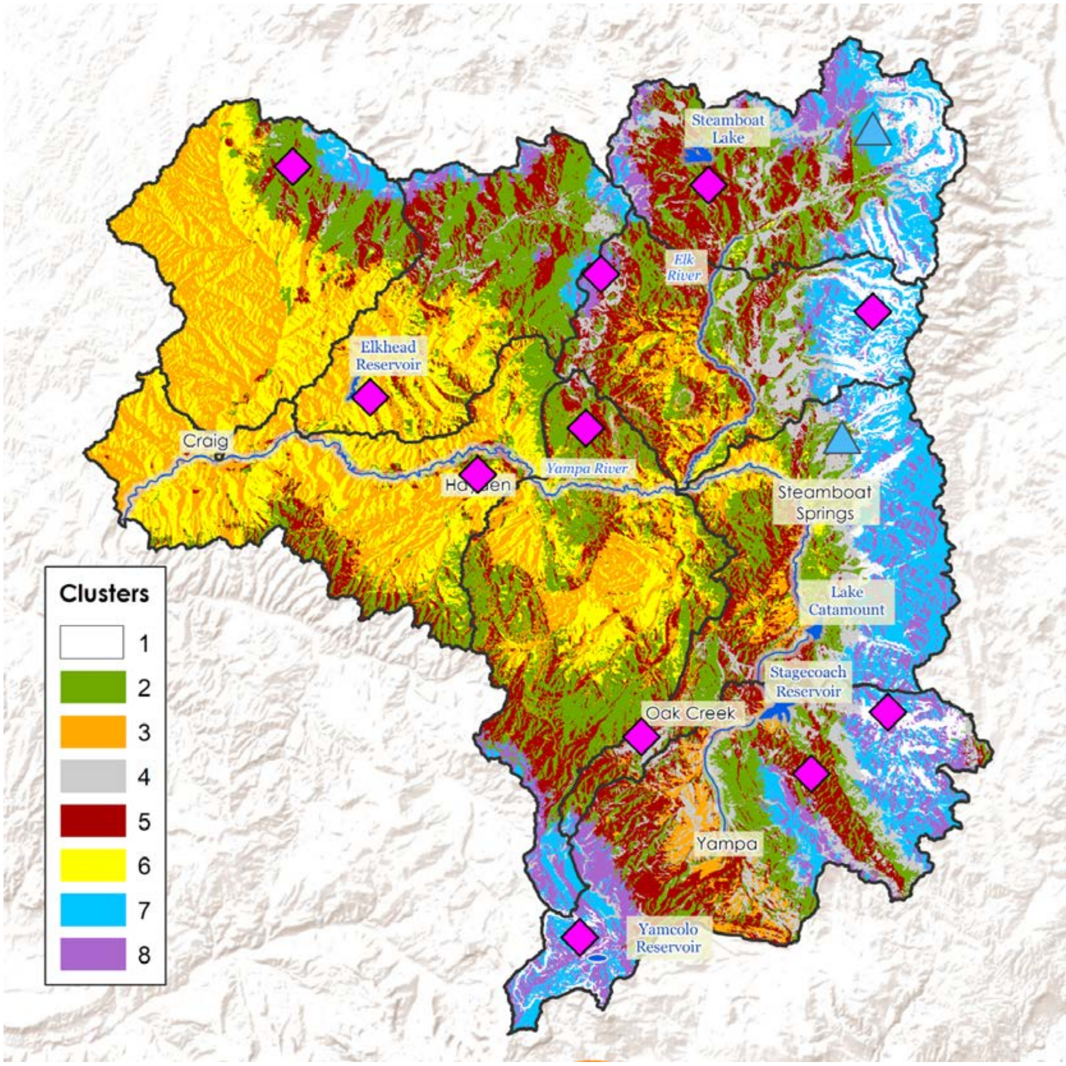


Figure 4.1 Map of the clusters identified by k-means, with HUC10 outlines, existing soil moisture stations (blue triangles) and proposed new soil moisture stations locations (pink diamonds).

Acknowledgements

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